HIGH RESOLUTION AIRBORNE SHALLOW WATER MAPPING

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ABSTRACT:

In order to meet the requirements of the European Water Framework Directive (EU-WFD), authorities face the problem of repeatedly performing area-wide surveying of all kinds of inland waters. Especially for mid-sized or small rivers this is a considerable challenge imposing insurmountable logistical efforts and costs. It is therefore investigated if large-scale surveying of a river system on an operational basis is feasible by employing airborne hydrographic laser scanning.

In cooperation with the Bavarian Water Authority (WWA Weilheim) a pilot project was initiated by the Unit of Hydraulic Engineering at the University of Innsbruck and *RIEGL* Laser Measurement Systems exploiting the possibilities of a new LIDAR measurement system with high spatial resolution and high measurement rate to capture about 70 km of riverbed and foreland for the river Loisach in Bavaria/Germany and the estuary and parts of the shoreline (about 40km in length) of lake Ammersee. The entire area surveyed was referenced to classic terrestrial cross-section surveys with the aim to derive products for the monitoring and managing needs of the inland water bodies forced by the EU-WFD.

The survey was performed in July 2011 by helicopter and airplane and took 3 days in total. In addition, high resolution areal images were taken to provide an optical reference, offering a wide range of possibilities on further research, monitoring, and managing responsibilities. The operating altitude was about 500 m to maintain eye-safety, even for the aided eye, the airspeed was about 55 kts for the helicopter and 75 kts for the aircraft. The helicopter was used in the alpine regions while the fixed wing aircraft was used in the plains and the urban area, using appropriate scan rates to receive evenly distributed point clouds. The resulting point density ranged from 10 to 25 points per square meter. By carefully selecting days with optimum water quality, satisfactory penetration down to the river bed was achieved throughout the project.

During the data processing meshes for multiple purposes like monitoring sediment transport or accumulation and hydro-dynamic numeric modeling were generated. The meshes were professionally conditioned considering the adherence of, both, geometric and physical mesh quality criterions. Whereas the research is focused on the design and implementation of monitoring database structures, the airborne hydrographic data are also made available for classical processing means (cross sections, longitudinal section).

1. MOTIVATION

The motivation for working on a new technology approach in surveying shallow water structures were the demands for high quality and area-wide bathymetric survey data, up-to-date and short in time available and as a self-consistent dataset captured by one sensor for

1. engineering
2. politic and by law stated aims like the WFD
3. research

1.1 Engineering

For water engineering and research one of the most important aspects of hydraulic aspects deals with representing the topography of rivers, floodplains, estuaries or coastal areas. Although different fields of impact, characterising the hydraulic background of water bodies (e.g. 2d- or 3d-modelling) is one main effort. The difference of the needed hydraulic set-up can be found in scale and resolution for appropriate modelling but all of them need to work on close-to-reality numerical models.

Commonly, flood model applications use digital elevation models, based on high quality and high resolution topographic airborne laser data. The digital elevation model of the water body itself is normally represented by simplified and interpolated data based on manually collected terrestrial fieldwork data. As well as a lack of spatial and high resolution water body data, the modelling of shallow areas like meadows, estuaries or riverbanks is highly time consuming or even impossible. Frequent urban flooding over the past decades have identified an urgent need to improve and increase our modelling efforts and to address more explicitly the effect model input data has on the uncertainty in the simulation results. Society demands reliable and detailed information on magnitude and likelihood of hazardous flood events for design of flood mitigation. For this, the assumption of the shape of the water body has to be solved and modelling improved by using the actual shape. Furthermore next to shape additional information's like surface roughness or the water surface are

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relevant to calibrate the models. The technology of hydromapping aims to solve this challenge.

1.2 Water Framework Directive and its political aims

The EU Water Framework Directive (WFD) is a radical and ambitious programme to protect and enhance the quality of aquatic ecosystems across Europe. It is fundamentally interdisciplinary in nature as it places ecology at the heart of the management objectives. This means that its implementation is predicated on understanding the complex interactions between hydromorphological, physico-chemical, biological and human pressures expressed in terms of water bodies' ecological status. Effective and sustainable implementation of the WFD requires a major commitment to developing new monitoring protocols and much better understanding of the biophysical linkages between anthropogenic pressures and their ecological response. Evidence to date indicates that many member states are struggling to meet their commitments to monitoring, and the introduction of programmes of remediation measures where water bodies are failing to meet WFD objectives.

In respect of the WFDs overall aim of cost-effective hydro-morphologic restoration and mitigation measures, datasets by hydromapping will deliver a better understanding for eco-hydro-morphological processes by the detection of new indicators and the deliverance of advanced or new methods, combined with models, tools, software and services. This is seen as a precondition to the development of cost-effective and sustainable remediation of damaged ecosystems and to future-proof the likely adverse impacts associated with climate change which will impact water bodies in different regions in Europe in a myriad of ways.

1.3 Research

Based on the complexity of the different scientific problems already at begin of the research project it has been realized that a task distribution between an industrial partner (*RIEGL* Laser Measurement Systems) and a research institute (Unit of Hydraulic Engineering of the University Innsbruck) was needed. Whilst the industrial partner was responsible for hardware development of the laser system, the academic partner was responsible for the water related issues and verification. With its extensive research experience on hydraulic, morphology and hydropower and knowing the practical problems in engineering practice first of all there had to be formulated the requirements for the water penetrating laser technology and also the necessary characteristics of the measurement procedure. In this meaning there were defined, among other parameters the desired penetration depth, measurement resolution or accuracy and always focused on the systems application for shallow waters. This approach constitutes a unique feature and will also be the future basis for the on-going research cooperation. The further research work referring to the laser scanner system includes hardware developments, experimental verification, data processing and software development as well as improving the survey process itself. But especially the new data quality offers the basis for a series of following-up research projects referring to hydraulic, sediment or water ecology problems. Out of this there may be expected a significantly better understanding of the process of sediment transport or an improved possibility for modeling habitats. In the future a series of university institutions will be active in the domain of these themes. At the moment, the Unit of Hydraulic Engineering deals among others with the possibility to improve hydraulic modeling based on the new

hydromapping data. Based on the complexity of bathymetric data and its contained information (e.g. turbidity, velocity) the necessity for new analysis and visualization tools resulted in software development activity for the new data within the frame of an academic research group.

2. THE TECHNOLOGY OF HYDROMAPPING

2.1 State of the art

Airborne laser scanning is unrivalled as the most effective concept for fast and economic mapping of large or recurring areas and collecting up-to-date, high-quality, and high-resolution survey data. Recent developments at the Unit of Hydraulic Engineering at the University of Innsbruck in cooperation with *Riegl* LMS allows for the first time comprehensive surveys of shallow water bodies using an airborne operated water penetrating laser system (airborne hydromapping).

2.2 Hydromapping sensor concept

Airborne Laser Bathymetry, also referred to as Airborne Laser Hydrography, is a method for measuring depths of shallow waters from the air. The first application of ALH was finding submarines and goes back to the mid 1960ies when the laser itself was invented. Following first successful tests, a series of systems have been developed till the end of the 1990ies. The general concept of former ALH systems involves the use of a pulsed laser transmitter with both green and infrared (IR) output. The green wavelength is selected because it penetrates water with the least attenuation. IR light, in turn, penetrates water only very little and can, thus, be used for detection of the water surface (air/water interface).
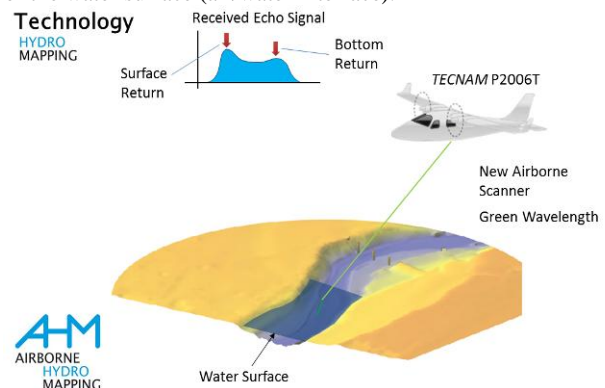
Figure 1: Principal representation of the penetration and deviation of the laser impulse on and in the water. The runtime difference between water surface and sole allows determination of the waters' depth.

The design of the new bathymetric laser scanner system (*Riegl* VQ-820-G) in cooperation with the Unit of Hydraulic Engineering can be summarized as follows: The scanner operates in the green wavelength spectrum (λ=532 nm) since signals in the wavelength range of 400-600 nm are capable of penetrating water columns. Very short and narrow pulses are emitted at high frequency (pulse duration: 1 ns, beam divergence: 1 mrad, pulse repetition rate: 250 kHz). Short pulses (1 ns≡30 cm) are necessary to separate returns from the water surface and the river bed in the shallow water environment the instrument is designed for. Narrow pulses (1 mrad≡50 cm footprint diameter on the ground at a nominal flying altitude of 500 m) together with the high net measurement rate (110 kHz) ensure a high spatial resolution of typically 20-50 points/m2. The green laser pulses are tilted

about 20° w.r.t. the flight direction. The deflection mechanism based on a rotating multi-facet mirror results in an elliptical arc-like scan pattern on the ground. This ensures that the incidence angle of the laser beam hitting a horizontal water surface does not deviate more than ±1° over the entire scan range of 60°. The instrument consists of a scan head (scan mechanism, transmitter and receiver optics, waveform processing unit) and a separate laser source housed in a 19" rack. Both components are connected via an armored glass fiber cable. This compact and lightweight design enables the installation in light aircrafts and helicopters. The backscattered signal is recorded in the waveform processing unit with high temporal resolution. Online waveform processing is performed in real time during the flight mission neglecting the different propagation velocities and refraction effects in the water. The preliminary point cloud, however, enables the operator to assess the completeness of the coverage while still airborne. Refraction correction and, if necessary, more sophisticated waveform processing is performed in postprocessing in the office considering the pulse distortion due to distributed reflections, the slanted angle of incidence, refraction and the reduced propagation velocity within the water column. The instrument is designed for measuring water depths of several meters in relatively clear water conditions. Turbidity causes distributed reflection at suspended particles and, attenuates the reflected signal and, thus, limits the effective range. The maximum measurable water depth of the sensor is in the range of one Secchi depth, i.e. , the depth at which the pattern of a circular black-and-white disk with a diameter of 20 cm is no longer visible. In contrast to existing sensors focussing on maximum depth using high pulse energy, the new system is dedicated to shallow water environments and to provide high point densities and range resolution utilizing only moderate pulse energy. This is exceptionally important w.r.t. to eye safety. The instruments' NOHD/ENOHD (i.e. eye safety for the naked/aided eye) are 100m and 500 m, respectively.

3. FIELDS OF APPLICATION

The potential and the big benefit of this technology is the possibility to survey flowing waters, shallow areas or reservoirs in close intervals with an accuracy and information density that can be compared to the topographic laser scanning. Monitoring of changes is possible the first time. The scope is to offer the data basis for water engineering and economic and political decision short in time and by a cost effective measurement method. The fields of application are tremendous and summerized within this short overview:

3.1 Hydraulic:

Hydrodynamic-numerical simulation, also referred to as Computational Fluid Dynamics (CFD) modeling, is the state-of-the-art tool for flood prediction and prevention, disaster management, for modelling sediment transport as well as aquatic habitats. The most influencing input parameter for CFD models is the geometry provided as a Digital Terrain Model of the watercourse describing the riparian area including the river bank, the river bed, and all flow prohibiting objects like buildings or bridge piers. By now, the river bed data had to be captured independently from the flood plain topography either by single- or multi-beam echo sounding or by geodetic field survey (GPS, total station). The former poses the problem that shallow water areas (shoal, littoral zone) cannot by accessed by boat. In the latter case, cross sections at a relatively large interval of typically 20-200m are measured requiring

interpolation between two cross sections which is inaccurate as well as cost-intensive. In both cases the necessary fusion of river bed and topographic data is time-consuming and prone to errors (Gallant and Austin, 2009). With the new hydrographic laser it is, for the first time, possible to capture all necessary geometric data for CFD modeling in a single flight campaign. That way, a homogeneous data source w.r.t. spatial resolution and height accuracy can be efficiently provided. This especially applies to small and medium rivers which are often difficult to access. Due to the required clear water conditions thorough flight planning becomes necessary. However, there exist several potential time slots distributed over the year. Larger rivers, in contrast, feature higher turbidity due to floating sediments and/or suspended material. A complete hydrographic survey for such water bodies is not possible but, still, there is a big advantage in capturing the shallow littoral zone. Furthermore, the new technique bears an enormous potential for surveying shallow groyne fields so that (multi-beam) echo sounding missions can be restricted to the permanently navigable channel. This would at the one hand dramatically increase the possible period of measurement as the waterborne hydrographic survey is no longer restricted to high water conditions. On the other hand, again, the fusion of topographic and hydrographic data would be facilitated and the precision increased given a certain overlap of bathymetric data from waterborne and airborne sensors. However, tests verifying this assumption are still outstanding.

3.2 Hydro-morphology:

Due to sediment transport the morphology of the river bed is subject to constant changes. In near natural environments accumulation areas (sedimentation) periodically alternate with removal areas (degradation). Rivers regulated by impoundments, in turn, often show a deepening of the channel due to the lack of upstream sediment load. Both natural and artificial changes of the river bed morphology have an impact on the river ecosystem and, thus, influence the overall quality of the riverine environment. Therefore, repetitive surveying is a crucial task which can efficiently be achieved by airborne hydromapping. Furthermore, numerical sediment transport modeling, either loosely or tightly coupled with CFD models, gained importance in the recent past. For such models inventories of the river bed morphology at the beginning and end of the modeling period constitutes an excellent source for model calibration and validation which, up to now, had to rely on historic data with poor spatial resolution and geometric accuracy.

3.3 Hydro-ecology:

Multi-dimensional CFD models deliver estimates of spatially distributed flow velocities, water depths and bottom shear stresses for certain discharge conditions. Together with the high resolution bathymetric data this data source yields optimum qualifications for modelling aquatic habitats as it allows the differentiation of different meso-habitat types like riffle, pool, shallow water, runs, fast runs and backwaters (Hauer et al., 2009). Especially the monitoring of shallow water and backwater habitats which are exceptionally important for breeding benefit largely from the new technology as existing bathymetric data cannot compete in terms of data density and accuracy. Adolescent stages, in contrast, often preferring higher energy habitats (riffle, runs, etc.) can also be mapped in higher detail based on hydromapping data.

As mentioned before, the instrument is designed for application in clear water conditions. Turbidity, in turn, is a measure of the water quality which is demanded to be monitored on a regular basis by the EU-Water Framework Directive. Given a sufficiently up-to-date survey of the river bed topography is available, an hydromapping survey can be employed to estimate the degree of turbidity caused by sediments and suspended particles. Laser returns reflecting somewhere in the middle between the water surface and the river bed can be identified by proper waveform analysis and by comparison with the ground truth stemming from a recent flight in clear water conditions. While it is clear that not all water quality aspects demanded by the WFD can be covered by airborne hydrographic laser scanning, it will most certainly play an increasing role for topics related to ecology and water quality and not only to pure geometry.

3.4 River restoration

The progressing river regulation measures of the past have contributed to an increase of the mean flow velocities. Flood events, therefore, often have a high impact on the near-shore infrastructure, residential area, and agricultural environment due to a lack of velocity detaining structures. This is only one reason why river restoration has become a topic of increasing relevance in the recent past. River restoration is a good example profiting from the combination of a topographic and hydrographic laser scan data. Truncated ox-bow lakes and cut-off meanders are typically shallow, thus, benefit highly from the high range resolution provided by hydromapping whereas the surroundings are normally dominated by different layers of vegetation.

3.5 Hydropower:

The energy transformation/revolution caused by the historical events of Fukushima assists the efforts and demands for alternative energy solutions. Hydropower as one of the oldest renewable energy experiences a new heyday. The now existing knowledge on ecological aspects need to be part of the engineering concepts and assisted by an overall basis data, reliable and comparable in different belongings. An airborne multi-sensor data acquisition (hydrographic and topographic scanning, high resolution aerial images and spectral analysis) includes primarily benefits from the perspective of the task of monitoring. The hydrographic mapping is blended with information from aerial and spectral images and offers next to the evaluation of changes to structures the detection of changes in soil consistence or the type of vegetation structures. The high scan resolution allows, for example as part of the initial evaluation, an automatic determination of the cross-sections roughness for discharge calculations or as part of a monitoring concept the comparison of the increase or decrease in vegetation. Especially the possibility of spatial comparisons by time fit the supervisory documentation requirements for changes due new constructions and the operation of hydropower plants.

Monitoring as a main scope of work within infrastructure projects is significantly extended by the technology of hydromapping. Due to its fast and spatial survey procedure for water areas large amounts of money invested in river restoration, river management or water projects can be saved. Their poor documentation and impact analysis was typically a result of missing information. Based on the new survey data and impact results an improvement in handling water sources can be achieved.

4. PROJECT WORK

In cooperation with the Bavarian Water Authority (Wasserwirtschaftsamt Weilheim) a verifiable pilot project was initiated by the Unit of Hydraulic Engineering at the University of Innsbruck and *RIEGL* Laser Measurement Systems. In order to assess the possibilities of the new LIDAR measurement system with high spatial resolution and high measurement rate, LIDAR data should be acquired for a river and the estuary of a lake. Within the survey phase during summer and fall 2011 the test sites were exceeded and finally over 500 km of different rivers and more than 60 km of shoreline of inland lakes were captured by using the hydromapping technology. In addition to the laser data, high resolution aerial images (~5 cm/pixel) were taken to provide an optical reference, offering a wide range of possibilities for subsequent research, monitoring, and management. The field of view of the aerial camera covered slightly more than the swath width of the laser scanner. Both a helicopter and a fixed-wing aircraft were employed. The airspeed of the helicopter platform was about 55 kts, that of the fixed wing aircraft was 75 kts. The article takes now focus on the test sites River Loisach and Lake Ammersee in Bavaria.

Figure 2: Helicopter carrying survey pod and integrated RIEGL system VQ820-G

Figure 3: Special configured slow flight twin engine aircraft including three survey openings for hydromapping system and cameras (RGB, hyperspectral)
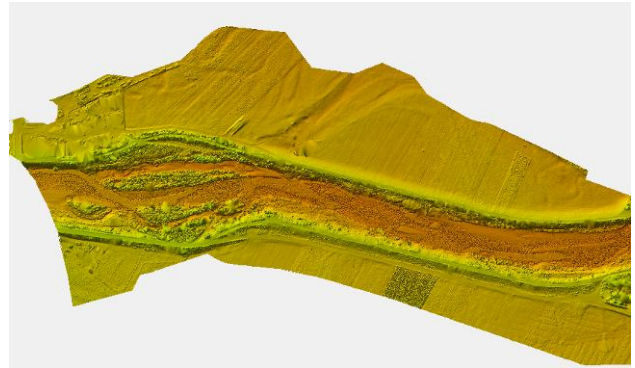
The reason to choose the Loisach as pilot river was based on its complex and rapidly changing river structure ranging from a steep-sloping mountain river over segments within cities heavily intruded by manmade structures to a wide estuary into lake Kochel.

Figure 5: Generated mesh based on a filtered dataset with focus on displaying the high resolution of the riverbed

While in the past gross estimates had to be used for building the meshes due to the lack of underwater information, we now even face the problem of decimating the high resolution information by filtering. It is one of the fields of research at the Unit of Hydraulic Engineering of the University of Innsbruck to find filter algorithms which not only observe the numerical and performance limitations of existing models but at the same time provide improvements on the quality and usability of the results. The data processing strategy is motivated by the demand of end users to have a new data basis to extract basic information on a daily basis without being forced to handle large pointcloud datasets.

Figure 4 and 5: Pictures taken during survey process and displaying the estuary of River Loisach into Lake Kochel and the river within a flood protection relevant area.

Figure 6: Scan-data point cloud and ground truth profiles of the weir sill located next to hydro power plant, upper stream reservoir and sediment structures. Colour corresponds to the local roughness of the pointcloud.
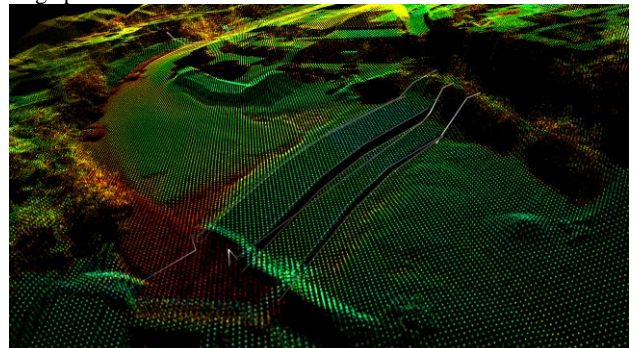
The survey of about 70 km of river Loisach was performed in July 2011 and took two days in total. The data acquisition of the analysed area was performed by helicopter and included two flight strips. One conducted from an altitude of about 500 m with a pulse repetition rate of 138 kHz and maximum laser pulse energy, the other in opposite direction at about 200 m above ground with a pulse repetition rate of 250 kHz at reduced laser pulse energy, maintaining eye-safety even for the aided eye. By choosing days with suitable water quality, satisfactory penetration down to the river bed was achieved throughout the project. While depths of up to 4 m were reached it was even more important to assess the performance in complex situations, i.e. with boulders in the river or splitting of the river into several shallow arms. The resulting point density ranged from 10 to 25 points per square meter per flight strip.

Data processing also comprised the generation of different derivatives of the raw pointcloud and RGB images as colored pointcloud-, mesh- and GIS-datasets. Data from terrestrial surveys was used to calibrate the processed pointcloud. The resolution of numerical meshes depends on the requirements of the related application like monitoring sediment transport, hydro-dynamic numeric modelling or habitat modelling.

The accuracy of the system was evaluated by comparing the laser scan data with 70 ground-surveyed reference cross-sections of the river also comprising the water level. The system's error range is in the range of +/- 5-10 cm, similar to conventional topographic airborne scanners. In contrast to traditionally waded terrestrial cross sections at a resolution of typically 200 m, small-scale channel bed or bank structure changes can be captured by the new high resolution survey method. The reduction of absolute point accuracy compared to terrestrially gained measurements is more than compensated by the overall accuracy arising from spatial point information – information bringing up a three-dimensional thinking of under water conditions and enabling successful and efficient monitoring for our water bodies. Novel algorithms are needed for pointcloud classification of vegetation, topography under vegetation or under the water surface and vegetation in the water. Due to the high resolution of the scanner it is possible to deliver DEMs with a cell size smaller than 0.2 m even for single flight strips. Being able to identify all structures relevant to the flow and habitat units from a single fly-by is an amazing progress. For comparison, to fulfil the requirements of habitat

modelling a two-day ground survey would merely cover an area of less than 200 m in length and by no means capture the complex structures of channels, pools and the relevant vegetation.

With the new airborne hydromapping LIDAR sensor it is possible for the first time to describe higher order hydrographic features and their spatial relationship. Information on hydraulic or ecologic underwater features as derivatives of distance, slope, curvature, area, or volume can be gained. Evaluation of the data captured in the course of the pilot project as well as the development of corresponding tools to extract the information required to fulfil the EU-WFD is still in progress. A dataset of about 8 km river length was chosen to pursue the steps from raw point information, data correction and calibration, filtering, linking the pointcloud information to aerial image information, and building up a fine digital waterbed model (cell size ~10 cm) for visual comparison and a coarse model (cell size ~ 1 m) for hydraulic and habitat modelling purposes.

From the perspective of morphologic and ecologic aspects the estuary of a river is to attach a high importance. By using the new hydromapping technology and its high resolution it should be shown how far it is able to detect small-scale changes in a lakes bed and equally if it's possible to capture data beneath floating vegetation. The flight also took place with a helicopter, one scan strip at about 30 kts and resulting in a resolution of about 45-60 points/m².
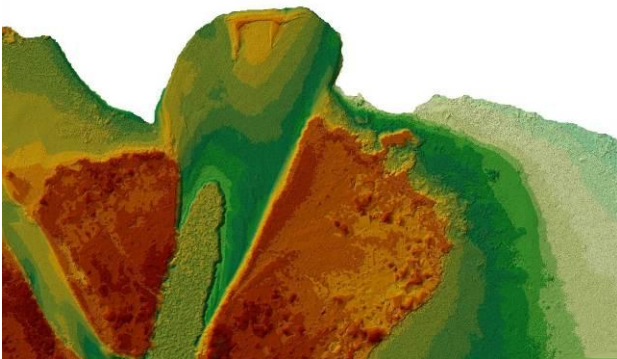
Figure 7 and 8: The estuary of Lake Ammersee showing a fine mesh and its corresponding aerial picture.

A special filter needed to be developed to recognize the difference between water surface echoes, echoes of floating plants or objects, intermediate echoes by water plants, echoes by turbidity and finally the ground echoes.

After filtering within the area of floating plants the point density reduced at a range of 10-15 points/m². Also a particular challenge was to determine the transition zone between water and foreland complicated by the strong water vegetation. Aerial pictures gave supporting information.

Compared to existing survey technologies never a similar high in resolution survey was done for this estuary. Due to missing almost comparable spatial data the verification took place by a few terrestrial survey points. Based on the results a monitoring concept was build up including fixed terrestrial points within the water to calibrate and verify the data and being able to compare scan results by time.

5. CONCLUSION AND OUTLOOK

The great importance of water monitoring is underlined by problems concerning climate changes, flood protection, ecology, management of sediment, hydro power or problems of water ways. There doesn't only exist the direct need of this new data and its evaluation, facts and open questions concerning our waters will accompany mankind middle and long term.

The new hydromapping concept is unchallenged with the possibility to acquire high resolution survey information on the hydrographic, topographic and vegetation structures of our shallow water bodies on a large-scale basis. Airborne hydromapping delivers for the first time the needed data basis to understand the complex interactions between hydromorphological, physico-chemical, biological and human-induced factors. An up-to-date, spatial, and integrative monitoring approach enabled by laser scan data and followed by analysis of the ecological impact meets the requirements to handle the present and future demands of our water bodies.

Especially monitoring tasks require a coupled analysis of all datasets related to rivers, standing waters or coastal shallow water areas. This provides a more comprehensive understanding of the actual condition and thus allows the identification of changes required for our water bodies. In order to facilitate these analyses the lidar data should be combined with data acquired by topographic scanner systems, RGB images and hyperspectral images. Due to the fact that besides data capturing data processing and evaluation is a fundamental part of water survey also high effort need to be imposed on software and technical engineering tasks.

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