BETWEEN SENSING, FORECASTING AND RISK ASSESSMENT: AN INTEGRATED METHOD TO MODEL HIGH RESOLUTION DATA FOR FLOODPLAIN REPRESENTATIONS IN HYDRODYNAMIC SIMULATIONS

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ABSTRACT

This paper focuses on automatic representation of topographic data for flood hazard modeling based on high resolution measurements. Accenting challenges in handling of high resolution (HR) data from remote sensing (RS) technologies, a mesh generation procedure for hydraulic simulations is presented embedded in a framework for accuracy assessment. Attempt is made to construct a digital terrain model (DTM) being used for hydrodynamic simulations. Regarding triangular irregular networks (TINs) derived by Delaunay refinements, the numerical solution of the 'Shallow Water Equations' is achieved based on a Finite Element Method. The paper spotlights the impact of terrain representation on these equations.

Keywords: LiDAR, remote sensing, floodplain modeling, Shallow Water Equations.

1 INTRODUCTION

Owing to intensive national flood events at Odra (1997) and Elbe (2002), airborne laser scanning has achieved a breakthrough in Germany as a technology to collect HR topographic measurements for river systems. Both LiDAR (light detection and ranging) and IFSAR (interferometric synthetic aperture radar) are new and meanwhile mature remote sensing technologies to obtain HR measurements. As emerging technologies, they are prominent subjects of leading international conferences focusing Geographic Information Systems (GIS) and engineering applications. The latest technological development phase raised a clear trend to international cooperation and expansion in the community of data providers. Parallel to the technological development in remote sensing, advances in GIS developments promote multidisciplinary associations, e.g. the U.S. National Digital Elevation Program (NDEP). This consortium includes representations of federal agencies for geological surveying (USGS), geodetic service (NGS), emergency management (FEMA), engineering (USACE), geographic information (NSGIC), land management (BLM), agriculture & forest service (USFS), oceanic & atmospheric surveying (NOAA) as well as the aeronautics & space administration (NASA). Achievements of these recent developments are new guidelines for digital elevation data and a proposal to revise US national geospatial positioning accuracy standards. The international trend towards higher resolution in available topographic data along with improved accuracy standards for DTMs establish LiDAR and IFSAR technologies as standard data sources. This trend motivated the development of a procedure to represent HR data as mesh representation for flood hazard assessment. The suggested procedure enables efficient hydrodynamic simulations and flood hazard modeling by means of automated mesh generation. It provides a framework for systematic impact studies to investigate the dependency of hydrodynamic simulations on DTM resolution. These studies contribute to assessing the uncertainty incorporated in hydrodynamic simulation models due to topographic resolution and the individual weight for a series of subsequent analysis, e.g. inundation mapping, sediment transport modeling or flood risk assessment.

2 HIGH RESOLUTION DATA SOURCES AND THEIR PREPARATION

Remote sensing technologies face problems while monitoring water surfaces. River system modeling based on LiDAR data faces the phenomena that mirror-like water surfaces tend to fail scattering the pulsed laser beam. Unless the beam is perpendicular to the surface, no light is reflected back to the detector. A different bias are intense reflections raising negative blunders, i.e. measurements being too low. Interpolations between nearest on-land points and sparse water points tend to produce triangular facets without truly reflecting the water-surface elevation. Consequently, measurements in inundated areas should be discarded for LiDAR measurements. Today, just one LiDAR system copes with this problem, providing both a hydrographic and topographic operation mode within one airborne sensor. This system uses green plus near infrared pulsed laser beams (SHOALS-1000T system; Optech, Canada). Its applicability is restricted to coastal zone management/nautical charting under conditions of low dissolved matter and limited waves. Merely one commercial provider is known today, offering this service by 2005 (Fugro, The Netherlands).

River system modeling based on InSAR measurements uses the reflective surface of the earth to derive range measures requiring a coherent scattering, i.e. phase preservation for the received signal. This implies that the phase information per pixel should primarily be based on geometry [1]. Temporary changing reflection characteristics within a resolution cell should be avoided. This is almost impossible for water since it changes its physical shape within very short time.

Figure 1 illustrates a filtered LiDAR data set for a reach of the River Elbe. It shows consistent airborne LiDAR measurements as grey relief image (left) and an orthophoto of similar reach (right). Clearly to be distinguished are dry river banks, floodplains enclosed by winter levees and groins in the river channel. Deficiencies due to inundated areas, blunders and surface object removal are shown as light colored gaps.

Owing to the inherent lack of information in RS data on water bodies compound river system modeling, including channel and floodplains, has no more than two options:

- Merging additional HR bathymetry measurements with LiDAR data (e.g. echo soundings) avoiding redundancies and conflicts due to overlapping. This strategy supports automatic meshing of the entire river system including feature detection based on the presented procedure.
- Meshing low resolution, cross-sectional bathymetry measurements and HR floodplain data separately to achieve the required accuracy for two initially independent models. This strategy commonly uses independent, semi-automatic mesh generation to build the bathymetry model. Finally both independent models are merged to a compound river system model.

Both strategies cope with the water body elimination from the point cloud to circumvent the rise of interpolation errors at the river boundary. The second strategy requires to state a common river boundary for both intermediate models at an accurate interpolation of elevations. Merely two means are available to delineate the boundaries of a water body: manual digitizing or automated, rule based delineation using imagery and/or DTM analysis. Purely DTM based methodologies for automated river course determination have a sound perform for topographies characterized by well-established natural drainage, but encounter difficulties in areas of low relief. They can partly be revealed by a intersection strategy for DTM and water level [2]. Complex river systems in shallow terrain oblige the use of imagery analysis. Strategies for automatic, pure imagery analysis perform the visible river extraction with classification rules, subsequent object determination and final raster to object transformation, separating lakes and ponds from rivers with tools from artificial intelligence. More complex strategies integrate multiple imagery, DTM analysis and additional vector delineation strategies to compensate occlusions in imagery, e.g. due to trees [3].

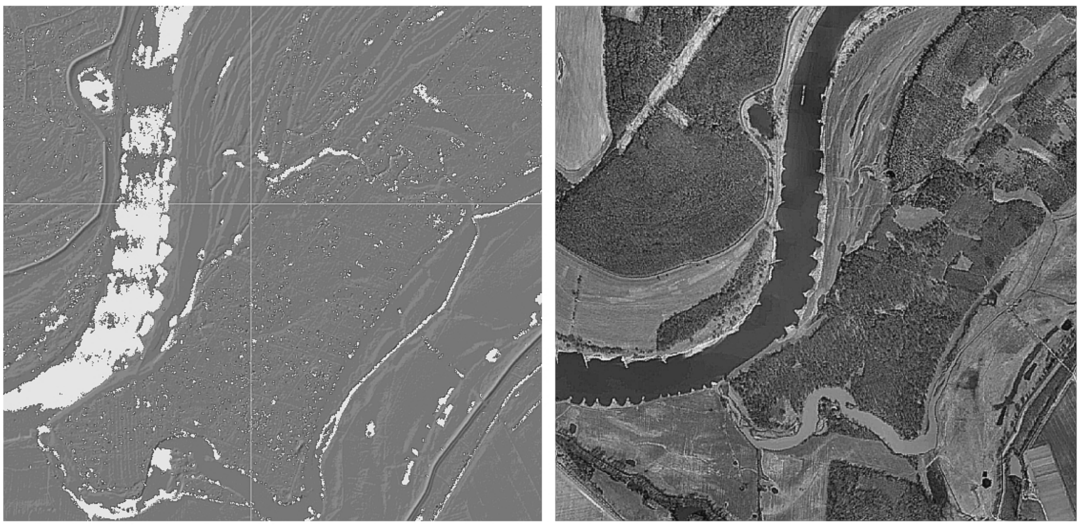

Figure 1. LiDAR data for survey campaign April/June 2003 (left), Orthophoto for similar area (right), River Elbe at Vockerode, Germany. [Data & Orthophoto provided by TopoSys GmbH. Courtesy of Bundesanstalt für Wasserbau].

3 DATA QUALITY AND ACCURACY REQUIREMENTS

Inaccuracies in open terrain data collection, whether from photogrammetry, LiDAR or IFSAR, are generally accepted to represent random errors in the sensor system, whereas vegetated areas contribute additional systematic errors for digital terrain modeling [4]. These additional error sources denote the systematic inability to penetrate dense vegetation, and/or systematic deficiencies in applied algorithms for generating bare-earth elevation datasets.

Commonly technical regulations corresponding to Digital Elevation Models (DEMs) are used to assess the quality of Digital Terrain Models (DTMs). For this assessment data users should bear in mind that the acquired point clouds are considered in semi-regular or regular grid representation. This detail is reflected in the use of the term DEM, usually employed to refer specifically to a raster or regular grid of spot heights. The data quality of such databases is frequently reported by the vertical component of spatial data accuracy. Nevertheless, the quality of a DTM is more than just accuracy [5]. Issues like breaklines, individual peaks and modest geomorphologic features are important for the reliability and completeness of DTMs. The data model-based uncertainty is recognized as differences between the form and shape of a terrain model and its actual elevation surface [6]. The accuracy of interpolated points is the most appropriate illustration for data model-based uncertainty.

Vertical accuracy is the primary criterion in specifying the quality of digital elevation data. Vertical accuracy requirements depend on the intended user category, determining the suitable technology for data collection [7]. Categories such as disaster preparedness/response, seismic monitoring, air navigation/safety or forestry can be satisfied with Interferometric Synthetic Aperture Radar (IFSAR) technology, advertised in the vertical accuracy range of 1-3 meters [8]. Higher accuracy needs can be satisfied with Light Detection and Ranging (LiDAR) technology, advertised in the vertical accuracy range of 15-30 centimeters, covering categories such as flood mitigation, storm water, floodplain and utility management, water supply/quality, environmental protection, coastal stewardship, marine navigation/safety, mining/earth moving, infrastructure construction, pipeline construction, vehicle and train positioning/safety or recreation. Merely one user category, subsidence monitoring, has DEM accuracy requirements at a 2-cm level. It can not be satisfied by LiDAR or InSAR technologies, but requires traditional ground surveying [8]. Alternatively, differential interferometry is applicable for precise mapping of elevation changes, allowing the detection of surface deformations on a scale smaller than the radar wavelength, being usually in the millimeter range [9]. Thus storm water/floodplain management in flat terrain and management of wetlands/ecologically sensitive flat areas are accepted to require high vertical accuracy [7]. A distinction is drawn between accuracy needs for hydrologic and hydraulic modeling [10]. Hydrologic modeling aims to compute peak discharges of water at key locations by predictions from rainfall, flood routing and diverse watershed characteristics. It refers to a 'watershed-scale' without the need for high resolution. Hydraulic modeling of floodplains aims to compute surface water velocities and levels at 'floodplain-scale', i.e. at specific flood profiles, points and boundaries. It requires the input from hydrologic models, highly accurate topographic data as well as bathymetric measurements.

Flood insurance studies (FIS) to update Flood Insurance Rate Maps (FIRM) can be referred to horizontal DTM accuracy requirements. Regularly compiled at a scale of $1'' = 500'$ their horizontal accuracy typically denotes 11 feet (3.35m) at a 95% confidence level [10], definitely assured by LiDAR and InSAR.

Accuracy standards for floodplain mapping based on LiDAR data, given by the US Federal Emergency Management Agency (FEMA) in accordance with the US National Standard for Spatial Data Accuracy (NSSDA) for digital products, claim that an accurate DEM should have a maximum Root Mean Square Error (RMSE) of 15 cm [11]. The RMSE is the square root of the average of a set of squared differences between LiDAR coordinate values and coordinate values from an independent source of higher accuracy for identical points, i.e. control points. Moreover, 95 percent of any sufficiently large sample should be less than $1.9600 \times \mathrm{RMSE}$, holding for normally distributed differences averaging zero. Thus, a RMSE of 15 cm denotes to a '30-centimeter accuracy at the 95-percent confidence level'. Contractors must test a least 20 test points for each major vegetation category and show that they accomplish

$$RMSE_{sample} \leq 15\sqrt{\frac{(n-1) - 2.326\sqrt{n-1}}{n}} \quad , \tag{1}$$

where n is the number of test points in the sample and $RMSE_{sample}$ is determined in cm-units. Random error magnitudes in LiDAR data accomplish ±20 cm on flat paved terrains, increasing to ±200 cm on hilly terrain with grass and scrubs [12]. Data users should realize that RMSE calculations for a large population of checkpoints can be totally skewed due to remaining single huge blunders although the checkpoints otherwise satisfy the accuracy criteria [4]. This holds particularly for forested areas. For hilly terrain, a decrease in vertical accuracy can be expected for increasing terrain slope [13].

A comparison for HR coastal dyke detection based on a one meter grid reveals the qualitative inferiority of InSAR data in direct comparison with LiDAR data in a floodplain context, although offering the more cost efficient data basis [14]. This study demonstrates the demand for critical impact assessment of topography representation in hydrodynamic modeling based on remote sensing data. This demand is strongly emphasized by the NDEP, recommending to assess vertical accuracy requirements in terms of potential harm that could be done to public health and safety in the event that the digital elevation data fails to satisfy the specified vertical accuracy [4].

4 MODELING PROCEDURE

The suggested modeling procedure is applicable for pure floodplain modeling based on HR data as well as for meshing entire HR data sets consisting of bathymetry and topography mass points. Realized as modular library its core framework and mathematical basis has recently been published [15]. Currently it experiences the first project applications, aiming to determine bounds for hydrodynamic mesh generation. It provides local adaptive mesh density and automatically represents breaklines while holding geometric requirements for finite element simulations. The modeling procedure uses an initial HR grid surface to categorize a binary breakpoint matrix via slope classification. This is transformed to a set of polygonal breaklines. Together with the essential outer model boundary and optional inner model boundary polygons, e.g. the river polygon, this breakline set serves to state supplementary boundary conditions for surface mesh generation. Meshes are derived by Delaunay refinements, i.e. the initial mesh is a TIN. The initial TIN can be improved in subsequent refinements to obtain a final TIN, holding user specified accuracy requirements. Figure 2 illustrates the modeling procedure schematically.

4.1 BREAKPOINT DETECTION BASED ON SLOPE CLASSIFICATION

Terrain slope is the governing characteristic for floodplain modeling in hydrodynamics, determining directions of flows and inundation extents. Dominant floodplain features such as levees, riverbanks and groynes are characterized by a relevant alteration of slope compared to the surrounding. They are detected based on a HR grid surface. This strategy uses efficient grid slope assessment and classification strategies. Grids support simplicity for delineation of breakpoints to breaklines in terms of raster based rules.

Two alternate concepts are feasible to determine breakpoints for HR grid DTMs: either first order derivative breakpoint localization, the so-called ‘slope methods’, or second order derivative breakpoint

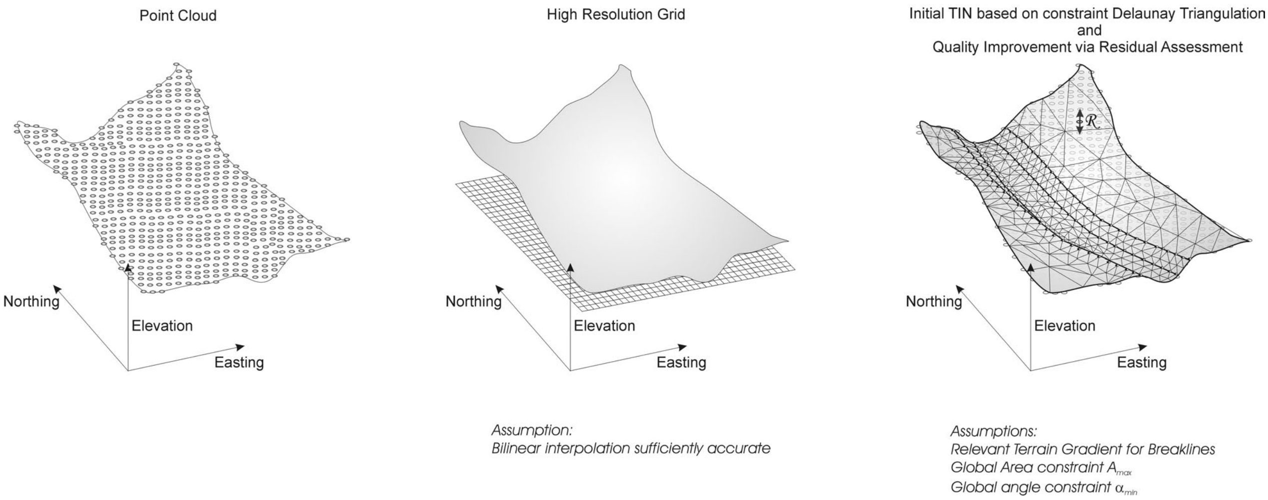

Figure 2. Modeling procedure - Meshing point clouds via automatic breakline detection based on slope classification on intermediate high resolution grids and subsequent representation in a TIN.

localization, the so-called 'change of slope methods' [15]. Slope methods generally use 3x3 kernels to calculate the bi-directional terrain gradient for a grid point with regard to its surrounding. Choosing an appropriate threshold for a critical slope of flow relevant features, their boundaries are extractable via a thinning procedure. Thinning discards breakpoints exceeding the critical slope and being completely surrounded by other breakpoints. The final achievement of slope methods is a thinned binary classification of the slope matrix referencing the breakpoints. Slope methods are well suited for generally shallow terrain of floodplains. In contrast, change of slope methods should be used when focusing on intensity changes, e.g. in mountainous grid DTM or image analysis. Applying the Laplacian, i.e. the bidirectional second order derivative of the Cartesian coordinate grid to a continuous HR grid elevation matrix gives the edge Laplacian. It is used to convolve the grid DTM surface and derive a corresponding zero–cross matrix, determining breakpoint locations in the second derivative [16]. Change of slope methods are to be favored for rough topographic regions, which generally can not be described by a critical slope threshold to depict relevant terrain features.

The accuracy of breakpoint detection is coupled with the horizontal resolution of the grid, the interpolation method used to derive grid elevations as well as with the inherent point cloud accuracy. The horizontal grid resolution needs to be chosen to most efficiently represent the size and frequency of terrain features to be modeled. There are no established rules that directly correlate the horizontal resolution of the digital elevation data with vertical accuracy [4]. For that reason, it is not reasonable to attempt a priori accuracy estimations.

4.2 BREAKLINE DELINEATION FOR RIVER SYSTEM MODELING

Breaklines are used to represent relatively abrupt linear changes in the smoothness or continuity of a surface slope or aspect [4]. Two common forms are distinguished. 'Soft breaklines', otherwise known as '3D-breaklines', maintain measured x/y/z-position along linear features for TIN representations, e.g. the course of a drainage ditch, a pipeline or the road centerline. 'Hard breaklines' define interruptions in the surface smoothness and are commonly used to define amongst others streams, shorelines or dams. They are depicted by 2D-digitizing including subsequent height interpolation or 3D-measurements. This chapter focuses on automatic delineation of hard breaklines, subsequently referred to as breaklines.

Automated delineation of breaklines from depicted breakpoint matrices involves a framework of following conventions: Only breakpoints are connected. Concatenation candidates are grid-neighboring breakpoints. The slope between line segments varies continuously and less than a critical slope threshold.

These conventions derive contiguous breaklines, avoid interpretations due to gaps in breaklines and prevent inclusions of unrealistic terrain steps. Following priority queue suites to derive breakpoint concatenations with a dynamic 3x3 kernel processing the breakpoint matrix: Breakpoints marking the start of new breaklines initialize n paths directed towards their n neighboring candidates. Except for opening new breaklines, breakpoints are not referred to more than one breakline during delineation. Considering breakline courses during concatenation, suitable candidates do not exceed the current trend for more than ±90°. In shallow areas such as floodplains or deltas the most appropriate candidate amongst others, fulfilling these priorities returns the concatenation with the least slope. In terrains with considerable terrain slope the most appropriate candidate returns the least change of slope for its breakline. Situations raising uncertain concatenation situations despite these priorities are overcome enlarging the kernel to 11x11 cells, using stochastic determinations for breakline evolution before applying finally strictly path-evolution related rules.

This breakline delineation is based on the HR grid. Thus polygon features are depicted with average point distances relating to the grid. Usually the ratio of points per polygon feature can be enhanced drastically. Line simplification is performed requiring a tolerance bound for simplification. Generally this bound does not need to introduce additional loss of accuracy. Tolerance bounds close to zero contribute to a significant point reduction for the suggested delineation. In GIS systems line simplification is commonly performed via the 2D Douglas Peucker algorithm. The consideration in 2D instead of 3D is justifiable, as long as no severe loss of vertical accuracy is introduced within the truly 3D course of the simplified line. The modeling procedure applies the 2D Douglas Peucker algorithm based on following justification: Simplified breaklines maintain points at an overall accuracy of the HR grid, connecting them without considering the impact of vertical simplification. This transitional simplification is assumed to be compensated during the Delaunay Refinement. The Delaunay Refinement causes recursive splitting of simplified breaklines while adding additional Steiner Points to obtain user requested demands to the mesh. All additional Steiner points require elevations via interpolation from the HR grid. So do all recursive splits of the breaklines. This recursive refinement of previously simplified breaklines is supposed to introduce sufficient compensation for the local breakline accuracy. The data model accuracy including automatically detected breaklines is assessed and enhanced a posteriori as described in Sect. 4.4.

Meshing compound river systems based on initially independent floodplain and bathymetry models provides further challenges for breakline delineation. It is required to support a data band wide enough to perform interpolation and breakline detection to maintain high data model accuracy for a floodplain representation with its river polygon and adjacent breaklines. The model procedure uses breaklines delineation for the entire grid and subsequent blending of breakline information at the river polygon. The blending strategy supports exact intersections of breaklines with the river polygon at accuracy of the interpolation from the HR grid. It allows subsequent discarding of irrelevant breakline information. These are breaklines in the river polygon, segments reaching into it, segments originating from it or irrelevant segmented parts from multiple crossing with the river polygon. They need to be discarded for the Delaunay Refinement to avoid boundary polygon distortions by polygonal overlapping.

4.3 DELAUNAY REFINEMENT

The modeling procedure suggests Delaunay refinements for adaptive hydrodynamic floodplain meshing and representation of breaklines. It uses a Planar Straight Line Graphs (PSLGs) description as input definition, representing breaklines and model boundaries a set of vertices and segments [17]. This conforming triangulation applies constraints while using the Delaunay criterion to govern the concatenations of the node set. It requires that the circumcircle of a triangle encloses no other vertex of the triangulation. Initializing a triangulation based on breaklines and the domain boundary, additional Steiner points are introduced while meshing the floodplains to fulfill the constraints as well as the Delaunay criterion. A minimum-angle-bound prevents ill-conditioned equation systems within the finite element method [18] and implicitly prevents large angles, implying errors in the gradients of the interpolated surface [19]. A maximum-area-bound ensures local accuracy for the allocation of element-to-node-contributions by means of the weighting function. Both constraints are handled via Rupert's Refinement algorithm [20]. Steiner Point elevations are available via interpolation from the grid elevation matrix. The modeling procedure realizes the Delaunay refinement based upon the open-source algorithm Triangle [21].

4.4 MESH ENHANCEMENT AND ACCURACY ASSESSMENT FOR HYDRODYNAMICS

Mesh enhancement strategies for automatic meshing of remote sensing data focusing hydrodynamic simulations are challenged from three distinct perspectives. The final mesh needs to represent the measured data at a specified accuracy level. Misinterpretation of a posteriori accuracy assessments caused by remaining blunders in the filtered data should be avoided. An appropriate local mesh resolution for the simulation under consideration needs to be achieved.

Commonly, these three perspectives are competing and equally important. The suggested modeling procedure performs local residual assessment for a randomly chosen subset of the available measured data. A residual classification into three classes permits to classify TIN elements being represented sufficiently accurate, critical or insufficiently. Selecting two thresholds is supposed to esteem the genesis of remote sensing data, bearing in mind that filtering does not remove all spurious blunders and objects from the bare ground. Evidently the preferable choice for mesh enhancement is to perform local mesh refinement exclusively for critical elements of the TIN. Insufficient representations are considered to be raised by blunders. This strategy is in accordance with FEMA guidelines, suggesting histogram productions to serve as justification for rejection of a small number of outliers. Blunders are considered to exceed 3 times the standard deviation, and/or skew values about ±0.5 [10]. Alternatively, critical elements can be refined and insufficient data point representations can be directly incorporated to the TIN. This alternate strategy for local mesh enhancement tends to significantly increase the number of mesh vertices.

5. MESH RESOLUTION IMPACT ON SHALLOW WATER EQUATIONS

Equation 2 gives the complex notion of the Shallow Water Equations (SWEs). Locally it comprises the impact of terrain discretisation on the continuity and both momentum equations by means of the spatial derivatives

$$\frac{\partial \mathbf{w}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} + \mathbf{s} = \mathbf{0} \quad , \tag{2}$$

where **w** denotes conservative terms for mass and momentum; **f** and **g** represent flux terms for mass and momentum including diffusive terms; **s** embodies source terms with respect to friction- and bottom slope:

$$\mathbf{w} = \begin{bmatrix} H \\ uh \\ vh \end{bmatrix} \qquad \mathbf{f} = \begin{bmatrix} uh \\ u^2h + 0.5gh^2 - \nu h \dfrac{\partial u}{\partial x} \\ uvh - \nu h \dfrac{\partial v}{\partial x} \end{bmatrix} \quad . \tag{3}$$

$$\mathbf{s} = \begin{bmatrix} 0 \\ gh\left(I_{fric,x} - I_{bottom,x}\right) \\ gh\left(I_{fric,y} - I_{bottom,y}\right) \end{bmatrix} \qquad \mathbf{g} = \begin{bmatrix} vh \\ uvh - \nu h \dfrac{\partial u}{\partial y} \\ v^2h + 0.5gh^2 - \nu h \dfrac{\partial v}{\partial y} \end{bmatrix}$$

The computation of local waterlevels H refers to local waterdepths h and local vertice elevation z, i.e. $H=h+z$. The computation of waterlevels along with velocities u and v requires additional models to determine friction slope I_{fric} and viscosity υ at vertices of the generated mesh. Without considering further details this can be the DARCY-WEISBACH law for friction slope together with the COLEBROOK-WHITE equation to incorporate the bottom resistance of the land coverage. Viscosity modeling might exemplarily consider that turbulence is merely generated by bottom roughness holding for wide straight channels. On this basis hydrodynamic finite element simulations directly incorporate the local vertical data-model accuracy via H and the bottom slope I_{bottom}. Moreover the local data-model accuracy has a potential global impact, affecting the computation of the surrounding flow field trough the solution scheme for the SWEs. Horizontal mesh discretisation has a manifold impact of on the solution of the SWEs. Governing the resolution of the simulated flow field, it is supposed to represent an optimum relation between flow field accuracy and efficiency for solving the SWEs while granting sufficient numerical stability for the numerical scheme.

6. MODEL APPLICATION

A point cloud of 330000 measurements serves to spotlight the modeling procedure for a domain of 0.135 km², located at the river junction Stoer-Bramau, Northern Germany. Figure 2 shows that automatically detected breakpoints within the domain boundary to be meshed are in high accordance with the map. The breakpoints serve to incorporate breaklines after performing a Douglas-Peucker Thinning at a tolerance of 0.5 m. The presented mesh holds a maximum area bound of 25 m² and a minimum angle bound of 20° at a mean accuracy of 0.017 m and a standard deviation of 0.10 m. Remaining blunders due to bushed raise single breaklines traces and cause local small elements. This implies that blunder elimination is sufficiently performed a priori to mesh generation or requires a topology based concept to evaluate the relevance of detected breaklines.

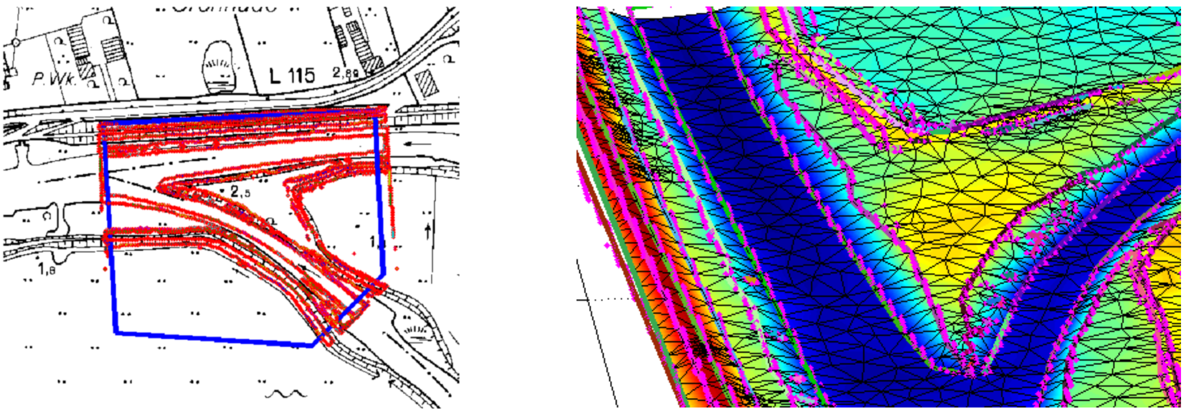

Figure 2. Model Application – River junction Stoer-Bramau, Northern Germany. Mesh (right) generated from breaklines delineated using a 10° threshold for One-Over Distance Slope computation on 1m HR grid.

CONCLUSIONS

The presented modeling procedure for automatic meshing provides fast and efficient exploitation of high-resolution data. It generates adaptive scales of terrain representation at user defined accuracy bounds. Global and local accuracy requests are available after mesh generation and may serve for local improvements. This flexible modeling allows to conduct efficient automated revisions to evaluate the impact of DTM resolution on hydraulic simulation parameters. These revisions may help to determine and reduce one source of uncertainty in predictions of flood risk and fluvial geomorphology monitoring.

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