1 Introduction

In July and August 1997, an extreme flood event occurred on the River Oder, inflicting vast economic damages on all the riparian states: the Czech Republic, Poland and Germany (Lauschke, Oppermann, 1998). To be better prepared in future events of this kind and to avert damages, numerous preventive activities have been implemented in the past few years or were initiated at least. This comprises not only constructive measures (e.g. maintenance and strengthening of flood defences) and improved disaster prevention. Moreover, advanced hydraulic models for flood-flow and low-flow forecasting or scenario simulations should be developed.

Many of these preventive actions depend on modern, highly detailed geo-data as an indispensable prerequisite. In the German point of view, priority was due in this context to the development of digital terrain models (DTMs) of the River Oder along the German/Polish border (Grenzoder) including the so-called Westoder.

2 The project "Watercourse DTM of the Grenzoder"

2.1 Background

The end-users requested two kinds of DTMs.
Especially the water managers in the "Land Brandenburg" demanded an up-to-date DTM of 5-m grid size of the areas protected by dykes on the German territory. These specialized demands are equivalent to a standard product of the Brandenburg State Mapping Authority (LVermA), also for a larger area. Therefore the project area was extended to 3,075 km².

Moreover, an up-to-date DTM of the watercourse (DTM-W) was needed in any case. This DTM-W had to describe the flow-effective area of the riparian forelands as well as the riverbed. Regarding the reaches of the Westoder with a length of 17 km and the Grenzoder with 163 km, this meant that essentially the area between the dykes covering some 273 km² both on Polish and German territories had to be surveyed and modelled (cf. Figure 1). Main users of the DTM-W are the Brandenburg State Office for Environment (i.e. the supreme water-management authority), the Waterways and Shipping Office (WSA) Eberswalde (responsible for operation and maintenance of Federal waterways), and the Federal Institute of Hydrology (BfG - the scientific institution of the Federal government in the fields of hydrology, water-resources management, and conservation of waters) and the respective authorities on the Polish side. The DTM-W is especially needed for the development and operation of a water-level forecasting model and the updating of data on the riparian forelands and the documentation of the state of the groyne (Groynes are structures built transverse to the direction of flow into the river; their main purpose is acceleration of flow to minimize sediment deposits in the main channel (fairway); a secondary effect is a slight increase of the water level). The following paper gives a detailed description of the model development in view of the particular important requirements on the DTM.

The demand for the two DTMs led to a joint project between the LVermA and the BfG. The aim was to bundle as many sub-tasks as possible. For economic considerations the project partners agreed to use the airborne laser-scanning technique for acquisition of the terrain data (Brockmann, 2000).

2.2 Requirements on the watercourse DTM

The acquisition of the terrain data and the processing of these measured data before the DTM-W modelling that were commissioned to a consultancy. The partially very high requirements are summarized as follows:

- Density of measuring points: Dp < 1 point per 2 m x 2 m grid cell;

- Hydrological boundary conditions; i.e. airborne data acquisition:
  - at low-flow conditions;
  - in the no-growth season, if it is possible after the first frost at the ground;
  - during absence of ice or snow covers;

- Classification (filtering), i.e. separation of laser points:
  - of the riparian forelands;
  - of the flow-effective built structures;
  - of the water surface;
Criteria for quality checks; limit for differences in elevation ($d = \text{rated value} - \text{actual value}$) with a probability of $p = 95\%$:

- flat to slightly sloped terrain with sparse vegetation: $d = 0.20$ m;
- flat to slightly sloped terrain with dense vegetation: $d = 0.40$ m;
- steeply sloped terrain with sparse vegetation: $d = 0.50$ m.

The DTM-W areas of the covered terrain with ground points should be modelled at least in 2-m grid-cell size. This necessity is mainly due to the required highly resolved reproduction in the DTM-W of the riparian forelands and of the groynes in the Grenzoder. Out of the DTM-W, longitudinal groyne sections should be derived (cf. Figure 2). The final settings for the DTM computation should be performed only after the assessment of the data material collected in the flight missions.

The riverbed should be modelled along the river axis on the basis of echo-sounder data along cross sections measured in one epoch (cf. Figure 6.). Ground measurements of the forelands at these cross sections were not available. Because of the intensive, short-cycled morphodynamics of the Oder riverbed, this density was considered sufficient. Since these cross sections covered the groyne fields only slightly, their description had to be made by laser-scanner data as far as possible.

The DTM-W had to be modelled from the laser-scanner data of the riparian forelands, the groynes and the areas of the groyne fields fallen dry (cf. Figure 3) as well as the echo-sounder data of the riverbed in such a way that all these areas are reproduced as realistically as possible. It should be possible to derive cross sections at every location. Consequently, the Delaunay-Triangulation, which is frequently used in hydrology, could not be used without appropriate pre-treatment of the data. The program system SCOP was chosen with the special developments (i.e. the morphistic cross-sections fitting) resulting from the BfG pilot project "Hydrological GIS-Saar" on the river Saar (Brockmann, Kraus and Mandlburger, 2001). For more details, refer to Chapter 4.1.

3 Database
3.1. Terrain Data
The terrain data were collected by the airborne laser-scanner "Optech 1020" late in November 1999 according to the requirements listed above. The actual mean laser point density after the classification (cf. Figure 3) achieved was 1 point per 2.5 m x 2.5 m. Of course one must keep in mind that the considerable lower laser-point density on the water surface (making up roughly 1/4 of the area) is included in this value, so that the above-mentioned requirement was reached.

Before the actual computation of the DTM-W, the laser points of the "solid" surfaces (land, groynes, dry-fallen areas in the groyne fields) had to be separated from those of the water surface. This should be effected possibly by an automatic routine. As - because of varying water levels - no other measurements were available for delineating water and land surfaces, and results of water-level computations of flowing waters (in contrast to impounded rivers (Brockmann, Kraus und Mandlburger, 2001)) can usually not be used here, the water-land boundaries (WLBs) had to be derived from the laser-scanner data of the water surface.

3.2 Riverbed data and other information of the waterway
It was necessary to use here riverbed cross sections at distances of 50 m, 100 m and 200 m, that were recorded by single-beam echo-sounder at mean flow in 1998 according to the local conditions. Because these sections usually extended into the groyne fields, they were used for DTM modelling, what made the description of the wet parts of the groyne fields possible at all.

Additional basic data could be gained from orthophoto maps on the photo scales of 1 : 34,000 and 1 : 10,000, which had been taken at considerably higher water levels than those prevailing during the laser-scanner mission, as well as from necessary transformation parameters, axis points and control points of the waterway in cross-section distances.

4 Watercourse DTM modelling
4.1 Fundamentals
As mentioned in the previous chapter, the program system SCOP was used to compute a DTM-W from the available original measurements. The terrain model system SCOP was developed at Vienna (Institute of Photogrammetry and Remote Sensing - I.P.F.) and at Stuttgart (INPHO GmbH). The outstanding feature of SCOP is the interpolation method used, namely the linear prediction with a covariance function locally adapted to the data (KRAUS, 2000). This approach allows a qualified smoothing of the terrain model based on statistical analysis, what eliminates random errors in elevation measurements and also smoothes the contour lines. Another essential element of the strategy of SCOP is the integration of structural lines (e.g. breaklines, lines of framework) which are generally considered as necessary components of high-quality DTMs.

A precondition for deriving a DTM-W is the correct classification of "solid" areas (forelands, groynes, dry-fallen groyne fields) and the water surface. This means, in fact, the delineation of the WLBs. The extraction from the digital orthophoto maps was not possible, because of the different water levels during the laser-scanner mission and during the orthophoto mission. Therefore a photogrammetric identification of the shoreline, that is available at the LVerma, could not be used here. Consequently, the WLBs had to be derived from the available laser-scanner data, with the aim of a possibly high degree of automation. The identification of the WLBs is described in detail in the following chapter.

The successful application of the linear prediction needs a certain homogeneity in the distribution of the points of support. While this precondition is sufficiently met in the case of the laser-scanner data, the widely spaced echo-sounder cross section data need higher density. To this end, additional sections at regular distances are computed by means of morphistic cross-sections fitting in such a way that along the river axis the shape of the initial section is successively transferred into the shape of the next section (Mandlburger, 2000).

4.2 Identification of water-land boundaries
It was intended to use a possibly automatic routine for the determination of the WLBs. The underlying idea was that this boundaries results from an intersection of the DTM-W with a digital model of the water surface (DWM).

For this DWM, first all laser points within a band of 30 m to the left and to the right of the river axis were determined. These points are then transferred into the coordinate system of the section (distance on the cross section, river-km, and elevation) and sorted for increasing river-km. Through averaging, one dimensonal water levels representative elevation values could be determined for river reaches of 100 m each. By means of SCOP, a digital model of the water surface was then computed from these water-level data, neglecting possible sloping or upbulging of the water surface.

Now, the WLBs could be determined in a 2-step process:
- Step 1:
  • Computing a DTM from all laser points (DTM Laser; including the water surface);
  • Computing a difference model (DTM Laser minus DWM) by means of SCOP.INTERSECT;
• Deriving the preliminary WLBS from the contour line 0.00 m, respectively 0.20 m, difference model by means of SCOP.ISOLINES.

Fig. 4: Principle of deriving the WLBS

- Step 2:
  • Eliminating all laser points within the preliminary WLBS;
  • Inserting the densified cross-sections within the preliminary WLBS;
  • Computing a preliminary DTM-W;
  • Computing a difference model (preliminary DTM-W minus DWM);
  • Deriving the final WLBS from the difference model.

Fig. 5: Orthophoto map, original laser points (yellow) temporary (white) and final (green) WLBS

One can see in Figures 3 and 5 that here only relatively few laser points exist on the water surface. Thus, the DTM Laser was very inaccurate on the water surface (Step 1). Moreover, drag intersections occurred in the areas of the banks in the intersection of the DTM with the DWM. The zero-elevation line of the difference model often consists of non-continuous fractures and numerous short continuous lines. Only the 20-cm elevation line (offset) forms a nearly continuous line and may be used as preliminary WLBS (white line). However, it is still very uncertain, and there is a high risk of mis-classifications. For this reason, the laser points within the preliminary WLBS were at first eliminated and substituted by the riverbed points of the echo-sounder. This improved in Step 2 the intersection conditions on the bank slopes. The intersection of the preliminary DTM-W with the DWM allowed now to define the WLBS with higher accuracy (Figure 5, green line). This final WLBS is used for the actual classification in terrain and water surfaces.

4.3 Computing the DTM-W and results

After eliminating all laser points within the WLBS and the densified echo-sounder cross sections data (cf. Figure 6), the preconditions were created to compute the DTM-W by means of SCOP.
An output listing for a DTM-W computation of a test area of about 7,000 m² (cf. Figure 7) shows that a grid-cell size of 1.25 m was used. This value is below the mean distance between points of about 2 m. The grid-cell size was chosen so small to ensure a sufficiently detailed description of the groyne structures. Furthermore, it was found in an examination of the data distribution pattern that especially on the groynes, point densities of one point per 1 m x 1 m square occur, what justifies the use of a grid-cell size of 1.25 m for the DTM-W. For applications that need less detailedness, reduced resolutions (2.5 m, 5 m, and 10 m) may be derived. The mean filter value of 0.117 m indicates, on the one hand, the good quality of the laser-scanner data and, on the other hand, also that the laser-scanner data could be successfully fit together with the echo-sounder data.

DIGITALES HOEHENMODELL
KARTENBLATT: 3353SO

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Fig. 7: Output listing for a DTM-W computation

Figures 8 to 10 visualize the DTM-W in the forms of contour lines, hill shading and perspective view.
4.4 Description of groyne structures

The WSA, one of the users of the DTM-W is particularly interested in assessing the state of groyne structures by means of this model. Here, the possibly correct depiction of the longitudinal section of the groynes is in the foreground (Figure 11).

The Figures 8 to 10 visualizes that the present state of the groynes is far from the ideal, as it is shown in Figure 2. The WSA officials now have the possibility to identify and localize groynes in poor condition by means of the longitudinal sections derived from the DTM-W or from other forms of visualization.
5 Summary and outlook

Manifold tasks in hydrology, water management, hydraulic engineering and geodesy need digital terrain models of watercourses (DTM-Ws), as it is illustrated here by the River Oder. The modelling of the DTM-W was based on laser-scanner data and echo-sounder data (cross sections) of the riverbed. In order to run the DTM-W nearly automatically, methods were developed for the separation of the laser-scanner data of the terrain from those of the water surface, and for the derivation of water-land boundaries as well as for morphistic cross-section fitting in the environment of the program system SCOP.

The results of the first applications show that the expectations of the users could be satisfied. The software modules that were used on the River Oder will also be applied in the future for modelling DTMs on other Federal waterways, e.g. on the rivers Elbe and Rhine. The Federal Institute of Hydrology (BfG) has the opinion that the development of such methodologies is necessary also for economic reasons, especially against the background of the new possibilities offered by laser-scanner technique, parallel recording of radiant intensity and multi-channel digital imaging for instance for orthophoto mapping.

Moreover, the BfG sees further chances for applications of laser-scanner technique. Through further research and development it should be possible in the future to derive roughness parameters (flow resistance) and flow-effective breaklines in sufficient resolution and exactness for use in hydraulic modelling.

Literatur


