Collection and Interpretation of Point Clouds of Terrestrial Laserscanning as a Basis for Hydraulic Flow Modelling

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Key words: terrestrial laserscanning, digital terrain model, hydraulic modelling, vegetation filtering

SUMMARY

Terrestrial laser scanning (TLS) is a relatively new and reliable 3D survey technique which is now widely used. This method is particularly used in projects in which the geometrical structure of objects at the earth's surface is to be determined. This paper reports on a project in which terrestrial laser scanning is applied to the threshold range of air and water. Using hydraulic modelling, this project aims to demonstrate that the structural and hydraulic conditions of a water body can be significantly improved by natural river restoration projects. The development of a high resolution digital terrain model (DTM) of the river channel with its foreland and the description of vegetation zones in potentially flooded areas are the foundation for this modelling. It is discussed, which geodetic survey methods provide the required data. Application of TLS to measure the topography of river beds, here in the project area at the river Wiese, is described. Effects are addressed that occur when scanning submerged zones of the river bed. Furthermore, a technique is introduced which classifies the registered point cloud as terrain points and vegetation points.

ZUSAMMENFASSUNG

Terrestrisches Laserscanning (TLS) ist ein 3D-Messverfahren, das sich in den letzten Jahren zur Erfassung von 3D-Objekten sehr gut bewährt hat und weit verbreitet angewendet wird. Dabei kommt dieses Verfahren insbesondere in Projekten zum Einsatz, in denen die geometrische Struktur von Objekten an der Erdoberfläche bestimmt werden soll. In diesem Beitrag wird von einem Projekt berichtet, in dem das Terrestrische Laserscanning im Grenzbereich zwischen Luft und Wasser eingesetzt wird. Mittels hydraulischer Modellierung soll nachgewiesen werden, dass der strukturelle und hydraulische Zustand eines Gewässers durch Renaturierung signifikant verbessern werden kann. Grundlage für diese Modellierung ist sowohl die Bereitstellung eines hoch auflösenden digitalen Geländemodells (DGM) des Flussbettes mit seiner Umgebung sowie die Beschreibung von Vegetationszonen in potentiell überströmten Zonen. Es wird diskutiert, welche geodätischen Messverfahren die benötigten Daten zur Verfügung stellen. Anhand eines Testgebietes an der „Wiese“ wird beschrieben, wie TLS zur Erfassung der Topographie des Flussbettes eingesetzt werden kann. Insbesondere wird auf die Effekte eingegangen, die beim Scannen auf überflutete Bereiche des Flussbettes entstehen. Weiterhin wird eine Technik vorgestellt, die ein Klassifizieren der registrierten Punktwolke in Boden- und Vegetationspunkte vornimmt.

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1. INTRODUCTION

Within the framework of a joint research project, funded by the German Federal Ministry of Education and Research, the *Institute for Water and River Basin Management (IWG)* of the *Karlsruhe Institute of Technology (KIT)* is planning to design an assessment tool for urban river sections. In the evaluation procedure, a stream segment will be appraised, based on parameters collected during on-site inspections, as well as on results of detailed hydraulic simulations. This pilot project involves the assessment of both heavily modified and naturally formed streams in urban areas. The latter often exhibit complex structures and flow patterns. Therefore, an important part of this project is the development of a highly detailed 2D hydrodynamic numerical model of such a river section. An urban section of a small stream was chosen as the project area (see chapter 2). Since the numerical model will be based on a digital terrain model, the DTM development is a major aspect of the project. The geometric data of the riverbed and the foreland of the chosen river section must, however, first be collected. Therefore, a cooperation between the *IWG* and the *Geodetic Institute* of the *KIT* was started, with the intention of learning more about the suitability of the terrestrial laser scanning method (TLS) for the survey of riverine zones. Additionally, a concept was to be developed that comprises the steps of post-processing and DTM creation using TLS-data.

1.1. Hydraulic modelling

Hydrodynamic numerical models are common means for analyses in the fields of hydraulic engineering and water management. A hydraulic model describes flow and transport processes and is used for verifications, predictions, and as a decision support tool. Flow description is based on mathematical models of differential equations, which describe the balance of mass and momentum in three dimensions. Since these equations cannot be solved analytically, numerical methods are applied to approximate the solutions. Depending on the degree of simplification of the hydrodynamic governing equations, a distinction is drawn between 1D, 2D, and 3D numerical models.

1.2. Data requirements

A hydraulic model requires input data, such as hydrological information (discharges and water levels), which is mainly defined in terms of initial and boundary conditions. Additionally, information concerning flow resistance on the river section to be analysed must be specified. The topographic information of the relevant river section, however, is of prime importance. While in the case of a 1D-model the geometry is modelled by a sequence of cross sectional profiles, 2D and 3D simulations require digital terrain models, which are covered with computational mesh. As results of a numerical simulation, one receives computed hydraulic parameters (flow velocities, water levels) for each profile/mesh cell of the project area. The size of the river section to be modelled can vary. The area to be modelled can encompass complete river basins; specific river sections, such as loops or the mouth of a river; or the direct surroundings of specific hydraulic constructions, for example.

In Germany, 2D hydraulic models are mainly based on digital terrain models, the data of which is usually collected through airborne laser scanning (ALS). The DTM of the river foreland is generally supplemented by hydraulically significant information in the river channel, at the riverbanks, and on the foreland. This includes the riverbed and hydraulic structures and constructions, the geometry of which is mainly measured using different survey methods.

Regarding the envisaged development of a small-scale hydraulic model of a naturally formed or nature-oriented river section, the requirements considering point density and accuracy are considerably higher than usual. In the river channel and along the riverbanks there are structures and flow obstacles, such as stones, sills, or deadwood. The aim is to create a model, whose level of detail is high enough to realistically resolve these structures and their induced flow patterns. The digital terrain model must be at least as detailed as the envisaged resolution of the computational mesh.

2. COMPARISON OF SURVEY METHODS

When regarding a relatively small natural stream, as is the case in the project area, the terrain is predominantly characterised by a great diversity of hydraulically relevant objects, which must be captured in adequate density and accuracy. Within the river channel, we find:

a) wide, flooded areas
b) individual objects (stones), partly in the water and partly outside
c) sills to control water flow and reduce water velocity
d) vegetation of different sizes along the embankment and in the shallow water zones
e) temporary objects, like deadwood
f) areas of shallow water with gravel and mire

Dependent on the water level, these objects are more or less covered by water. Outside the river channel, we find:

a) vegetation, such as trees, bushes, grass, and reed
b) shoreline stabilisation
c) walks of gravel
d) buildings and other man-made structures

Several surveying techniques are available to obtain the data of the digital model of the river channel and that of the natural environment.

- Topographical data collection based on tacheometry is a well-known standard technique and is the most accurate measurement method, describing the terrain using discrete point approximation. The test area is divided into cross sections, and there is a linear interpolation between the points inside the profiles. The result is a rough outline of the terrain. The river section, however, with all its hydraulically relevant structures, cannot be described with reasonable effort in the required level of detail (see Fig. 1, Profile a).

- Alternatively, the data of the terrain and all above-ground objects can be collected via airborne laser scanning (ALS). This method allows extensive description of the surface. Using a pulsed laser, the first and the last reflection of the signal yield the ground surface and the elevation of vegetation (see Fig. 1, Profile b). The resolution and height accuracy of such a DTM are determined by the physical characteristics of the project area, as well as by the instruments used. These DTM usually show a point density up to 20 points/m², with an accuracy of about +/- 0.15 m in position and height, and do not conform to the high requirements specified by hydraulic modelling. Furthermore, the red lasers used are not able to enter bodies of water because of total absorption of the laser light by water. First results of new developments with a green laser are reported by Steinbacher a. o. (2009).
- Terrestrial laser scanning (TLS) can be applied to provide a digital terrain model in a highly resolute hydrodynamic numerical model. From a user-defined station, the scanner provides distances, horizontal and vertical angles to random points of the terrain, and the surface of all aerial objects. The produced 3D-point cloud covers the river channel and all objects within and without in variable density, varying between a few millimetres to some centimetres with high accuracy (see Fig. 1, Profile c). The measurements can be organised at short notice, corresponding to a low water period, so that the river channel is nearly completely captured.

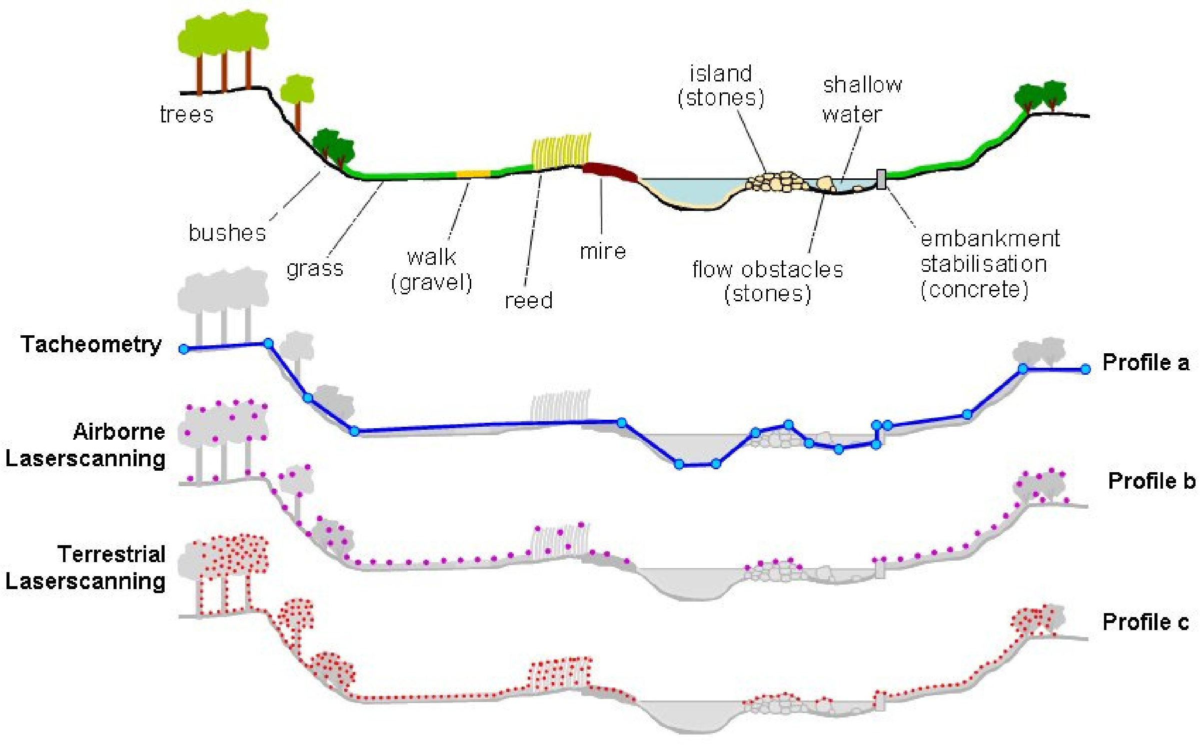

Figure 1: Example of a cross section of a small natural stream; schematic results when using different survey methods

The significant advantage of using TLS rather than tacheometry or airborne laser scanning is a considerably higher point density. Furthermore, the height accuracy is very high and the irregular form and dimension of all aerial objects (structures and vegetation) is captured completely in 3D through observation from different stations. Due to these properties, terrestrial laser scanning was applied in several research projects to collect terrain data for hydrodynamic numerical models of limited river sections. Although research is currently being pursued, different issues concerning the surveying of submerged zones using laser scanning must be investigated. How the reflections of points of flooded structures are interpreted must be thoroughly investigated.

3. TLS MEASUREMENTS AT THE TEST AREA "WIESE"

A section of the river "Wiese," within the city of Lörrach was chosen as a project area. The small city of Lörrach is located in the southwest of Germany, close to the French and the Swiss borders. The river Wiese has its source in the Black Forest; its course runs south-west until, after 55 kilometres, the river flows into the Rhine, in the city of Basel.
In 2007, several measures were realised to enhance the structural diversity of the Wiese in the urban area of Lörrach. The river channel had been widened, for instance, and weirs and barriers which are not passable for aquatic creatures, were replaced by rock ramps. Since this river section shows both nature oriented structures (for example, stone sills and groynes) and heavily technically modified sections, it was chosen as a project area to validate and optimise the assessment method. The river section of which a hydraulic model is to be created is approximately 200 m long and 50 m wide.
The TLS-measurements in this test area aimed to build a DTM of very high resolution with all irregular forms. Because the sensitivity of hydraulic modelling with regard to the DTM-resolution is unknown, the measurements were designed using a scanner providing a scan density of less than 1 cm in distance. In a second step, this high resolution had to be reduced to see the critical value, at which the hydraulic model shows modifications.
Because of their irregularity, the objects within and without the river channel had to be measured all around. This made a high number of stations necessary. To reduce the amount of measuring time and to provide high scan density and accuracy, the laser scanner Leica HDS6000 was chosen. The HDS6000 is the industry's most popular phase-based scanner. Its main properties are an ambiguity interval of 79 m, different resolutions, and a very high scan rate (up to 50000 points / sec). The chosen mode "highest" provides a horizontal/vertical step size $\Delta = 0.018°$, a point spacing of 7.9 mm (range 25 m), and about 7 minutes to scan a panoramic view.

3.1. Processing and first results of the measurements

As previously mentioned, the terrain was very rough, and no discrete points could be used to register multiple scans. Leica black/white targets were used to provide proper registration and to increase their detectability. Thirty-four target stations, distributed throughout the test area, were scanned from 17 scanner stations. The average time of measurement of one station was around 50 minutes. No RGB texture pictures were taken.

The preview of scanned data already painted a detailed reproduction of the riverbed and its environment. Figure 2 compares a digital photo and a grey value image. On first sight, a very high accordance was found. In addition to this view, many other scans contained reflections of both the solid aerial objects and of submerged objects.

Figure 2: Photograph (above) and TLS point cloud (below) show a stone sill in the project area

Unexpected reflections enabled a vision of the riverbed pattern, particularly in shallow water. Such object reflections were found near the station, as well as far away or completely inundated within sills. Due to the use of a red laser light, which is absorbed by water, these reflections are not explainable.

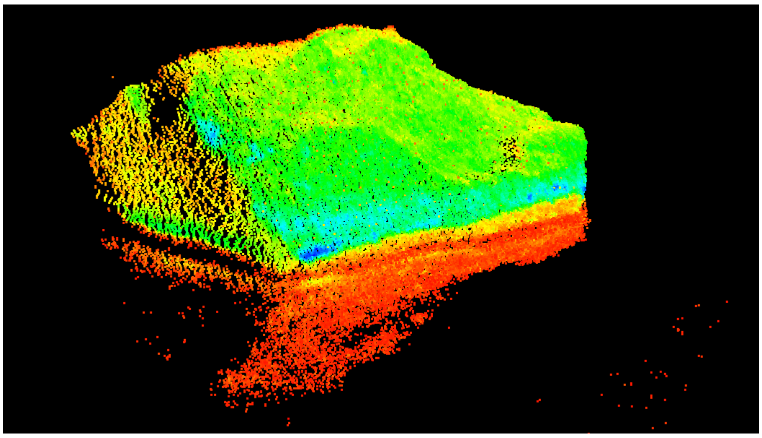

Figure 3:
Scan of a single stone in the water, partly above, and partly under the water. The intensities (portrayed through different colours) depict the surface of the stone very well, whereas the underwater geometry of the stone is merely a fragmentary documentation. Reflection intensity is significantly reduced underwater.

The expansive influence of the water surface becomes visible in the detailed view of a single stone (Fig. 3). All points scanned above water level obtain a high intensity value. The surface of the stone is reliably depicted by these points. The scan of the stone object is not interrupted when the water surface is penetrated, but continues underwater. The recorded intensities clearly show the borderline between water and air. The registered intensities of the reflected laser beams are vastly reduced underwater.
Converting the frontal view of Figure 3 to a side view, the impression is given of a mirroring of the stone surface above the water to the points underwater (Fig. 4).

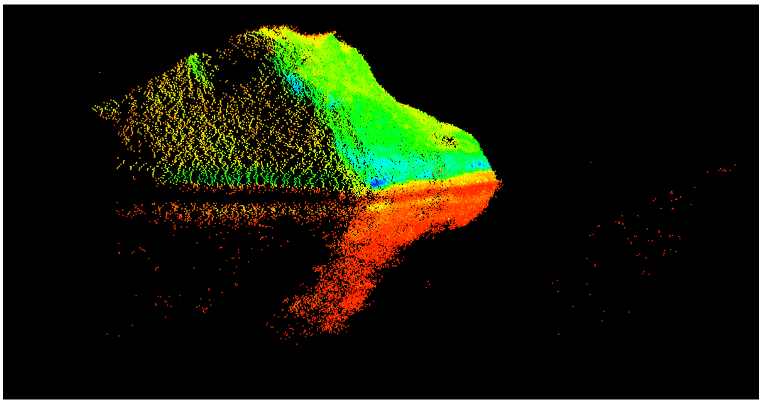

Figure 4:
Side view of the stone in Fig. 3. The shape below the water surface seems to mirror the shape above the water.

An investigation of this effect in a controlled experiment inside a special water laboratory is planned. As long as no function to correct the underwater points is found, the outline of the water-air border is extended perpendicular to the riverbed.
Similar effects are found in shallow water areas (Fig. 5). The water cannot totally absorb the red laser beams because the water is only a few centimetres deep.
The same mirroring effect as displayed in the single stone is found in the stones above the water surface. The interspaces between the stones are flooded with water of varying flow velocities. Nevertheless, the laser beam is reflected and low intensity is recorded. It is currently unclear whether the recorded riverbed surface has been correctly positioned, raised, or lowered.

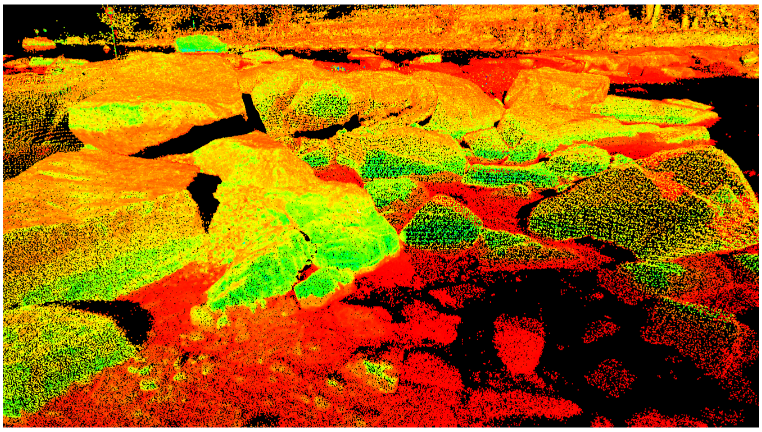

Figure 5:
Detailed view of a stone sill consisting of several large and small stones. The interspaces are flooded, and there is multiple repetition of the mirroring effect of the single stone (see Fig. 4). Reflections of low intensity are observed in the interspaces.

It seems, however, that the flow velocity has no influence. Interpretation of the points must be discussed, but for the time being, these points have been excluded from DTM determination. Controlled experiments in a water laboratory should clearly indicate the possibility of correcting distorted data so that it is usable for DTM interpolation.
Furthermore, levitating points are recorded as interfering points; this also applies to recordings of unnecessary objects, such as walker, cars, and measurement equipment. The appearance of levitating points is significantly preferred in the area of water. Reflections of faraway objects with very high reflectivity may also be recorded. If the distance exceeds the unique ambiguity of the scanner, the observed distance is shortened by this unique ambiguity and the object is translated near the station. These incorrect points are generally placed in the airspace.
The pre-processing of the point clouds comprised different steps from the norm. The registration process transformed the single point clouds into a common reference frame. The Leica black/white targets were used as well-defined reference points between the single point clouds. The result of this registration showed a mean absolute error in the enabled constraints of 0.004 m. Following registration, the interfering points were deleted and the point cloud was segmented into different parts. Due to the high variation of point density caused by diverse distances from the scanner to the objects from which the laser signals were reflected, the resulting point cloud was reduced to common spot spacing.

3.2. Data post-processing, vegetation filtering, and DTM creation

Vegetation filtering was a significant step of data processing, in which the point cloud was divided into terrain points and off-terrain points. For this purpose, filtering software which has been successfully applied on ALS data for years at the *Landesamt für Geoinformation und Landentwicklung* was used. The processing is done using the hierarchic robust filtering method, which is implemented in the software SCOP++ (Inpho Gmbh / IPF 2007). Here, in an iterative approach, a temporary surface is computed using linear prediction. The points of the point cloud will either lie on, above, or below the computed surface. Depending on the vertical distance of the points to the surface, weights are assigned to the points, according to a specific weight function. If a point is given a low weight, it will have little influence on the run of the surface in the next iteration. If the distance to the surface exceeds a given value, the weight of the point is specified as zero, which corresponds to a sorting out of this point. In the next iteration a new surface is computed considering the weights of the remaining points. As a result of the last iteration, the point data is categorised into several classes, for example, ”ground points,” ”low,” ”medium,” and ”high vegetation points.”
The parameters of the weight function were adjusted in advance, to conform to the much smaller scale when handling TLS points instead of ALS points. An example of the result can be viewed in Figure 6. Only the ground points were used to develop the DTM. Vegetation points provide important information concerning the roughness of the terrain, which always must be considered for the calculation of energy loss during hydraulic simulation.

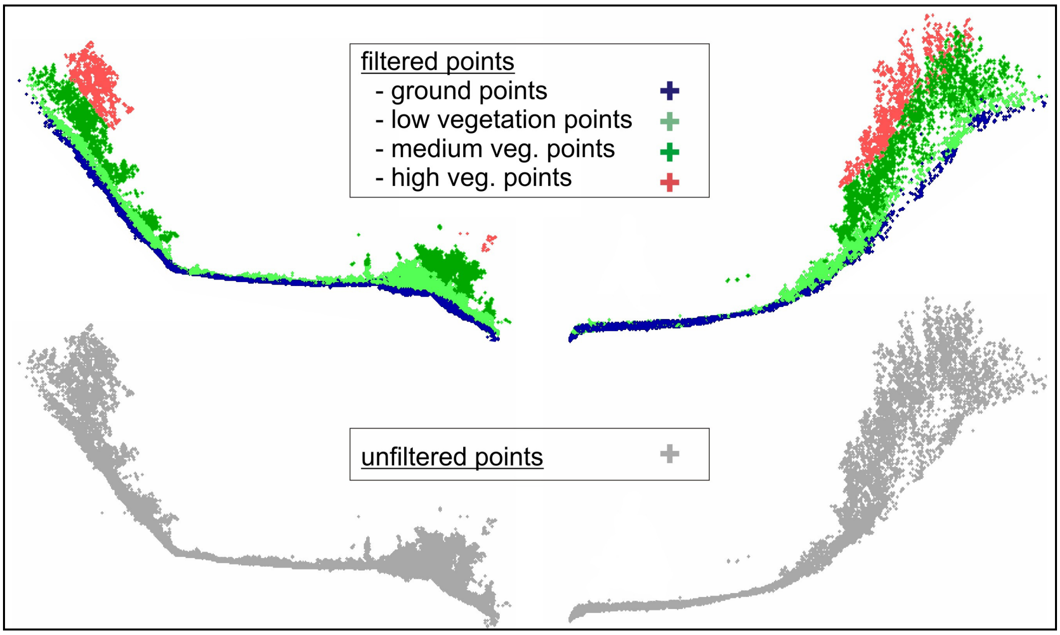

Figure 6: Example of a result of vegetation filtering: sorted (above) and unsorted (below) TLS points indicate the left and right bank slopes of a river

The application of vegetation filtering was thus more difficult for TLS data than for ALS data, due to the direction of the scan. ALS data points are scanned from above and therefore comprise mainly points which are at different heights (on the ground and on roofs and tree tops) and can comparatively easily be categorised. In contrast, TLS points are scanned from horizontal and inclined directions. This results in the continuous spreading of the points over all heights, complicating the sorting process. While the filtering method worked very well in areas where mainly vegetation occurs (for example, at the banks of a river), problems appeared when filtering regions with both clusters of stones and vegetation. The filtering of areas in which there are breaks in the terrain (such as berms at dikes) is also problematic. Here, the filtering method causes a rounding of the vertexes. Therefore, such error-prone regions should be separately considered and manually post-processed. Furthermore, when interpolating the DTM, insertion of break lines at such spots should be considered.
In case of gaps in the TLS data set (for example, due to submerged areas), it is necessary to survey these zones using a different approach. Since the river section to be analysed was rather small and shallow, the river bed was measured using tacheometry. A triangulation of all points was done (under consideration of break lines) after having merged the tacheometry and TLS points in one coordinate system. The construction of the DTM was completed after rasterisation of the triangulated irregular network.
The DTM delivers the basis for the computational mesh on which the hydraulic equations are numerically approximated. Mesh generators, such as *Triangle* (Shewchuk), create Delaunay triangulations. Here, the height values given by the DTM will be mapped to the nodes of the mesh. Before running the hydraulic model, initial and boundary conditions, roughness zones and parameters, as well as numerical parameters must be defined.

4. Future work

The initial interpretations of point clouds in a river environment show that the red laser beams of the HDS6000 are able to penetrate the water surface and are reflected in shallow water. These recorded reflections do not correctly describe the topography of shallow water or the geometry of objects placed in the water. It is intended to build a man-made test area to compare such an effected point cloud with one without water. The first aim is to transfer the differences found to a common interrelationship between water depths, water velocity, inclination of the laser beam, frequency of the laser beam, and other parameters. The second aim is to develop a numerical procedure to apply this empirical formula to point clouds that indicate underwater objects.

Concerning data post-processing, research must be done to address the issue of the effective aggregation of high resolution TLS data and low resolution tacheometry data. When developing the DTM, interpolation errors at the junctions of TLS and tacheometry point clouds and near partially submerged structures should be avoided. In this pilot project, therefore, additional points and lines were manually defined to more precisely specify these areas. Options to automate such extensive manual digitalising efforts are to be tested. Possibilities of using the TLS vegetation points to model flow resistance along the stream course must additionally be more profoundly investigated. Furthermore, a sensitivity analysis concerning the DTM and mesh resolution is planned.

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BIOGRAPHICAL NOTES

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