COMBINED APPLICATION OF AEROPHOTOGRAMMETRY, LASER SCANNING AND DYNAMIC SEGMENTATION TO RECONSTRUCT THREE-DIMENSIONAL WATERCOURSE NETWORKS

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ABSTRACT

The data generation of highly detailed digital terrain models including an integrated 3D watercourse network is a requirement of the extensive approval and monitoring process within the environmental assessment for German coal mining. This paper provides an overview of the evaluation methodology of the application of photogrammetry in conjunction with GIS, and discusses the application of modern surveying procedures.

1 INTRODUCTION

Since the Department of Geoinformation Services (DG) at the DSK was set up in 1996, all GIS activities – particular in the field of environmental planning – for the entire DSK area (approx. 1500 km^2) are centrally managed.
From an environmental planning aspect, the extraction of hard coal is subject to extensive approval and monitoring procedures by the relevant authorities. Of particular significance is the general operation planning process, of which the assessment of environmental compatibility is an integral part. The environmental impacts on the population, animals, plants and their surroundings, ground, water, climate/air, landscape, heritage and property are investigated in GIS-supported environmental compatibility studies.

2 WATER AS A PROTECTED RESOURCE IN THE ASSESSMENT OF ENVIRONMENTAL COMPATIBILITY

Water as a protected resource, in the form of near-surface ground water, rivers, streams and lakes, plays a central role in the environmental assessment of underground hard coal extraction. The mining of hard coal produces a cavity which is largely filled by the overlying strata within a period of usually less than 1 to 2 years. This ground movement continues up to the surface, where a subsidence cavity develops above the extraction area. The subsequent ground movements (subsidence and shifting) influence the natural environment – particularly the ground water and surface drainage. Therefore, in addition to the environmental assessment involving ecological investigations, a separate study from a water resource and ecological aspect is being carried out. This involves the recording of the initial status in the fields of hydrology, surface waterways and hydrogeology. Among other things, it is based on a digital terrain model (DTM) with an integrated three-dimensional watercourse network and a ground water flow model. Using the initial status as a basis, the result forecast investigates changes in flowing and still waters (e.g. gradient change, gradient reversal, overflowing) as well as the ground water conditions (e.g. changes in the ground water isobath, waterlogging) which would arise from mining – if the required regulation measures were not implemented. In the subsequent program, regulating measures (e.g. bed deepening, stream displacement) will be developed for those watercourses and terrestrial areas influenced by the mining and their effectiveness checked with simulation calculations, taking into account existing water resource and ecological objectives. From this investigation, measures or alternatives will be suggested, which should be put into practice within the context of a monitoring program regarding scope and starting date.
The three areas of near-surface ground water, flowing and still waters are closely interconnected. This study, however, describes only flowing waters – under special consideration of the combined application of photogrammetric evaluation techniques and GIS methods.
This began with a two-dimensional watercourse network, determined on the basis of official topographical maps, aerial photographs etc. The course, direction of flow and description (name and abbreviation) of the individual waterways were clearly identified.

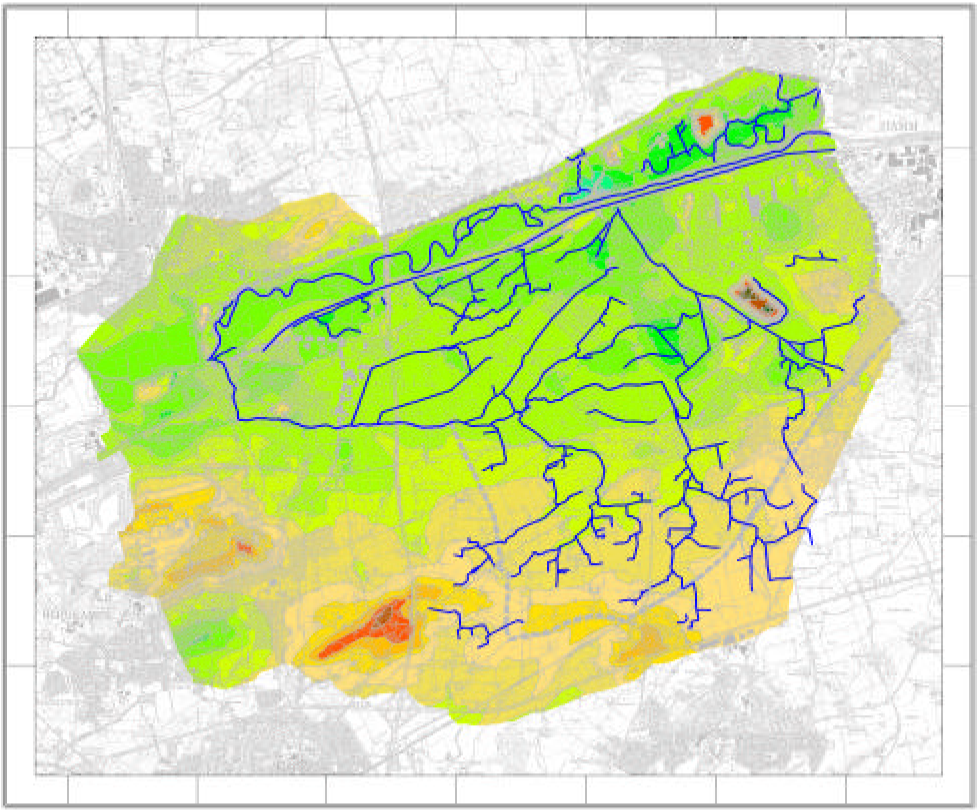

Figure 1. Elevation levels from the DTM and two-dimensional watercourse network
(DTM elevation levels from green (approx. 50 m NN) through yellow to red (approx. 100 m NN))

The watercourse network was divided into the three categories of principle waterways, tributaries and other waterways. Principle waterways and tributaries were incorporated in the DTM and assessed from an ecological and hydrological aspect, whilst the other waterways served only to complete the illustration of the watercourse network in the corresponding thematic maps.

3 DIGITAL TERRAIN MODEL

3.1 Automatic DTM Generation using MATCH-T as an Example

The digital terrain model applied in these environmental compatibility studies can cover an area of over 100 km^2, and is crucial for the investigation of water as a protected resource. Due to the necessity of up-to-date, accurate information, as well as cost-effectiveness, aerophotogrammetry (usually a scale of 1:6000) is the only feasible method of recording a large part of the data required by DSK. Digital photogrammetry is being increasingly applied by DSK-DG to achieve accurate results, which since 1978 have largely been obtained using analytical photogrammetry methods. However, research and development projects have indicated that the automatic construction of digital terrain models can lead to equally accurate results in certain areas.
In the Department of Geoinformation Services, due to the high standards required (assessors, water boards), a two-stage procedure was agreed upon for the measurement of the digital terrain model. Firstly, the DTM stage 1 was reconstructed by measuring a regular grid of 50 metres mesh size and the subsequent triangular mesh (ArcInfo Module TIN). The mesh size depends on the exactness of the approximation of the terrain, and on the justifiable expense. This DTM, initially roughly structured, was available to the specialist bodies involved within a very short time, for example, for the calibration of the ground water model.
In order to reproduce the morphology of the terrain surface, including the areas in which the rough grid cannot record the fine-structured terrain forms, the next stage involved the measurement of additional stations along breaklines. Once the extent and nature of the object types to be recorded in the second stage, e.g. artificial breaklines or slopes along the banks of drainage channels, had been agreed on with those responsible, the DTM stage 2 could be calculated by the density of the grid. Terrestrial surveys in areas not visible from the air, information about the beds of flowing

watercourses, analogue map material, and the analytical (P1) or digital (PHODIS-ST10) photogrammetric images all ensured an elevation accuracy of 20 – 30 cm.
Compared with manual photogrammetry, the DTMs generated completely automatically using MATCH-T (feature-based matching) were distinguished by a very dense DTM grid with a very small mesh size. Approx. 1 million points (pixel size 30µm or 2.5 million points for pixel size 15µm) per stereo model were matched, of which as a rule some 80,000 mesh points represented the DTM, according to the finite elements interpolation (pixel size 15µm).
According to the manufacturer, in favourable flat areas a DTM accuracy of 0.05 per thousand of the flying altitude can be attained or in hilly terrain 0.2 per thousand of the flying altitude. The generation was based on the classification of homologous points and the reconstruction of DTM bases. Corresponding with each level of the image pyramid a DTM was calculated. The result was a DTM pyramid illustrating the terrain surface more densely and precisely from level to level. The criteria according to which MATCH-T made the provisional classification were the epipolargeometry, the parallel axis value, the gradient signs, the interest value and the correlation coefficients. First, using an intersection of lines, calculation points were provisionally allocated for each model. The use of robust methods allowed the identification and elimination of interfering surface objects such as individual houses or trees. Additional, previously recorded data can also be added to the process of the DTM calculation, i.e. breaklines, recess areas and outlines.
Within the context of research and development, the correlation approach for the DTM calculation was analysed from an economic and qualitative aspect. Parallel, analytical measurements on the C100 were taken for several selected areas as reference measurements for comparison of the correlation results at a later date. Each test area was selected according to prominent object structures. So that a separate assessment of the correlation accuracy in dependency on the object structure could be undertaken later.

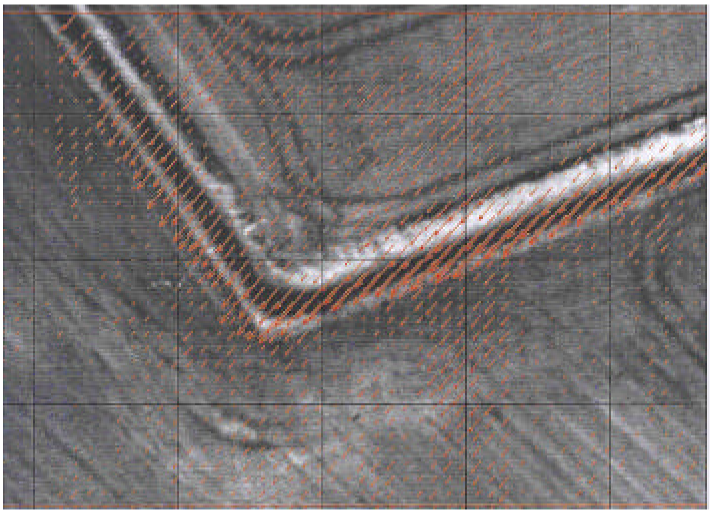

Figure 2. Illustration of the elevation differences of analytical / digital photogrammetry

For a detailed illustration of the errors in elevation between manual measurement and automatically calculated digital terrain models, the test areas 1 and 5 of the stereo pair 680/681 were selected as examples (for further information concerning the test set-up, please contact DSK-DG). An analytical measurement twice is available for both test areas. The square mean of differences for Area 1 was ± 0.053 m and for Area 5 ± 0.057 m. This represents an accuracy 0.06 per thousand of the flying altitude.

Both examples were calculated with 19 different parameter combinations in two different scan resolutions. They contrast with the other test areas in that they were not disturbed by the shadows cast by trees, bushes or urban structures such as houses or bridges. They were simply examples of agricultural land (farmland). The error vectors in the orthophotos showed that the accuracy of the correlated DTM sharply decreased for the ditch systems, a particularly sensitive segment of the watercourse network between farmland and meadows.
The square mean of differences for the whole of Area 1 was 17 cm (for 1000 and 2000 dpi) and for the whole of Area 5 it was 24 cm for the 2000 dpi images and 47 cm for the 1000 dpi images. However in both Area 1 and Area 5, especially in the field borders, errors in the order of 0.80 – 1.20 m were not uncommon. This can probably be accounted for by the thick vegetation of the ditch. Figure 2 shows an example illustrating the uncertainty regarding elevation accuracy which is inherent to the system of a correlated DTM. Depending on the topography, the original data record can attain accuracy levels of 20 cm to 3.50 m (cf. Figure 3).
In many places in recent years, intelligent filter techniques have been developed which reduce and correct either incorrect correlations or a surface distorted by the actual topography. Scattered trees or groups of trees are smoothed out and recess areas are interpolated. Depending on the required accuracy and the topography, re-working of this kind can certainly be effective. However, the DSK-DG has established that the systematic error rate of manual or semi-manual re-working techniques, particularly for breaklines, does not represent a realistic alternative to manual stereo photogrammetry for cost and quality reasons.

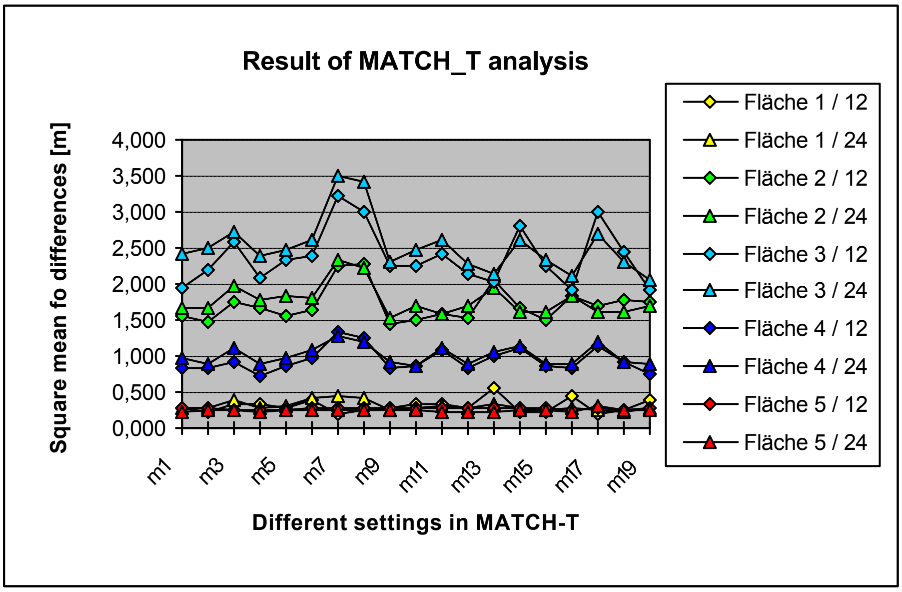

Figure 3. Statistical Analysis of the Elevation Accuracy in Dependence on the Scan Resolution (12 or 24 µm) and Topography (area1 – area 5)

3.2 Automatic DTM Generation using OrthoMax as an Example

For the second project discussed here, the program package Ortho*MAX* (VISION International Inc., Earth City, USA) was used to automatically reconstruct a DTM from high-resolution scanned aerial images of slag heaps on the basis of homologous points. For a detailed description of the program, the individual steps to be followed and the algorithms implemented in the software, please see ERDAS.
The main activities of DSK focus on the monitoring of slag heaps which are being filled. This involves an annual photogrammetric evaluation of the slag heap site and of the current body of the heap combined with the creation of a digital terrain model, a volume calculation and the determination of the remaining capacity based on the planned heap. For further investigations a digital terrain model was correlated under Ortho*MAX* and its accuracy was analysed using a reference model from the analytical photogrammetry.
Particular attention for this contribution was paid to the accuracy of the breaklines. As a rule, the geometry of the body of a slag heap is especially suited to the detailed study of this, due to the prominent berms. In this example the body of the slag heap was divided into 4 assessment zones due to the different characteristics of the surfaces (for example, the northern zone is being filled, whilst the southern zone is already completely recultivated). The overall result of all 4 zones together is shown in the table below.

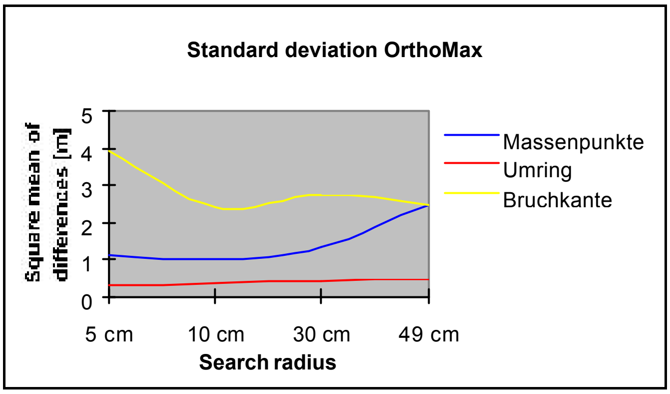

Figure 4. Standard Deviation Reference Measurement / OrthoMax (Massenpunkte = masspoints, Umring = border polygon, Bruchkante = breakline)

On the one hand, it is evident that in the clearly visible area (characterised by the "border polygon" measurements) accuracies in the order of 20 to 30 cm can be achieved. On the other hand, it was the breaklines which again showed a significantly lower level of accuracy.

3.3 Automatic DTM Generation using Laser Scanning as an Example

Due to the high accuracy requirements of the data used to produce the terrain model, the quality of laser scanning (TopoSys 1998) was verified using analytical comparative surveys of an analysis area (100 km^2 in total), giving an insight into both the potential and the restrictions of the processes. The regional survey department of North Rhine-Westphalia provided the DSK with a second laser scanner terrain model (TopScan, 1996/97) of an area for which the two data records overlapped. It was then possible to compare the accuracy of both laser scanners with the analytical reference survey.
The result of the "last pulse" registration of the TopoSys scanner was a grid with a mesh size of 1m. Not least as a result of the "last pulse procedure" and the high resolution, it is possible to clearly illustrate the route structure in this example, in spite of dense coniferous forest.
For the digital situation model, a representative value in each of the resulting 1m cells was determined from 4-5 values per m^2. Analyses at the Institute for Photogrammetry and Engineering Surveying (IPI) produced an altitude accuracy of 20 – 30 cm compared with the analytically measured reference grid (Koch 1999). The location accuracy is quoted by the manufacturer at 0.9 m. The comparison of the DTM by TopoSys with that of TopScan produced a relative location displacement in the order of 4 –5 m in the least favourable case. The inaccuracy of the DTM produced by laser scanning can be explained by the occurrence of systematic errors. A large proportion of these errors are in the positions and direction determination by GPS or INS. Different error influences overlap and are thus difficult to separate from one another. As a result, only a hypothetical explanation can be offered concerning elements affecting accuracy (Koch 1999). DSK implements a third party product for the automatic generation of breaklines (CB-DHM-Laser, by C+B-Technik) in order to increase the accuracy and reliability of the digital terrain model. In this way, DSK aims to accelerate the manual processing
The result shows that a large number of breaklines can be identified which must be selected. On the other hand, good results can be obtained, depending on the morphology – however the location accuracy of the breakline identification is naturally impaired, as described above, by the general location inaccuracy of the laser DTM. For certain tasks, these could considerably automate the process in combination with manual surveying. Naturally, the automatic process is not capable of, for example, differentiating between artificial breaklines (highways) and natural breaklines (ditches). This task will continue to be left to the additional contribution of the operator in the foreseeable future.

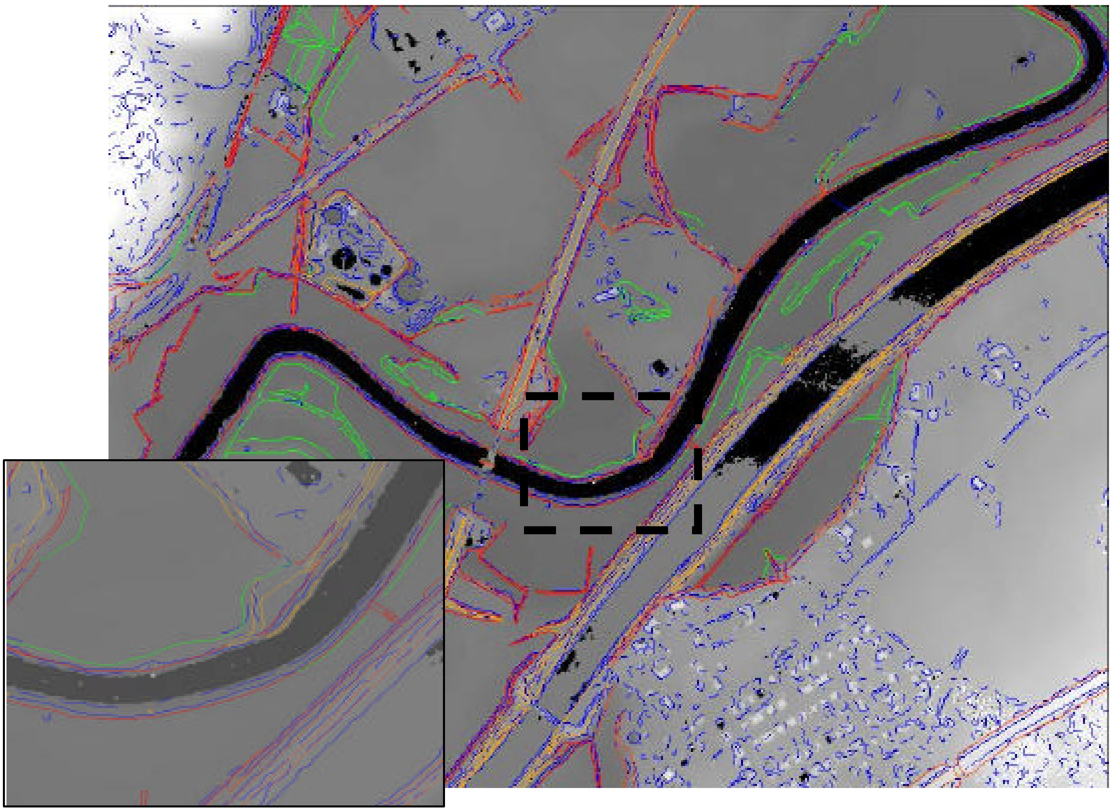

Figure 5. Lippeaue: Measuring Elements of Breakline Identification (blue), Manual Recording (other colors)

The resulting photogrammetric data are entered into the GIS ArcInfo from ESRI to calculate the detailed terrain model.

4 WATERCOURSE NETWORK

4.1 Structure of the Route System

By extracting from the terrain model, all hydrologic relevant elements were used by the ArcInfo module Dynamic Segmentation to reconstruct a three-dimensional water course network (route system) representing the water flow status at the date of fly. The module also generates event tables labelled with descriptions of the watercourse.
The routes of the individual waterway axes and slope edges are set for one waterway at a time in three route systems (beds, slope edges to the left of the direction of flow, slope edges to the right of the direction of flow) with the compilation of the appropriate Route Attribute Table (RAT) and Section Table (SEC).
As a rule, the stationing corresponds with the real length of the waterway and is set – beginning with 0 meters at the mouth – against the natural direction of flow. The determination of this natural direction of flow is sometimes difficult, since many watercourses no longer show a clear direction of flow throughout their entire course as a result of subsidence which has already occurred in recent decades.
In some cases – especially principle drainage channels – stations of the channel floor already exist (e.g. by the water board responsible), which do not always reflect the true length of the watercourse. For the illustration of this fixed station, dynamic segmentation offers a large number of ways in which all previous situations (e.g. swelling/lineation for an entire waterway or stretches of it, stationing with faults) can be put into practice without difficulty.

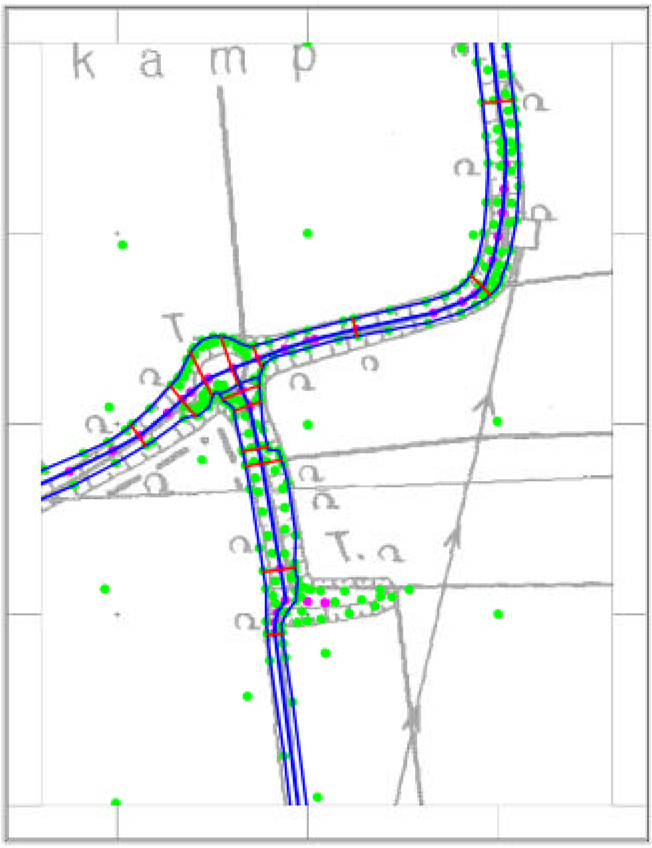

Figure 6. Detailed view of the construction elements for DTM and watercourse network (DTM grid and breakline points: green, channel floor points: magenta, watercourse axis: thick blue line, flood-relevant slope tops: thinner blue line, triple points: red line)

Finally, all slope edges must be stationed in dependence on the corresponding channel floor using allocation elements, referred to as triple points (cf. Figure 6).
These route systems now represent the two-dimensional status of the watercourse network and the flood-relevant slopes at the date of flight. The course corresponds exactly with the breaklines of the DTM.
A third dimension is added to the two-dimensional watercourse network by classifying the respective elevations from the DTM for all route points in a joint point event table.
As described in Chapter 2, underground extraction leads to subsidence at the surface. For the assessments and forecasts within the environmental compatibility survey and the water resource and ecological assessment the expected subsidence must therefore be calculated on the basis of the valid extraction plans for a number of clearly defined periods until approx. 2020. The starting point for this is always the date of flight.
For these periods the DTM stage 2 is lowered whilst retaining all linear structures. All points of the three-dimensional watercourse network are also linked with these subsidences, and the point event table is extended by the corresponding elevations of the individual periods. Between the date of flight and start or finish of the extraction to be authorized, geometric changes in the waterways can take place due to binding watercourse development plans (e.g. deepening, displacement) – both in the location and in the altitude. These changes are also taken into account in the respective DTMs and watercourse networks.
This can lead to the definition of new routes in the route systems. At the same time, old routes must no longer be considered for other periods.

To enable this period-based observation, the RATs of the watercourse network are supplemented with details of the validity of a route.

4.2 Creation of Longitudinal Sections

This "four-dimensional" watercourse network is then used to generate site plans – including the route-measured watercourse system - and longitudinal sections. The geometry of the sections results from the station and elevation data of the respective periods to be illustrated. Any number of period combinations of floor and terrain slope edges can be combined. The illustration of the correct location of floor and corresponding terrain slope edges is ensured by the triple points described in Chapter 4.1. As a rule, the length of the floor corresponds with the allocated station, whilst the terrain slope edges are illustrated as either shortened or extended. The sections are also accompanied by details about special punctiform and linear features (e.g. pipelines) as well as any further information (e.g. origin of the data) from event tables in the appendix. These longitudinal sections form the basis for the assessment of water flow changes resulting from underground extraction and for the planning of appropriate measures.

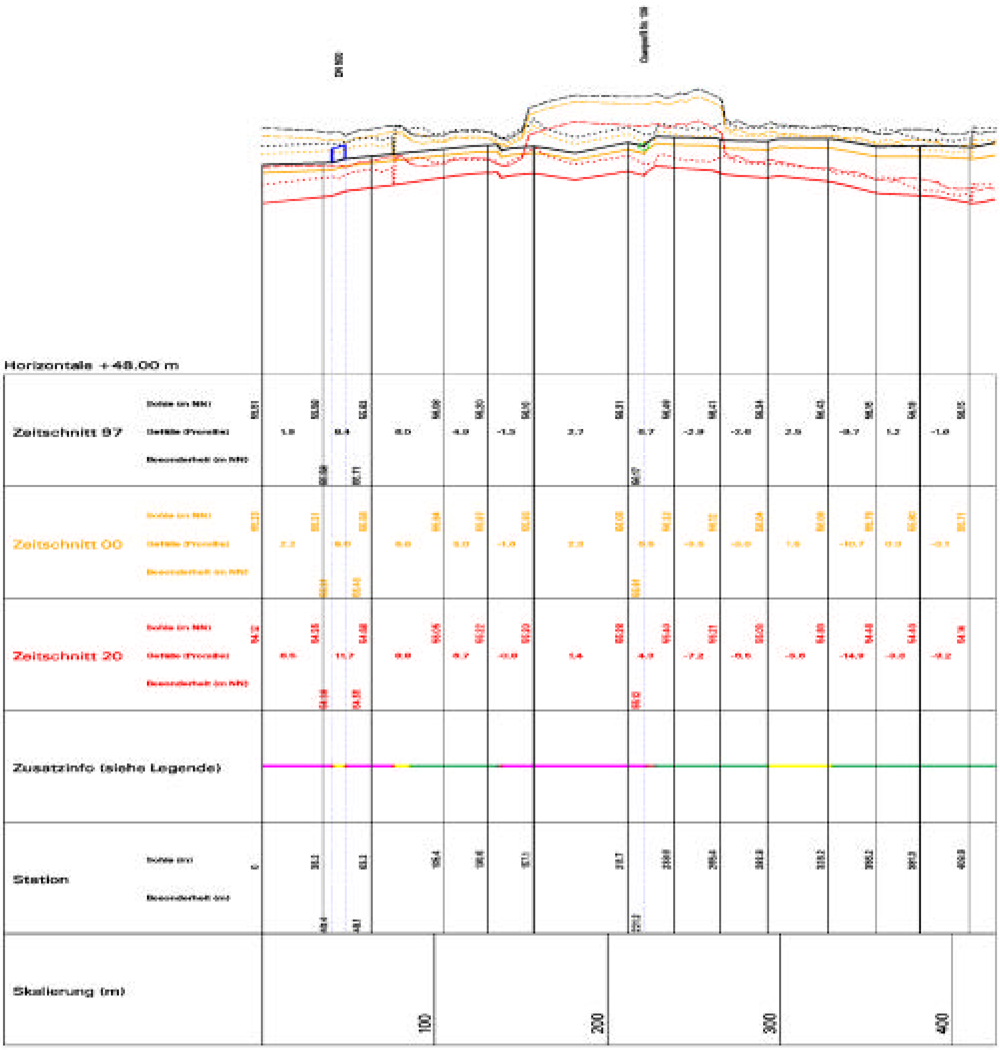

Figure 7. Longitudinal Section of a Watercourse
(situation in 1997: black, in 2000: yellow, in 2020: red)

4.3 Creation of Thematic Watercourse Maps

Special applications are used to build standardised databases which are linked to the watercourse network in the form of further event tables, enabling a description of the ecological status of the rivers and streams. This is then assessed and – taking changes in flow and isobath ground-water table into account – the impacts are forecasted, and the results are linked to the watercourse network in further event tables.

This data basis, combined with the implementation of specially developed methods, produces high quality cartographic illustrations of the results for the environmental compatibility studies, in the form of status maps, assessment maps and forecast maps. These watercourse maps are created with AML programming, using the standard ArcPlot facilities. To emphasize the most important information, the maps are opaque with appropriate overposts. To illustrate more than one line event per watercourse on a single map, up to two coloured lines are illustrated on each side of the watercourse. A priority setting ensures that, where watercourse illustrations overlap (e.g. in the vicinity of estuaries) the information about the most important of the two watercourses is shown. Point events are either illustrated on the watercourse axis itself or on the relevant side of the watercourse (e.g. at inlet points).

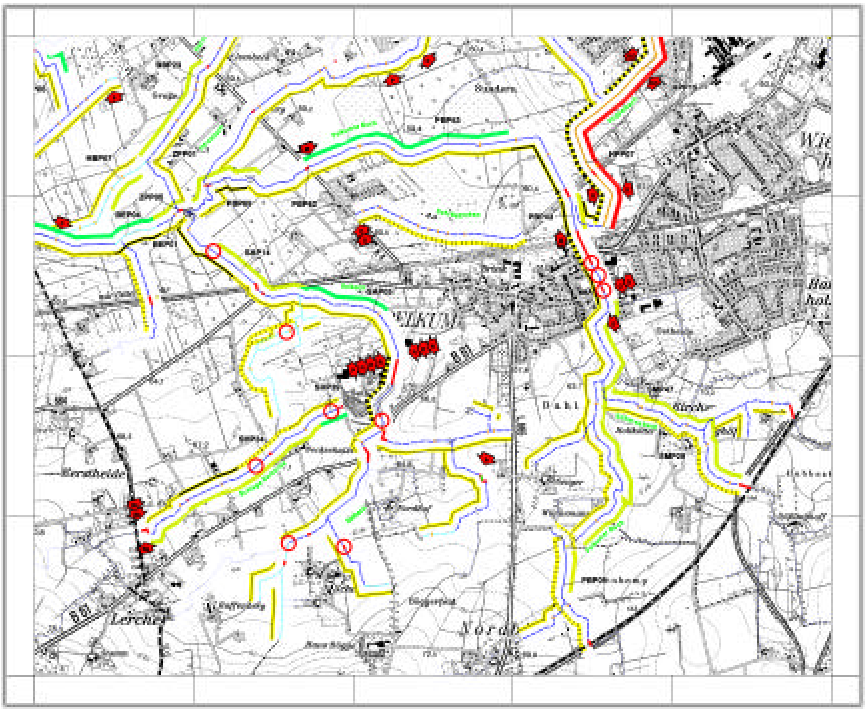

Figure 9. Ecological status map (yellow lateral lines: morphology; red/green lateral lines: water quality; blue central lines: water channel; red central lines: pipeline; red arrows: inlets; red circles: track erosion; further illustration of punctiform and linear features)

5 CONCLUSIONS

This paper documents the efficient application of modern photogrammetric and GIS processes and methods in regional environmental planning. Thus in order to reduce time and costs, DSK-DG also implements laser scanning processes in addition to the traditional manual photogrammetric recording methods used for terrain modelling, which mainly provide details of mass points, breaklines and topographic lines. The laser scanner complements this data with satisfactory results in areas not visible from the air. Attention is focussed largely on the breaklines. Initial tests using a program for reconstructing breaklines, CB-DHM Laser by C+B Technik, show on the one hand the great potential of the laser scanning method, on the other hand that the next step towards automated DTM calculation was made as a combination of classical photogrammetric evaluation and laser scanning. The method presented for the integrated creation of digital terrain models and a “four-dimensional” watercourse network using TIN and particularly Dynamic Segmentation under ArcInfo enables the compilation of a homogenous and yet “dynamic” data basis for all parties involved in the creation of the general plan of projected mining for the first time, and thus consistent processing at different points. Dynamic Segmentation allows the simple addition of further thematic levels. This is certain to be of great significance for watercourse monitoring in future. The data created for the environmental assessment is stored in the central GIS data pool of DSK. It will therefore be available online to all interested parties via Intranet/Internet and is likely to provide the basis for studies which go beyond the creation of general plan of projected mining.

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