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Determination of bank structures and river width variations using remote sensing data

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ABSTRACT

The European Water Framework Directive commits the member states to achieve the good ecological status for all waterbodies. For this purpose on the level of the national states monitoring programs are established with the aim to verify the actual status by means of regular surveys. Already in the past remote sensing data in conjunction with methods of geospatial data analysis revealed the added value in terms of monitoring strategies regarding the European Water Framework Directive. Depending on the type of data they can be used for example for the determination of several parameters of rivers and streams. The present analyses show how it is possible to determine the parameter of width variation of small and medium rivers based on digital orthophotos. Because this parameter strongly depends on the geometric quality of the riverbank line, its determination is given particular attention. It turns out that mainly riparian vegetation has a large impact on the visibility of the riverbank line. In a multi-stage process different methods for the identification of affected areas are developed with the aim to reconstruct the true riverbank line in a second step. Finally these data form the basis for the determination of river width variations.

Keywords: riverbank structure, river width variation, European Water Framework Directive

1. INTRODUCTION

With the European Water Framework Directive the European Union committed there member states to prove the good ecological status of all rivers. This status includes the biological quality of the water body, such as the benthic invertebrates or the aquatic flora, as well as the physical-chemical quality (e.g. temperature, nutrient conditions).¹⁻³ The entire monitoring of watercourses is based on the use of a variety of different methods. These methods are oriented towards the multiple parameters to be collected. In this context remote sensing data, remote sensing methods and methods of applied geoinformatics are of particular interest, especially for the determination of hydromorphological parameters.⁴⁻¹⁴

The implementation of the directive takes place at the level of the member states. In the Federal Republic of Germany the German Working Group on water issues of the Federal States and the Federal Government represented by the Federal Environment Ministry (LAWA) has developed a mapping procedure for small and medium rivers. This approach comprises two different mapping procedures (on-site-method; overview method). For the overview method the use of remote sensing data is strongly recommended.^{15, 16}

1.1 Motivation

It has become clear that remote sensing is already in use as a method of data acquisition in the domain of water research. That applies in particular for the analysis of radiometric information. At the same time it is noted that geometric information about rivers are only barely or not available. For most rivers centrelines are provided by the local authorities. In exceptional cases geometric information about the riverbanks are available. Furthermore it was found that the quality of this information can have a direct impact to the assessment of a river section in accordance with the European Water Framework Directive.¹⁷ Karrasch and Hunger (2016)¹⁷ showed that the mean distance of an administrative river centreline compared to a river centreline determined from remote

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sensing data for a small river in the Free State of Saxony is about 2 m. This seems to be a high accuracy but for more than a quarter of river segments this deviation is more than 4 m and reached high values of up to 20 m.

Geometric information about a river are for example the river centreline, the river sinuosity, the riverbank or the river width variation. In this regard it appears that the line of the riverbank is of particular importance. By means of these lines it is possible to determine the river centreline or the sinuosity of a river.^{17,18} Therefore they have a direct impact on the assessment of a river. However, the riverbank line is also a very important information regarding the analyses of erosion or channel migration.^{19–22} A detailed overview of analyses of river bed morphology using remote sensing data is given by Lane et al. (2010).²³ Furthermore analyses also show that processes of channel migration can have a direct impact on the vegetation in the environment of the river.²⁴ Depending on the width of a river different remote sensing products are available to extract the riverbank lines. For large rivers satellite images are quite useful.^{22,25,26} In contrast, for small and medium rivers it is necessary to use data with higher geometric resolution.^{27,28}

Figure 1 shows a small part of a digital orthophoto as well as the extracted riverbank line.

Figure 1. Sub-image of a digital orthophoto of the Freiburger Mulde with clearly visible overhanging vegetation

It is very clear that the visible riverbank line is strongly influenced by the riparian vegetation. In such areas the true riverbank line is covered by overhanging vegetation. If this riverbank line is used for the determination of the river centreline it will have a negative impact on the accuracy of the centreline and subsequently to other parameters like the river sinuosity. The same applies for the determination of river width variations. For the usability of remote sensing data the determination of the true riverbank line is a necessary precondition.

The objective of this research is to introduce a semiautomatic approach for determining the river width variation of a medium river in conjunction with the determination of overhanging vegetation and the modelling of the true riverbank line. The analysis follows a sequence of four steps:

1. Determination of visible riverbanks
2. Detection of overhangig vegetation
3. Modelling the true riverbank line
4. Determination of river width variations

All analyses are not performed on an entire river. For the development of the methods it is sufficient to use a well-chosen section of a river (cf. chapter 1.2).

1.2 Data and Study Area

The most important data sources are digital orthophotos provided by the *Saxon State Spatial Data and Land Survey Corporation* (GeoSN). The orthophotos are four channel data and include information in the visible spectral range (rgb) as well as one additional spectral channel of the near infrared. The geometric resolution is 20 cm; the radiometric resolution 8 bit. The recording of data was performed in July 2015 and the data are georeferenced in ETRS89 UTM, Zone 33. Furthermore a digital terrain model (DTM) and a digital surface model (DSM) are available. Both elevation models have a geometric resolution of 2 m and a height accuracy of 0.2 m. Both digital orthophotos and DTM/DSM are provided by the GeoSN. As a part of data preprocessing a normalised digital surface model is calculated by computing the difference between DSM and DTM.

The study area has an extent of about 2 km of the river Freiberger Mulde. It is located north of the small town Döbeln between Westewitz and Leisnig. The Freiberger Mulde has its source in the Eastern Ore Mountains and merges with the Zwickauer Mulde after 124 km to form the river Vereinigte Mulde. After additional 147 km the Vereinigte Mulde flows into the river Elbe between Dessau and Roßlau. The chosen section of the river is characterised by different riverbank structures. The overhanging vegetation which is visible in the orthophotos is characterised by single trees, groups of trees and rows of trees with a length of several hundred meters covering the true riverbank line. But there are also areas with no overhanging vegetation especially at the right riverbank. Due to the heterogeneity of overhanging vegetation the chosen river section is suitable for the development of methods regarding the introduced research question.

2. METHODOLOGY

2.1 Determination of visible riverbanks

The visible riverbank lines were extracted using digital orthophotos and the normalised digital surface model (nDSM) using eCognition Developer 8, one of the most powerful software tools for object-oriented image segmentation. The software provides a number of different methods of segmentation to generate image objects. The segmentation of the orthophotos is performed using the multiresolution segmentation with a scale parameter of 40, a shape value of 0.1 and a compactness value of 0.7 (cf. figure 2).

Figure 2. Segmentation result (eCognition Developer 8) of the sub-image of a digital orthophoto of the Freiberger Mulde

The nDSM is primarily used to extract bridges over the river and to assign these segments to the river polygon. By means of the Normalized Difference Water Index²⁹ (NDWI), the Normalized Difference Vegetation Index³⁰ (NDVI), the hue and saturation components of an IHS colour space transformation³¹ of all orthophotos and conditions for the mean layer values of the image objects as well as the ratio between the length and the width of an image object, the water surface could be extracted. All water surface objects are merged to form a single image object. The boundaries of this image object are also visible riverbank lines. The thereby extracted data of visible riverbanks are divided in segments (20 cm) using the ArcGIS Tool divide line by length.³² Finally for the left and right riverbank a list of coordinates of riverbank points is available for all further analyses.

2.2 Determination of overhanging vegetation

A detailed statistical analysis of the visible riverbank line extracted from the digital orthophotos (c.f. chapter 2.1) forms the basis of the determination of overhanging vegetation. It is assumed that these lines have a characteristic behaviour that allows to draw a conclusion about the structure of the riverbank. Furthermore it is supposed that in an area undergoing a transition from an uncovered riverbank line to an area influenced by overhanging vegetation, the sinuosity of that apparent (visible) riverbank is also changing. To detect these areas, in a first step it is necessary to analyse the sinuosity of that specific visible line. Karrasch et al. (2015) introduced a quasi-continuous approach for analysing the sinuosity of river centrelines.¹⁸ This approach is also usable for analysing the sinuosity of the visible riverbank line. The approach is based on the calculation of the simple ratio between the visible length of riverbank segment ($2 \cdot n$) and the direct distance between the start and end point ($P_{l-n}P_{l+n}$) of that segment (cf. figure 3).

Figure 3. Concept of quasi-continuous determination of riverbank sinuosity¹⁸

$$\begin{matrix} l=\max-n \\ k_l \\ l=\min+n \end{matrix} = \frac{2 \cdot n}{P_{l-n}P_{l+n}} \quad n = 1 \dots \frac{\max}{2} \quad (1)$$

$$\overline{P_{l-n}P_{l+n}} = \sqrt{(X_{l-n} - X_{l+n})^2 + (Y_{l-n} - Y_{l+n})^2} \quad (2)$$

The parameter n corresponds to the interval of discretisation. In the particular case that value is identical to the geometric resolution of the underlying digital orthophotos $n = 20 \text{ cm}$. The advantage of this approach is the variability of size of a considered riverbank segment as well as the interval of sinuosity calculation which also corresponds to the geometric resolution. The different length of the interval and the size of the considered riverbank segment causes overlaps and therefore each point of the riverbank line is included in the calculation of sinuosity k_l several times. The result is a quasi-continuous image of sinuosity. The decision, which segment size is relevant for a final assessment of sinuosity can be taken individually for each section of riverbank and depending on the purpose. The resulting triangle of sinuosity forms the basis of all further analyses.

The separation between riverbank sections covered by overhanging vegetation and sections without overhanging vegetation is done by means of two criteria. The first one is the sinuosity of the riverbank line. As already explained these values can be determined for each point along the riverbank line using different segment sizes. This results in a sinuosity signature ($\text{sinuosity} = \text{function}(\text{segment size})$) which can vary widely depending on the characteristics of the considered riverbank segment. Figure 4 shows an example of the signatures for three selected riverbank points at the Freiburger Mulde.

The selection is based on the characteristics of the river introduced in chapter 1.2 and the river section analysed in the presented use case. Therefore there is not only a differentiation in section with and without overhanging vegetation, especially in sections with overhanging vegetation there is also a distinction between single trees (solitary trees) and sections where trees are lined along the river (tree-row vegetation). The results show, that in the particular case differences are detectable. Especially the chosen point representing the *solitary tree* is in contrast to the other two sinuosity signatures. Comparing the sinuosity signatures of *tree-row vegetation* and *no overhanging vegetation* it becomes clear that a differentiation is considerably more difficult. It can be noted that a separate determination of the characteristics of single trees can be useful. Furthermore it is already visible that the exclusive use of the sinuosity signatures will not lead to sufficient results. Therefore in a next step the number of samples in the three classes is increased and the statistical spread of the sinuosity signatures of

Figure 4. Sinuosity signatures for three selected riverbank points of the Freiburger Mulde

all riverbank points is analysed. These analyses can provide the information for which segment size the sinuosity itself can be a useful criteria for separation.

Based on the sinuosity signatures (cf. figure 4) it can be expected, that the variance of sinuosity over different segment sizes can also be a useful indicator. That means, that the variance of the median sinuosity signature for different window sizes is calculated. This is performed for the whole median sinuosity signature. The goal is to find a useful combination of river segment size (from sinuosity calculation) and the variance regarding a specific window size calculated as moving window over the median sinuosity signature for the separation of classes. For the criteria of sinuosity as well as the criteria of variance thresholds for the assignment to classes are derived. Due to the fact, that two criteria are available, four different cases of decision are possible to classify a riverbank point (TRUE/TRUE, TRUE/FALSE, FALSE/TRUE, FALSE/FALSE).

In a final step the received classification results are filtered by a majority filter. This filter is also used as a moving window for the whole riverbank line and removed rare unusual point classifications within a river section.

After this filtering, a final classification of the entire analysed part of the river in the study area is performed. Therefore a point on the riverbank is only assigned to the merged class *overhanging vegetation* if the point fulfils the requirements of both criteria (sinuosity, variance).

2.3 Reconstruction of true riverbanks

The reconstruction of the true riverbank line is performed using an iterative approach. This approach is performed separately for every river section which is classified as overhanging vegetation (cf. chapter 2.2.). The mathematical model is based on a polynomial regression:

$$y = a + b \cdot x + b \cdot x^2 + c \cdot x^3 + d \cdot x^4 + \dots + z \cdot x^n \quad (3)$$

The model has two essential parameters to control the form of the polynomial function. The first one is the degree of the function and the second parameter describes the type of modelling. For all further analyses orthogonal polynomial functions are used. The modelling includes two processing steps:

1. Calculation of a polynomial depending on the degree
2. All riverbank points on the waterside of the polynomial are shifted to the polynomial (cf. figure 5).

This process is repeated successively until a termination criterion is reached. The termination criterion is based on the results of a residual analysis. It is assumed that the maximum residuum between two iterations is not lower than a well-defined threshold. In this use case the threshold is set to 20 cm and corresponds to the geometric resolution of the orthophotos. Smaller shifts of less than 20 cm are below the maximum possible

Figure 5. Iterative concept of reconstruction true riverbank lines

accuracy of the visible riverbank line. The iterative process terminates if the difference of the maximum residuals between two iterations does not exceed this value.

For the calculation of the polynomials all riverbank sections classified as overhanging vegetation are extended by 10 % of their length or at least 60 m on both sides. But the use of the final polynomial as the true riverbank line is limited only to the section classified as overhanging vegetation.

2.4 Determination of river width variations

The calculation of the river width variations is based on the true riverbank lines. This could be performed using a simple distance calculation between the left and right riverbank. However, especially in river bends effects of an apparent river widening occur. In order to minimize these negative effects, the calculation of the river width and therefore also their variations is performed based on the river centreline. This river centreline is the result of a Delauny-triangulation between the true left and right riverbank line.³³ The sides of the triangles crossing the river are halved. These points represent the river centreline with the same distance to the left and right riverbank.

Based on these data the variability of river width can be calculated for different river sections. Comparable to the determination of riverbank sinuosity (cf. chapter 2.1) the introduced quasi-continuous approach can be adopted for this. Therefore it is possible to calculate the river width variations for each point on the river centreline with varying size of the considered river section. The variability itself is given by the standard deviation of the used river widths.

3. RESULTS

3.1 Results of determination of visible riverbanks

Figure 6 (left) shows the results of the extracted visible riverbank lines. The flow direction of the Freiburger Mulde in this section is from east to west. Furthermore it is visible that the left riverbank has a significantly higher variability (cf. figure 6, right) which also implies that overhanging vegetation arise more frequently.

Figure 6. Result of the determination of visible riverbank line

For this reason all further analyses are performed using the left visible riverbank line. The developed algorithms and parameters are used to transfer the methodology to the right riverbank line. At this time of analysis both riverbank lines are available as list of coordinates.

3.2 Results of detection of overhanging vegetation

3.2.1 Determination of riverbank sinuosity (left / right)

Based on the quasi-continuous approach introduced by Karrasch et al. (2015)¹⁸ two sinuosity triangles are calculated for the entire river section (Figure 6, left) separated for the left and right riverbank line. For a better understanding figure 7 shows only a sub-triangle of riverbank sinuosity for a section of 300 m on the left riverbank.

Figure 7. Result of the determination of visible riverbank line

Furthermore the figure shows that depending on the observed segment size, the sinuosity for a point on the riverbank can be different. These sinuosity signatures will serve as the basis for the assessment of selected sections of the river. With these information it will be possible to distinguish different types.

3.2.2 Analysis of the sinuosity for selected river sections

The selected section of the river can be distinguished in three categories and comprises a different number of points depending on their specific characteristics. For the category *single/solitary tree* there are significantly less points involved in the analysis, than in the category *no vegetation* or *overhanging vegetation*. Figure 8 shows the statistical variance as box plots for all half segment size (hSs) up to 200. With a geometric resolution of 20 cm (orthophotos) this corresponds to a length of the riverbank of 40 m.

The results of these statistical analyses show that the median values as well as the variances differ between the categories (*solitary tree*, *tree row*, *no overhanging vegetation*). Especially the median value of the category *no vegetation* reached a stable level quite faster. Furthermore it is noticeable that the statistical variance of the sinuosity varies for different segment sizes and categories. Here again it becomes apparent that in the category of *solitary tree* the variability is significantly higher. For a better comparison the median values for all three categories are shown in figure 9.

The diagram demonstrates that the geometric resolution of 20 cm (orthophotos) reflects the median values for very small segment sizes. This effect is even in all categories and reaches values of $\sqrt{2}$. With increasing segment size the distinction of categories is clearly better. The maximum is reached for a half segment size of approximately 150 (~ 30 m). At this point a differentiation between the categories of *tree row* and *no overhanging vegetation* is still possible. The impact of *solitary trees* to the sinuosity values decreases with increasing segment size and stabilises on the level of the category *no overhanging vegetation*. Based on these results for the further analysis a half segment size is set to a value of 150 (30 m).

Figure 8. Statistical variance for all half segment sizes up to 200 (40 m); top: single/solitary tree, middle: tree row; bottom: no vegetation

Figure 9. Median sinuosity values for the categories overhanging vegetation (solitary tree), overhanging vegetation (tree row) and no overhanging vegetation

Although the median values (figure 9) imply a clear separability, the box plots and the statistical variance in figure 8 also point out an overlap for that value of the half segment size. For this reason a second criterion is introduced (cf. chapter 2.2). Therefore the median values of the sinuosity signature (for each category) are analysed by calculating the variance (standard deviation) by means of a moving window over the median sinuosity signature. Also for this part of the analysis the different moving window sizes (mws) are tested (10, 20, 50, 100). The results are shown in figure 10.

Figure 10. Results of the test of different moving window sizes for the analyses of the variance of the median sinuosity signatures; top left: mws = 10, top right: mws = 20, down left: mws = 50; down right: mws = 100

It becomes clear, that the separability depends on the chosen half segment size as well as on the size of the moving window. Especially for small window sizes there is a high variability of the standard deviation for only small differences of the half river segment size (cf. figure 10, top left, mws = 10). This variability decreases with increasing size of the moving windows. But the major drawback is, that because of the characteristics of a moving window, it is not possible to calculate values for small riverbank segment sizes (cf. figure 10, down right, mws = 100). A compromise is the use of a moving window size of 50 (cf. figure 10, down left, mws = 50). For this moving window size in conjunction with a half riverbank segment size of also 50 a good separability between the both vegetation categories (*solitary tree*, *tree-row*) and the *no overhanging vegetation* category is demonstrated.

3.2.3 Classification of the riverbank line

The determined values for the criteria sinuosity (hSs = 150) and variance of sinuosity (mws = 50 for hSs = 50) are now used for the analysis of the entire river section (left riverbank). Figure 11 shows the results for both criteria.

Basically it can be seen, that the highest values of both criteria are present at the position on the riverbank where overhanging vegetation can be expected. The visual interpretation of the results also shows that not many differences are perceptible. Therefore it is questionable if the use of a second criterion adds more information about the riverbank line to support the process of classification of overhanging vegetation. As an indicator the correlation coefficient between the criteria is used. It is assumed that, the smaller the correlation, the more different is the information content between the first and the second criterion. Figure 12 show the results as a smoothed scatter plot.

Because the values are not normal distributed Kendall's rank correlation coefficient is used. The tau-value of only 0.4 indicates a moderate correlation of the criteria. Therefore it can be expected that both criteria make their own contribution to the separation of categories.

Figure 11. Results of the calculation of the criteria sinuosity and variance of sinuosity for the left riverbank line; left: Sinuosity for a half segment size of 150 (30 m), right: Standard deviation of sinuosity for a half segment size of 50 (10 m) and a moving window size of 50 (10 m)

Figure 12. Smooth scatter plot of the criteria *sinuosity of riverbank* and *variance (standard deviation) of sinuosity of riverbank*

According to this it is necessary to find thresholds for both criteria that allow the separation of overhanging vegetation (solitary trees, tree-rows) and no overhanging vegetation. For this reason statistical analyses are performed for the three categories. Figure 13 shows the statistical distributions of the sinuosity values (cf. figure 13, top) and the standard deviation of sinuosity (cf. figure 13, down).

The comparison of the three categories shows that the combined category of overhanging vegetation (*solitary tree, tree-row*) has a large overlap with the category of *no vegetation* for about a quarter of riverbank points (cf. figure 13, top). In this range values between 1.5 and 1.6 the assignment of a riverbank point to one of the two classes will not clearly be possible. The distribution of standard deviations shows a similar result (cf. figure 13, down). Here the third quartile of the category *no vegetation* coincides with the first quartile of the category *overhanging vegetation (tree-row)*. For this reason this value is chosen as the threshold (overhanging vegetation / no overhanging vegetation) for the criteria of the variability of the median sinuosity. For the determination of a threshold for the first criterion initially two scenarios are checked. In the first scenario (A) the threshold is set to the third quartile of the category *no vegetation*. The second scenario (B) used the value of the second quartile of the category *overhanging vegetation (tree row)* as threshold.

The classification of the riverbank points is performed on a system of four classes according to the thresholds of the already mentioned criteria:

1. criterion Sinuosity: TRUE and criterion Variance of sinuosity: TRUE
2. criterion Sinuosity: TRUE and criterion Variance of sinuosity: FALSE
3. criterion Sinuosity: FALSE and criterion Variance of sinuosity: TRUE
4. criterion Sinuosity: FALSE and criterion Variance of sinuosity: FALSE

Figure 14 shows the results of this classification for the scenarios A (left) and B (right).

The visual comparison of the results shows, that on various positions of the riverbank line different assignments to the four classes have been carried out. For a better evaluation of relevant changes of the assignment between the scenarios, all changes between class 1 (in scenario A or B) and all other classes are displayed in figure 15.

Figure 13. Statistical distributions of the sinuosity values (top) and the standard deviation of sinuosity (down) for the three categories

Figure 14. Classification result of overhanging vegetation; left: Scenario A, right: Scenario B

The results show, that especially in the transition zones between the categories *overhanging vegetation* and *no overhanging vegetation* changes in the assignment are present. Since these areas play a decisive role in the later reconstruction of the true riverbank line the classification is repeated using a new scenario (C). Therefore it seems to be appropriate to use the average value of the thresholds of scenario A and B. The threshold for scenario C is set to 1.574.

The result of the classification using scenario C shows that the chosen threshold leads to a quite better assignment (cf. figure 15). Areas identified as overhanging vegetation in the orthophotos are assigned to class 1 or 2 more frequently. For all further analyses the results of the classification using scenario C are relevant.

Nevertheless, it can be stated that within a section of the riverbank line where an assignment to class 1 is dominant, sometimes a few riverbank points are assigned to another class. To eliminate these artefacts a majority filter is used (cf. chapter 2.2). To check the mechanism of the filter on the left riverbank line of the Freiburger Mulde the filter is applied with different sizes (51, 101, 151, 201, 251, 301). The results of this filtering are shown in figure 16.

As expected it appears, that with increasing filter size smaller sections of a class getting closed (cf. figure 16, down right) while for small filter sizes these areas are preserved (cf. figure 16, top left). The visually best result is achieved with a filter size of 201 (40 m).

Figure 15. left: Changes of the assignment of riverbank points between the scenarios A and B regarding class 1; right: Classification result of overhanging vegetation for scenario C

Figure 16. Results of the test of different moving window sizes for the analyses of the variance of the median sinuosity signatures; top left: filter size = 51, top right: filter size = 101, middle left: filter size = 151, middle right: filter size = 201, down left: filter size = 251; down right: filter size = 301

3.2.4 Transfer of methodology to the right riverbank

The transfer of the methodology from the left to the right riverbank line results in a classification shown in figure 17. The former four classes (cf. chapter 3.2.3) are reclassified to a simple binary classification with only two classes (overhanging vegetation / no overhanging vegetation). Thereby a point of the riverbank line is classified as overhanging vegetation only if it fulfils both criteria (TRUE/TRUE, former vegetation class 1).

A first visual verification of the classification results implies a high quality of detection of overhanging vege-

Figure 17. Final result of classification overhanging vegetation on the left and right riverbank

tation for the majority of the points on the riverbank. For some areas it also becomes clear, that partially large areas couldn't be detected. This includes in particular the northernmost part of the right riverbank (cf. figure 17). At this point of the analysis both classified riverbank lines are available for the following reconstruction true riverbank line.

3.3 Results of reconstruction true riverbanks

The reconstruction of the true riverbank line is in accordance with the methodology explained in chapter 2.3 and is performed for all vegetation sections separately. Figure 18 shows the results of one of these vegetation sections with three single trees on the left riverbank line.

Figure 18. Reconstruction of the true riverbank line using an iterative polynomial approach (7 iterations) for a vegetation section

It becomes clear, that for the displayed vegetation section at least seven iterations are necessary until the termination criterion is fulfilled. Figure 19 (left) shows the development of the residuals of the polynomial interpolation for each iteration as well as the differences of the residuals of two consecutive iterations (cf. figure 19, right).

The results show a gradual decrease of the residuals. The presented workflow is executed for all vegetation sections on the left and right riverbank. For this, polynomial functions are calculated up to a degree of 20. A final decision was made after a screening of the results and individually for each vegetation section. Figure 20 shows this process exemplary for the already known vegetation section.

Figure 19. left: Development of the residuals of the polynomial interpolation for each iteration; right: Differences of the residuals of two consecutive iterations

Figure 20. Examples of the results of a polynomial interpolation for different degrees (1-6)

In the particular case a polynomial function of 3rd degree is chosen. This function is based on an iterative process that fulfils the termination criterion after eight iterations. The comparison of the results with the underlying digital orthophotos implies a good accordance with the true riverbank line (cf. figure 21).

3.4 Results of Determination of river width variations

For the determination of the river width variations it is necessary to extract the river centreline using the just computed riverbank lines. The results of this calculation are shown in figure 22 as the red centreline. For the increment on the river centreline a distance of 1 m is chosen.

For the actual calculation of the river width variation once again the quasi-continuous approach is used (cf. chapter 2.2). The results of this calculation are shown in figure 23.

It is visible that the river width variation depends on the position of river and the size of the considered river section (hSs), which is used for the calculation of the standard deviation. In the particular case it turns out that the river width variation tends to increase down the river. This affects the standard deviation of a specific point on the river centreline depending on the size of the considered river section. For the purpose of the assessment of rivers it can be stated that (regarding the parameter of river width variation) it could be crucial how a river is

Figure 21. Final result of a reconstructed riverbank line

Figure 22. Determination of the river centreline using a Delauney-Triangulation (red line) and calculation of the river width using the true left and right riverbank line (yellow lines)

Figure 23. Final result of calculating river width variations (standard deviation) using a quasi-continuous approach¹⁸

divided during an official administrative river monitoring. The representation of parameter in the present form can help to find favourable limits for those river sections.

4. DISCUSSION

Basically it is necessary to distinguish between a content oriented discussion based on the usability of the extracted information and a more methodologically oriented discussion regarding the processing of data.

In terms of the usability of data it can be concluded that it is possible to determine information about the river width variation using riverbank lines extracted from digital orthophotos. However, a direct determination of river width variations can strongly be influenced by overhanging vegetation especially on small and medium rivers. For this reason the necessary reconstruction of the true riverbank line is given. Extending the spectrum of applications of these lines it becomes clear, that a riverbank line with a high positional accuracy can play a key role in other scientific domains. These include, inter alia, questions of bank erosion and bank stability.

From a methodological point of view different aspects have to be discussed, oriented to the workflow. The determination of the visible riverbank lines strongly depends on the quality of the segmentation of the digital orthophotos. The results of the segmentations show that especially in areas where no clear visible riverbank line exists, difficulties may arise. This often occurs for shallow water zones near the riverbank. Further limitations are present due to the geometric resolution of the digital orthophotos. Although in the particular case digital orthophotos with a geometric resolution of only 20 cm are used, the results show that the geometric resolution becomes more important, the narrower a river. Another aspect which may occasionally occur are bridges that intersect the river. In this analysis it was possible to use a normalised digital surface model to detect bridges. Furthermore it is important to emphasise that the position of the riverbank line strongly depends on the water level of the river during data acquisition. Finally the used orthophotos represent only a snapshot of a situation of the riverbank. Depending on the topography of the surrounding terrain, this aspect can have a tremendous impact on all other parameters that are derived based on the riverbank line.

For the detection of overhanging vegetation, a method has been developed that only uses the extracted visible riverbank line. The method is based on the assumption that the sinuosity of the line significantly changes in the transition area between overhanging vegetation and free visible riverbank line. The comparison of the results with the digital orthophotos shows a high degree of agreement. Nevertheless it must be noted that areas with very less overhanging vegetation could only be detected insufficiently. The purpose of this study was to derive the overhanging vegetation only from the visible riverbank line. In the future potentially overhanging vegetation should be directly extracted from the digital orthophotos using remote sensing methods of image classification. This would also have the advantage to validate the presented methodology.

The modelling of the true riverbank lines is based solely on mathematical models. For this purpose, in the present case only polynomial functions are used. The high number of detected points on the visible riverbank line permits the use of high polynomial degrees. Nevertheless, it is an open question whether other mathematical models could better describe the true riverbank line. Regarding the reconstruction two further aspects need to be considered. Firstly, it must be noted that a validation of the positional accuracy is currently not yet possible. In the future images should be taken or acquired during a time when the deciduous trees are defoliated and the true riverbank line is visible. For this the highly flexible use of an unmanned aircraft system (UAS) is considered. The second aspect concerns the use of a mathematical function for the reconstruction. In the present case the main flow direction of the river is from west to east. If the water course exhibits a more north-south direction, or if there are one or more changes in the east-west flow direction within a section of vegetation, it is no longer possible to use the polynomial approach in the presented form. In this case it is necessary to perform a coordinate transformation of all points of the visible riverbank line into a local coordinate system. The subsequent modelling of the true riverbank line is carried out in this coordinate system and the result is finally transformed back to the initial coordinate system. For defining the x-axis of the local coordinate system the first and the last point of a vegetation section can be used. In fact it is also possible to perform such transformation separately for each vegetation section and regardless the actual flow direction as a mandatory part of the analysis.

The determination of the river width variation in the presented form has the advantage that the user of this information is not limited by pre-defined positions or lengths of to be assessed river segments. The introduced approach does not allow to make a final assessment of the parameter width variance but it can significantly support the actual process.

5. SUMMARY

The presented results show that it is possible to determine width variation of small and medium rivers based on the analysis of digital orthophotos. Therefor a workflow was developed and implemented, with a focus on the consideration of problems of overhanging vegetation. The developed methods offer a simple opportunity to detect that kind of vegetation with the objective to reconstruct the true riverbank line using different and individual mathematical models. For both aspects the underlying methodology has been described in detail. The results show that the quality of detecting overhanging vegetation can be considered as good. The same applies for the reconstruction of the true riverbank line. Both statements are based on the visual comparison of the results with the underlying digital orthophotos.

Primarily the introduced approach of reconstruction of true riverbank lines may be of interest in other scientific domains. Especially for the determination of bank erosions the presented methodology can make a valuable contribution as part of the data pre-processing.

Finally, this paper also shows that remote sensing data and methods can support the monitoring of rivers in terms of the European Water Framework Directive.

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