The influence of high resolution LiDAR bathymetry on flow resistance calculations in Mountain Streams

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2.1. Relevance of fluid mechanics

Fluid mechanics in streams are relevant for the process of mobilizing sediment. During regular flows and during peak flow the forces, which develop as a result of the flow, control bed and bank erosion and the transport of mobilized particles or sediment from external supply sources. Fluid mechanics are important information for the assessment of flood hazards during peak flows as they influence inundation, destabilization of bed, banks and floodplains, and the erosion and deposition of debris and sediment. At higher and at lower flows they influence habitat characteristics for plants and animals in a river, the water chemistry and its evolution while running along a stream, and also they affect a river's communication with its surrounding ground water (i.e. Buffington and Montgomery, 1999, Beffa, 2005). Flow hydraulics on macro- to micro scales influence the dimensioning, functionality and safety of river engineering structures. It depends on the particular character of an engineering problem, an ecological assessment or hazard assessment, at which scale, at which flow stage and to which degree of detail the information about the hydraulic flow field in a river is needed (Landesanstalt für Umweltschutz Baden-Württemberg, 2003).

Wrongly calculated fluid mechanics in river engineering can lead to the malfunctioning of restored ecosystems or river engineering structures due to erroneous dimensioning. It can lead to unwanted sediment erosions and depositions or can cause additional cost due to too largely dimensioned flood protection structures, due to damages resulting from events of unexpected magnitude (and too small protection structures) or due to unexpected and damaging erosion of riverbeds or banks and floodplains.

2.2. Specifications of Mountain Streams

Different definitions for the term mountain Streams are available. In his study of flow resistance in mountain Streams Bathurst (1985) included high gradient gravel and boulder-bed Streams with slopes of 0.4 % to 4 %. He also considers streams with slopes steeper than 5 % as mountain Streams. At this slope they tend to develop a series of short pools and falls, and are likely to show a different resistance behavior (Bathurst, 1985).

In general mountain Streams are characterized by a wide range of sediment sizes and temporarily and spatially variable sediment sources. Significant sediment transport occurs only during large floods. Large boulders, bedrock constrictions and woody debris are likely to be present. Such elements have a strong influence on bed morphology and channel structures. As a result channel geometry, streamflow velocity and roughness, are typically highly variable in mountain streams. Common bedforms are pool and riffle series and alternating bars with a meandering thalweg. Mountain Streams are characterized by Froude numbers of high, or in some cases even supercritical values. Relative flow depths are typically low (especially compared to roughness elements) and the flow is influenced by substantial form drag (Bathurst, 1985, Rickenmann et al., 2006).

2.3. Flow regime

The discharge in a river forms as a result of a river's or a river section's catchment properties and the occurring precipitation. The velocity and flow depth (flow regime) in a section or a reach of the river, then depend on the discharge and also this section's specific morphology. The exact way in which certain morphologic features interact with the flow field, especially in reaches with a complex morphology, vary with the discharge magnitude. It can be inconsistent at different flow stages and also at different slopes (i.e. Simons and Richardson, 1966, Bathurst, 1985, Jarrett, 1984, Rickenmann, 2006). It is a section's or a reach's velocity profile, its roughness features on micro and macro scales, resulting flow turbulences and the so caused energy dissipation that determine how fast, at which depth and accordingly with which energy, water passes through one flow section or reach, and how it proceeds to the next.

2.4. Velocity profile

The flow through a river section is never of a uniform velocity. At the minimum, it is a conveying structure's boundary roughness, which causes the flow field to have a slower velocity along its circumferences. This influences the velocity distribution in a vertical and in a horizontal direction. With increasing complexity of cross sections and of the course of a river, the velocity distributions (vertical profiles and horizontal profiles) keep getting more complex. The reaction of the velocity field on morphological complexities also is dependent on the riverbed slope and on the (relative) flow depth i.e. it varies spatially, within a river, and between different Streams and it varies temporarily within one river section, as a result of changing discharges.

Simons and Richardson (1966) showed that in alluvial channels the velocity distribution is as complex as its bedforms. Except for the case of flow over a very plane bed, the velocity distribution was spatially and temporarily highly variable. In order to study or estimate it, averaging to a certain degree will always be necessary. In natural channels, typically many measurements are needed to derive a good estimate of an average form of velocity distributions (Simons and Richardson, 1966). The degree of averaging of the velocity profile, in time or in space, in the calculation of fluid dynamics for a specific application will depend on the demands of the specific interest, and also on the capabilities of the chosen method (Landesanstalt für Umweltschutz Baden-Württemberg, 2003).

Vertical velocity profiles of mountain streams with higher gradients were found to differ from those of low-land Streams (Jarrett, 1984). Instead of a logarithmic profile they tend to a more S-shaped form with exaggerated surface velocities. Mountain boulder-bed channels with gentler slopes have a vertical velocity profile more of the shape of a right half of an U.

2.5. Flow resistance

2.5.1. Definition and classification of flow resistance

Depending on the form of the river bed, on the form of roughness structures within it and on the turbulence and retardance that form as an interaction between the discharge magnitude and these features, a resistance to flow develops. By this resistance it is then determined, at which depth and in which flow regime the water runs through a reach. In complex river reaches the total flow resistance is a combination of several factors. Irregularities between cross sections (*channel irregularities*), obstructions (*grain roughness and form roughness*), channel meandering and the channel shape (*channel geometry*), the vegetation, the existence of suspended material and the transport of bed load (*suspended material in flow*) all cause turbulence and retardance. In this way they influence how the flow passes through a reach (Jarrett, 1984, Simons and Richardson, 1966).

A systematic to organize causes of flow resistance in different scales is presented by Morvan et al. (2008). They distinguish between *skin drag*, *form drag* and *shape drag*. Skin drag is the flow resistance or roughness caused by surface texture and can be compared to grain roughness. The form drag represents roughness due to surface geometry, bedforms, dunes and flow separation at such features. Shape drag is the resistance/roughness that results from the effects of overall channel shape, meanders or bends, on the flow. The flow resistance is also referred to as dissipation of energy.

Simons and Richardson (1966) introduced a shape factor that can be derived for each particular reach to account for shape drag, which represents energy dissipation caused by local non-uniformity of the flow resulting from bends and the non-uniformity of the banks. For alluvial channels they describe different processes in more detail, which together cause the overall resistance to flow. In their systematic they distinguish between a *surface resistance* (or grain roughness), a *form resistance*, resistance caused through the acceleration and deceleration of the flow (or nonuniformity of the flow) and resistance caused through *breaking waves*. Surface resistance happens when the flow does not separate from the macroboundary. It does only separate from singular grains or microroughnesses. In sand bed Streams, for example, this type of resistance is very relevant on plane beds, on the back of dunes and limitedly on antidunes. Form resistance happens where the flow also separates from the macroboundary. A pressure reduction in the separation zone, called form drag, develops and is accompanied by large-scale eddies. Both of these processes dissipate energy. **Figure 1** schematically displays the turbulences or flow separations that form as a result of geometrical structures on different scales.

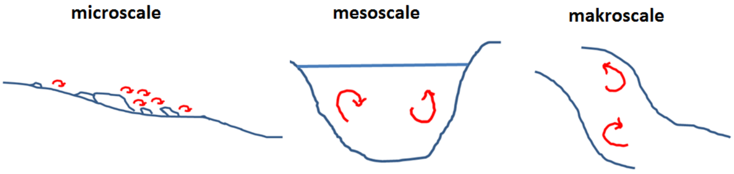
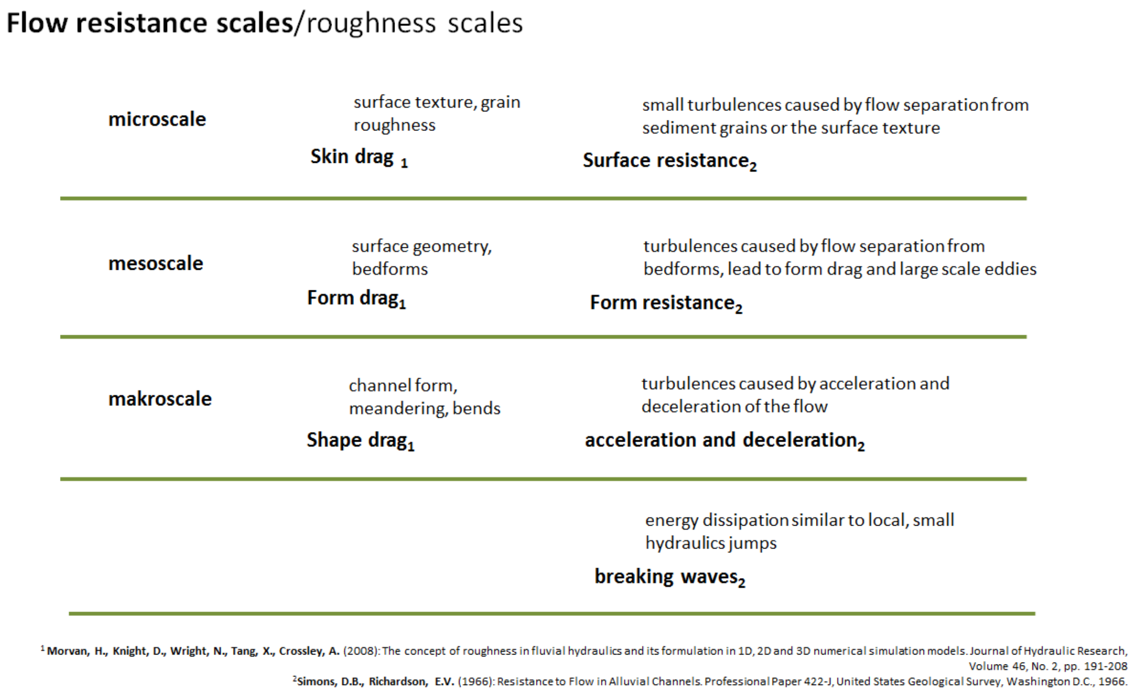


Figure 1: Turbulences or flow separation on micro-, meso- and macroscale

Flow acceleration and deceleration as well as breaking waves also dissipate energy. Eddies and turbulence that are generated by breaking waves dissipate an amount of the same order of magnitude as is dissipated in small hydraulic jumps. They are most relevant in the bed configuration of chutes and pools, but can also occur in the context of antidunes. Typically these bed configurations (plane bed, ripples, dunes, antidunes and chutes and pools) in a stream, as a result of the three-dimensionality of channel flow, varying depth, varying bank roughness and general nonuniformity of the flow, vary from point to point. The average resistance to flow in a reach therefore is the result of the combined effects of many different variable roughness elements and the turbulence that they create (Simons and Richardson, 1966). **Table 1** provides an overview of the systematics for flow resistance on different scales provided by Morvan et al. (2008) and by Simons and Richardson (1966).

Table 1: definition of flow resistance or roughness effects on different scales



Flow resistance scales/roughness scales

microscale	surface texture, grain roughness **Skin drag**[1]	small turbulences caused by flow separation from sediment grains or the surface texture **Surface resistance**[2]
mesoscale	surface geometry, bedforms **Form drag**[1]	turbulences caused by flow separation from bedforms, lead to form drag and large scale eddies **Form resistance**[2]
makroscale	channel form, meandering, bends **Shape drag**[1]	turbulences caused by acceleration and deceleration of the flow **acceleration and deceleration**[2]
		energy dissipation similar to local, small hydraulics jumps **breaking waves**[2]

[1] **Morvan, H., Knight, D., Wright, N., Tang, X., Crossley, A.** (2008): The concept of roughness in fluvial hydraulics and its formulation in 1D, 2D and 3D numerical simulation models. Journal of Hydraulic Research, Volume 46, No. 2, pp. 191-208

[2] **Simons, D.B., Richardson, E.V.** (1966): Resistance to Flow in Alluvial Channels. Professional Paper 422-J, United States Geological Survey, Washington D.C., 1966.

For some bedform geometries it is true that the actual grain size influences the roughness and flow resistance. For other bedforms the size of the grains is less important than the concrete geometric shape of a cross section (Simons and Richardson, 1966). Resistance to flow, for example, is independent of sand size when the bed configuration is one of ripples. This is because the ripple shape is independent of sand size and the effect of grain roughness is small, relative to the form roughness. Resistance on dunes, to the contrary, was found to depend also on the grain roughness (Knoroz, 1959). In the case of a plane bed, this is a bed without elevations or depressions that are larger than the largest grains of the bed material, the resistance to flow results mainly from grain roughness. Compared to the resistance on a plane bed, the resistance on dunes is generally by the order of 100 % bigger. This implies that, compared to the flow over a dune bed, the flow over a plane bed at the same discharge and slope would be double as fast (Simons and Richardson, 1966). For flow over a plane bed with sediment movement, the resistance to flow is slightly less than that for flow over a static plane bed. Elata and Ippen (1961) indicated that this was the case because the structure of the turbulence was changed by the movement of the sediment at the boundary.

Bathurst (1985) distinguishes *large-scale roughness*, *intermediate-scale roughness* and *small-scale roughness* by the indicator of *relative submergence* (also called relative roughness), which is calculated as the result of flow depth to an indicator of the sediment size (for example d/D_{84}). A ratio smaller than 1 represents large-scale roughness, a ratio smaller than 4 represents an intermediate-scale roughness and a ratio larger than 4 defines small-scale roughness (Bathurst, 1985). In mountain streams large-scale roughness is typically more prevalent than in low-land Streams. This can make it difficult to transfer empirical relations for flow resistance that were established for lowland Streams, with typically small- to intermediate-scale roughness, to mountain streams (Bayazit, 1982).

An alternative parameter, also introduced by Bathurst (1985) is the *relative roughness area* (Aw/At), which is the ratio of the actual area covered by water and the total area, which is calculated by ignoring the roughness features along the bed and the banks. Together with the *roughness concentration*, which is the proportion of the bed area occupied by significantly projecting boulders, it can provide a three-dimensional image of the bed material disposition in a channel (Bathurst, 1985). Bathurst (1985) found a close correlation between this relative roughness area and Dn/d, if Dn is a large percentile of the bed material size distribution and d is the flow depth. Smaller percentiles correlated less well, which implies that the relative roughness area depends mainly on the larger elements of the grain size distribution.

Flow separations on a larger scale also reduce the area that is effectively available for the conveyance. Simons and Richardson (1966) studied separation zones after the crests of ripples. In this case they found that an average velocity, based on the calculation of Q/A, and an average depth based on the average distance from the water surface to the bed surface was sometimes misleading. They suggested that an *effective depth* is defined, which is reduced to compensate for the zones of separation. Accordingly an effective velocity can be established. The increase in energy dissipation resulting from form roughness is in this approach (with an effective depth and an effective velocity) still not considered. In sand bed Streams this energy dissipation as a result of form roughness was observed with ripples, with dunes and sometimes, and to a smaller extent, with antidunes.

2.5.2. Variation of flow resistance

Resistance is subjected to between-sites and to at-a-site variations (Bathurst, 1985). Between-sites variations describe the spatial variation in roughness, caused through changes in the geometry of cross sections and spatially changing slope. At-a-site variations are the result of flow resistance that is variable with discharge. Also the way in which roughness varies with discharge is itself variable and depends again on a section's geometry and slope. This means at-a-site variations do also vary between-sites. For the same grain size distribution or bedform the resistance to flow is different when slope and flow depth vary. In some cases, with a changing slope (or flow depth), bedforms change. Whether they do, depends on the size of the bed material or its size distribution. However, even when bedforms stay the same, the resistance can show an increase with increasing slope (i.e. Simons and Richardson, 1966, Jarrett, 1984, Bathurst, 1985, Rickenmann, 2006).

Between the influencing factors which cause spatial and temporal variations in resistance, clearly a complex interdependency is given. Slope, depth, grain size or grain size distribution, bed configuration/bed geometry or bed material deposition and the resistance itself, are all linked to each other. They can all be both, dependent or influencing variables. It is therefore difficult and requires the knowledge of many different parameters to be able to isolate and quantify the effect of any one of these factors (Simons and Richardson, 1966, Bathurst, 1985).

2.6. Flow resistance in Mountain Streams

A distinction of flow resistance behavior can be made for different kinds of Streams. Bathurst (1985) states that, for example, the resistance variation acts differently in mountain Streams, than it does in lowland Streams. In mountain Streams with high gradients the Darcy-Weißbach equation and the logarithm of relative submergence tend to underestimate the rate of change of resistance at a site, with varying discharge. In such cases the Darcy-Weißbach friction factor, with changing discharge and flow depth can vary by 100 % at one site (Bathurst, 1985).

Bathurst (1985) showed in his work, that the patterns of flow resistance behavior in high-gradient, boulder-bed Streams does not parallel the behavior of lowland Streams, which can be expressed by a semilogarithmic type of equation. He observed, as already mentioned in 2.5, that more rapid rates of change of resistance with discharge were found at river sites with wider grain size distributions of bed material size and with steeper slopes. For narrower size distributions and gentler slopes observed rates of change were less rapid (Bathurst, 1985). As explanation Bathurst (1985) states that, with a wider bed size distribution the proportion of the total cross-sectional area occupied by significantly projecting boulders (roughness area Aw/At) becomes larger, and also that the proportion of the bed area occupied by significantly projecting boulders (roughness concentration) increases (chapter 2.5). In several studies it was observed that for flows in streams with a relative submergence h/d_{84} or h/d_{90} of smaller than 4 to 6 a marked increase in flow resistance occurs (i.e. Jarrett, 1984, Pitlick, 1992, Rickenmann, 1996, Bathurst, 2002). Moore (1980) found in a correlation analysis for mountain Streams, that the grain size distribution of the bed material only explained about 4 % of the observed variation in measured values of $(8/f)^{1/2}$. 86 % of the variation could be explained by slope and relative submergence (Moore, 1980)

2.7. Sediment transport

Apart from the magnitude of the discharge, the character of the flow field in a specific cross section or reach influences the power that is available for the erosion and transportation of sediment. If this power changes between two sections or reaches sediment can either be deposited, or can be eroded. The erosion of sediment can affect the riverbed as well as the riverbanks. If the energy that is available for sediment transport decreases from one section to the next, and if the sediment material accessible for transport is not limited, the decrease in transport energy will immediately result in sediment deposition. If the potentially available energy for transport exceeds the accessible amount of free sediment, erosion of the bed and banks becomes possible. However, it still depends on the condition of the reach boundaries if erosion actually happens or not. If grains of larger size cover or hide smaller sediment particles, they can protect them from eroding. On river banks also the existence of stabilizing vegetation can naturally inhibit erosion. Clearly, designed engineering structures to protect riverbeds and banks also influence the onset of erosion.

2.8. Sediment transport in Mountain Streams

For the sediment transport in mountain Streams it is relevant how much energy is dissipated through the effect of form roughness. This dissipated amount is not available for the actual transport. It is especially in steeper channels, that this form roughness appears to be more important for the energy dissipation than the grain roughness (Rickenmann et al., 2006). The effect of flow resistance due to form roughness on sediment transport can for example be taken into account by modifying the energy slope. The extent of this reduction can be related to different roughness structures, if they are known (Rickenmann et al., 2006). By accounting for the, through form roughness caused reduction of available energy, Palt (2001) could achieve better agreement with field measurements of sediment transport in mountain channels. Rickenmann (2001) found that observed sediment transport in steep and small streams was one to three orders of magnitude smaller than values predicted by a sediment transport capacity formula that did not account for form roughness. This can partly be caused by a limited sediment supply (as opposed to unlimited availability assumed in the formula); partly it is assumed to be caused by substantial bedform roughness (form roughness) that reduces bedload transport efficiencies (because of the additional energy dissipation). Rathburn and Wohl (2001) also found that predicted bedload discharges, based on formulas that were not taking form roughness into account, were overestimated by up to several orders of magnitude.

The energy available for transport is also important for the determination of incipient motion of bed material. This in turn is very relevant for river stability, is relevant for the availability of sediment for transport, and also for the evolution of flow resistance with increasing flow, as the beginning of motion has an impact on flow resistance (Simons and Richardson, 1966, chapter 2.5).

For a surround understanding of flow, deposition and erosion, especially in mountain streams, it is important to know how much energy is available for transport processes. It is also of interest at which discharge (or flow depth) the transport can start for a specific size of bed material.

3. Flow resistance in 1D, 2D and 3D calculations of fluid mechanics

3.1. Introduction

In common problems when studying stream flow hydraulics a link of discharge and flow depth, channel conveyance or velocity are needed. Such relations are useful when water levels are measured and related discharges are wanted, or when depths and velocities, for example, to assess the available shear forces, at a certain discharge (which is derived from measurements or hydrologic analyses) need to be known. The link between these parameters is the resistance to the flow. The velocity, the depth or the energy slope can be formulated as the dependent variables (Simons and Richardson, 1966, Bathurst, 1985).

These relations can be described as one-dimensional, two-dimensional or three-dimensional problems. Supporting software products for calculations in all these types of approaches are available. It is depending on the dimensionality of the approach, how a relation of the discharge, the conveying water body's geometry and the flow field is found; and also to which degree of detail the real flow can be replicated. The flow resistance defines how flow velocities and flow depths relate to a specific discharge in a specific geometry. In simplified approaches this relation is constant with discharge magnitude and in some also with slope. More elaborate approaches take the flow resistance's variability with discharge magnitude or even this variability's dependence on the channel slope into account (Rickenmann et al., 2006). Apart from their underlying basic equations and mathematical solution approaches, one-dimensional, two-dimensional and three-dimensional flow calculations differ from each other also in their requirements in terms of input information, which they need to fully exploit their simulation potential.

Flow resistance, or often also referred to as roughness, is a result of two things, the near boundary turbulences and the macro-flow structures within a given channel reach, which form as a reaction to a specific given boundary surface (macro and micro geometry). In (numerical) calculations of fluid mechanics simplified or discretized formulae are used, which do not fully account for these detailed physical processes. The degree, at which they are accounted for, depends on the degree of simplification or discretization of the calculations and also of the available geometrical input information. Adapted to this degree of simplification and discretization, specifically formulated roughness/resistance terms or factors (also called friction factors) are implemented in formulae or calculation models to account for the left out physical processes. They serve as a consideration of the momentum and energy dissipation that cannot be considered directly (Morvan et al., 2008).

In Reynolds Averaged Navier-Stokes equations for turbulent flow, which are a commonly used set of equations in 3D numerical calculations of fluid flow, all momentum losses and losses due to turbulence, shear- and drag force, are implicitly included. In this case they are omitted only as a result of discretization purposes. Discretization becomes necessary because of lacking computational power and lacking (macro- and micro) geometrical input information. In 2D and 1D models, additionally to being left out because of discretization, boundary turbulences and the macro-flow structures are also (to different degrees) left out conceptually. Compared to roughness terms in 3D calculations roughness/resistance terms (or friction factors) in 2D and 1D calculations become more uncertain, more empirical and less distinct, in their formulation. It is important to consider, that they do not account for the same thing in these different numerical approaches (Morvan et al., 2008).

A variety of empirical flow resistance/roughness equations for 1D and 2D numerical approaches were developed. Usually they link discharge, or unit discharge and velocity. One dimensional approaches link a discharge to an average velocity within a cross section or within a reach. Resistance factors are typically defined to account for external resistances (representing roughness features in the flow section) and internal resistance (representing viscosity or internal turbulence) are combined. The one dimensional calculations can be either based on empirical formulas that link discharge, flow depth and velocity within a reach or a cross section; or they can be based on a one dimensional representation of the St. Venant equations within a calibrated model.

Two dimensional models for specific discharges and geometries calculate flow depths and depth-averaged flow velocities across vertical columns within a cross section based on the shallow water equations (also 2D St. Venant equations). In two dimensional approaches the flow resistance resulting from external roughness features is considered in the source term of the 2D shallow water equations. The internal resistance can be considered through the use of a viscosity factor, a viscosity law or through simplified turbulence models (Nujic, 2009, EDF-R&D, 2013, Vetsch et al., 2014).

Three dimensional models for specific discharges and geometries calculate flow depths and horizontally and vertically distributed velocities based on different models that represent the Navier-Stokes equations. In three dimensional approaches the flow resistance resulting from bottom friction is considered for in the source term of the three dimensional Navier-Stokes equations. The internal resistance can be considered through the use of a constant viscosity factor or through a variety of turbulence models (EDF-R&D, 2014). By the use of complex enough turbulence models in calculations with the 3D

Reynolds Averaged Navier-Stokes equations, or by the use of 3D models that allow Large Eddy Simulations or even a Direct Numerical Simulation it is provided that the processes that need to be accounted for in the (bottom) friction term are more distinct than in 1D and 2D approaches. **Figure 2** shows the different degrees of spatial discretization of flow calculations in 1D, 2D and 3D approaches.

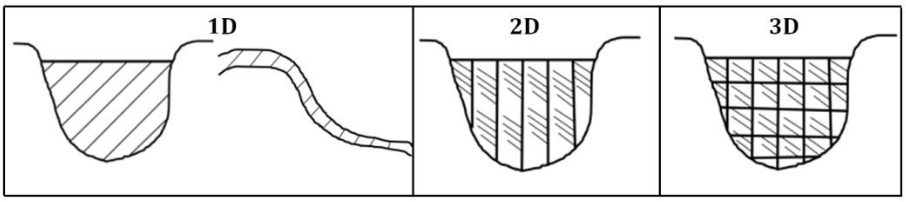


Figure 2: Spatial discretization in 1D, 2D and 3D flow calculation approaches

3.2. Flow resistance in 1D calculations

One dimensional approaches link a discharge to an average velocity within a cross section or within a reach. A major disadvantage in 1D approaches is the strong empirical character of flow resistance equations. As a result they cannot be unlimitedly transferred between Streams of different characteristics. A majority of the equations were developed for moderately steep gravel-bed Streams. Usually they are based on empirical functions which use a characteristic grain size as the basis for a parameter for flow resistance, but do not take other geometrical indicators into account.

Simons and Richardson (1966) developed different empirical relationships for five different types of bedforms in sand bed alluvial channels; a plane bed form, dunes, antidunes, ripples and a form called chutes and pools. Spatial and temporal variations of bed forms add extra complexity to the flow resistance situation that is hard to represent in a 1D approach. In field tests for channels that had the same pattern throughout, with their method, Simons and Richardson (1966) could predict average velocities within a range of +/- 10 %. When multiple patterns (multiple roughnesses) across a reach were present, the accuracy of the predictions was reduced (Simons and Richardson, 1966). Provided the complexity of the system and the manifold interdependencies Simons and Richardson (1966) stated that they do not believe in the possibility to generate a completely generalized function, which covers all types of bedforms, to predict resistance to flow or the velocity of flow.

Several empirical approaches were developed, which allow the calculation of friction factors or average velocities on a reach basis (1D) specifically for mountain streams, depending on particular grain sizes (Rickenmann, 1994, 1996), relative submergence (Bathurst, 1985) or on the standard deviation of a riverbed's elevation (Aberle and Smart, 2003). Bathurst (1985) presents the indirect slope-area method, as a common method used in mountain streams to calculate discharges, where it is difficult to gage water discharge directly, particularly at high flows. In this approach the discharge is calculated from channel conveyance and friction slope. In order to define a resistance law for mountain streams he adopted a method based on the semilogarithmic resistance law for gravel-bed Streams. This is a method that is limited to flows within well-defined channels with uniform bed slopes where there is no significant bank resistance or vegetation flow resistance, and where any sediment transport involves coarse (gravel and boulders) rather than fine (sand) material. His work was limited to streams where still no step pool structures develop (Bathurst, 1985). He found that in high-gradient channels, due to the fact that their vertical velocity profile diverts from the assumed semilogarithmic velocity distribution, actual velocities and as a result values of the Darcy-Weißbach friction factor were overestimated. He showed that, when assuming a semilogarithmic velocity profile, Darcy-Weißbach friction factors were calculated too high for conditions during which more of an S-shaped vertical velocity profile had to be expected. The difference was most relevant during flows where the boulders were covered by water (intermediate-scale roughness) (Bathurst, 1985). As a result of his work Bathurst stated that defining a 1D flow resistance equation for mountain streams is challenging, as it would need to allow for the quantification of wide variations in resistance at a site, with changing discharge and also between sites for various discharges. Along steeper slopes at-a-site variations in resistance with discharge were found to change more rapidly than along less steep slopes. To empirically find such a relation that is generally valid for a large number of streams and different slopes and grain size distributions is difficult (Bathurst, 1985).

In one-dimensional approaches also care has to be taken with three-dimensional features that can act as section controls. They can significantly increase flow resistance along a reach at low flows (Bathurst, 1985).

3.3. Flow resistance in 2D calculations

In two dimensional approaches the flow resistance resulting from external roughness features is considered in the source term of the 2D shallow water equations. The internal resistance can be considered through the use of a viscosity factor or through simplified turbulence models (Nujic, 2009, EDF-R&D, 2013).

Simons and Richardson (1966) use the term multiple roughnesses. It implies that different bed roughness elements are not exclusive in time or in space. They can form side by side in a cross section or in a reach or can also form in a temporal sequence. This multiple roughness is spatially related to spatial variations in shear stress ((φDS), stream power (VφDS), or alluvial bed material. This implies that it is necessary to be able to represent such changes in the scope of a model in order to be able to also account for this roughness variability (Simons and Richardson, 1966). Temporal variations can be represented in cross section or reach averaging 1D models. They cannot represent inter cross sectional variations or variations within a reach. Therefore, for questions of more spatial detail, it can become necessary to employ models that can replicate roughness variability within a cross section or a reach.

2D shallow water equations are derived by a vertical integration of the 3D Navier-Stokes equations. Flow resistance from external roughness is, similarly to how it is treated in 1D approaches, considered through friction factors (that are in theory mostly related to bottom friction). It is possible to include other terms in 2D equation that explicitly represent the effects of turbulence, as for example k-e modules. Often, however, the consideration of these effects is as well left to the friction term. The major difference between the use of friction factors and the representation of roughness/resistance between 1D and 2D approaches for which areas they are accounting for. While in a 1D representation the friction factor stands for the resistance influence from the entire bed and the banks bounding the flow, in a 2D model the factor represents the resistance/roughness only at the base of a vertical column of water. In 1D models the effects of turbulence on energy dissipation are not accounted for explicitly. In 2D models it is possible. If such turbulence models are included explicitly in addition to the friction term, the friction factor will differ from the one that would be used in a 1D model or in a 2D model without explicit turbulence representation (Morvan et al., 2008). Explicit considerations of turbulences in 2D numerical models are still of a strong empirical character (Nujic, 2009). Due to the strongly three dimensional character and complex resistance of flow in mountain streams, 2D numerical calculations still represent a strongly empirical representation of their flow characteristic.

3.4. Flow resistance in 3D calculations

The three dimensionality of the flow does have an influence on the flow resistance. With varying depth, varying bank roughness and nonuniformity of the flow in three dimensions also the flow resistance becomes very complex (Simons and Richardson, 1966). When flow is unsteady, an alteration of the turbulence structure occurs (Song and Graf, 1996). This in turn affects bed shear stress and resistance (Morvan et al., 2008). Therefore it makes it complicated for 1D and 2D approaches, especially when the three dimensionality of the flow is fully developed, to accurately account for it. Separation zones caused by bedforms (for example after the crest of ripples), alter the effective flow depth (Bathurst, 1985) and influence flow resistance (Morvan et al., 2008). As a result when the continuity equation is established on flow depths that do not account for these separation zones, calculated velocity results can be misleading. Considering the effective depth in the continuity equation would take the reduced conveyance profile into account when calculating velocities. Increased energy dissipation as a result of the form roughness would this way, however, still not be explained (Bathurst, 1985, Morvan et al., 2008). 1D approaches and 2D approaches are not able to reproduce separation zones or shapes of vertical velocity profiles, which are crucial for a thorough understanding of flow resistance processes. Only 3D models allow the replication of such phenomena. The degree of detail at which the flow field and turbulences are reproduced depends on the employed turbulence model, on the model discretization and on the resolution of the geometrical input data.

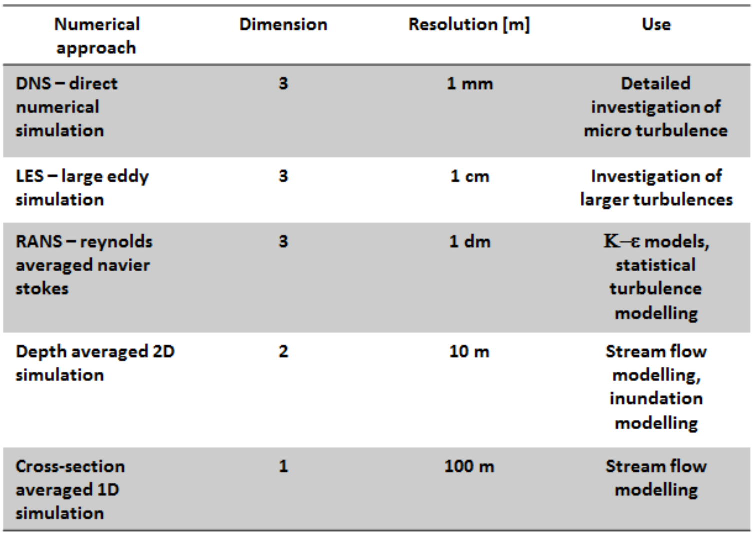
In the 3D Navier-Stokes equations roughness does not appear explicitly. It is however introduced at the walls to account for small momentum and energy losses that occur there. This becomes necessary because of the discretization of this problem, which in fact is continuous (Morvan et al., 2008). Only a very fine grid would be able to resolve the linear sublayer and the turbulent boundary layer of the flow, which form close to the walls. Therefore models of the boundary layer are embedded as a substitution. Such models are usually called wall functions and calculate this wall effect at the first node inside a computational domain. Then, via an extra shear term, the wall effect (representing the roughness/resistance exerted only from the boundary surface) is incorporated in the 3D model equations. The energy dissipation caused by turbulence is accounted for directly in turbulence models and, in this case, does not need to be represented in the boundary friction factor. Very much as opposed to the situation in 1D models, and also to the situation in 2D models, in 3D numerical modelling the mesh quality, the discretization of the geometrical situation and the turbulence modelling are as much, or even more, of importance for a correct representation of flow resistance than the friction factor at the boundary (Morvan et al., 2008).

4. Use of high resolution LiDAR bathymetry in numerical calculations

4.1. Introduction

The degree to which numerical hydrodynamic models can replicate the natural flow in rivers depends to a large part on the degree of detail at which information about their geometry is available (e.g. Bates, 2012; Bates and Anderson, 1996; Conner and Tonina, 2013; Gomes-Pereira and Wicherson, 1999; Horrit et al., 2006; Marks and Bates, 2000; Pasternak and Senter, 2011; Williams et al., 2013). At least at the level of detail at which the flow field can be calculated in 2D numerical models, deriving geometrical information from standard terrestrial surveys at a high enough resolution to fully profit from the capabilities of the model, becomes very elaborate. Providing data that is spatially resolved enough to allow a worthwhile use of 3D numerical model codes by standard terrestrial surveying, becomes even more laborious. **Table 2** gives a rough overview on numerical calculation models at different scales and at which level of detail of available geometrical information their use can be considered to be appropriate.

Table 2: Numerical approaches and reasonable geometrical resolutions (Loiskandl, 2006)



Numerical approach	Dimension	Resolution [m]	Use
DNS – direct numerical simulation	3	1 mm	Detailed investigation of micro turbulence
LES – large eddy simulation	3	1 cm	Investigation of larger turbulences
RANS – reynolds averaged navier stokes	3	1 dm	$K-\varepsilon$ models, statistical turbulence modelling
Depth averaged 2D simulation	2	10 m	Stream flow modelling, inundation modelling
Cross-section averaged 1D simulation	1	100 m	Stream flow modelling

4.2. State of Research

An important use of 2D flow models is the assessment of inundation zones during high floods. For this purpose, when these models became available, a growing interest in well-resolved digital terrain models developed (Bates, 2012; Gomes-Pereira and Wicherson, 1999; Marks and Bates, 2000). As a result digital terrain models of floodplains derived from airborne laser scanning data have become a common basis for the topographical parameterization of 2D flood simulation models. They are commonly available at resolutions of about 2.5 * 2.5 m. A limitation remains the geometrical representation of the riverbeds. Airborne laser scanning is typically based on the laser pulse of a red (near infra-red) laser source. At this wavelength the pulses cannot penetrate through water. Only parts of the landscape which are not inundated can be surveyed. As a result, the geometries of the actual riverbeds are usually available at a much lower resolution or the data assessment becomes extremely labor intensive.

Apart from the resolution of geometrical data, it is also important whether the information is available on a cross-section basis or whether it is spatially distributed. Spatially distributed data allows the recognition of 3D formations that can often be difficultly detected in cross-section information. Usually, it is however only such cross-section based information that is available for the riverbeds. This data is not always comprehensive, as the surveys are labor intensive and also it is not uncommon that the access to entire river sections is restricted. Such restrictions occur because of ecologically sensitive environments or because measurements would be too dangerous as a result of strong currents or too high water levels (Kinzel et al., 2013).

When studying the effect of floodplain's topographies on the results of flood simulations, it was found that that already small change in the geometrical representation had significant and complex effects on the results (Bates and Anderson, 1996; Marks and

Bates, 2000). It was expected and could also be shown that for calculations of low flows also the geometrical representation of the riverbed is important (Horrit et al., 2006). Marks and Bates (2000) however also found in their study of flood flows, that the geometry of the river bed had a significant influence. Numerical calculations of detailed instream hydraulics have been limited so far by the availability of well resolved representations of the streams’ geometries. The accuracy of numerical calculations of flood flows has been influenced also by the lack of this data.

Airborne LiDAR bathymetry (ALB), also referred to as airborne hydromapping (AHM) is a development where the laser source with a near infrared wavelength is replaced by a laser that emits pulses in the green region of the electromagnetic spectrum (λ = 532 nm). The specialty about signals at this wavelength is that they are able to penetrate through the water column (Kinzel et al., 2013; Steinbacher et al., 2012). This means it becomes possible to collect detailed data of the river bed and inundated parts of the river banks.

With this data it becomes possible to detect features such as large boulders and bedforms along the banks and in the river beds. Pools, riffles, steps or other mesoscale structures can be detected. This allows the representation of mesoscale structures (2.5.1) in numerical models, which so far could rarely be considered. Geometrical forms within macroscales could already be assessed by the use of infrared airborne laser scanning, which at least allowed the recognition of meanders, bends and larger bank formations. Detailed sediment structures, which represent geometrical influences on the hydraulic flow field on a microscale, at this point, also cannot be detected with a green laser source. In order to identify these structures an extremely high resolution and accuracy (in the range of tenths of a meter or even less) would be necessary.

In chapter 5 (figure 3) data examples of digital terrain models created from AHM information are displayed. With this newly available data it becomes necessary to investigate the effects of this increased accuracy of geometrical information on numerical calculations. It is expected that the effects on 1D, 2D and 3D representations of the flow field will be each of a different character. Ways to best imply the data in each kind of these models will have to be identified. The goal is to get the best performance out of the possible numerical calculations in combination with the newly available geometrical information. This intention comes along with a need of precise and also well resolved observational data, in order to be able validate and rate the models’ performances (Williams et al., 2013). Only then their best use can be identified.

5. Data examples

Figure 3 shows two examples of data generated from an Airborne Hydromapping point cloud. The picture on the left side shows two bends in the course of the river. The terrain model also allows the distinction of boulder clusters and of steps in the riverbed slope. On the zoomed image on the right side it can be seen that distinct boulders and sedimentation features can be identified. The orange circle in the image on the right side marks an area of intensified sedimentation.

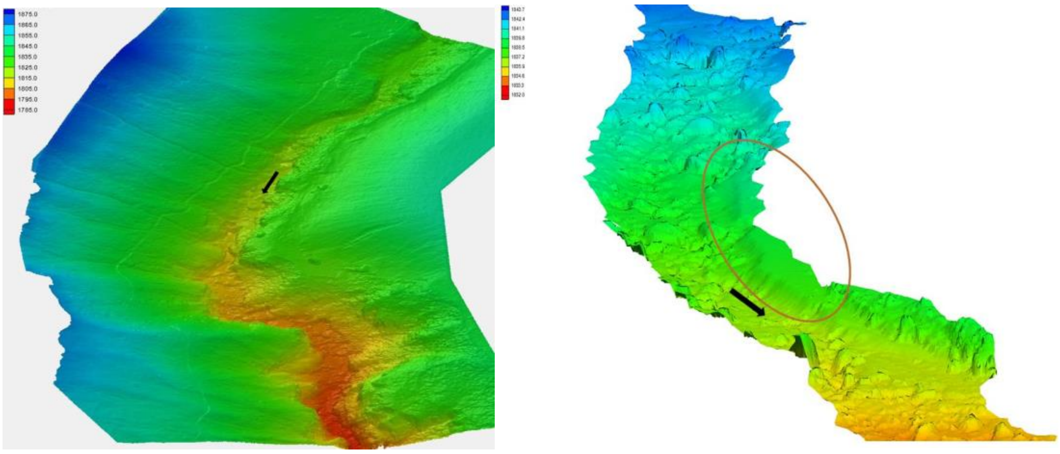


Figure 3: Terrain models created from Airborne Hydromapping information, macro- and mesoscale structures visible in the data (left), detailed view on mesoscale structures (right)

In **Figure 4** cross sections that were taken from terrain models at different resolutions are displayed. They were all derived from AHM data which was interpolated on grids of different resolution. The two different models had a resolution of 1 m and 0.2 m. Both representations of the cross sections provide data at a higher resolution than typically available from standard surveying techniques.

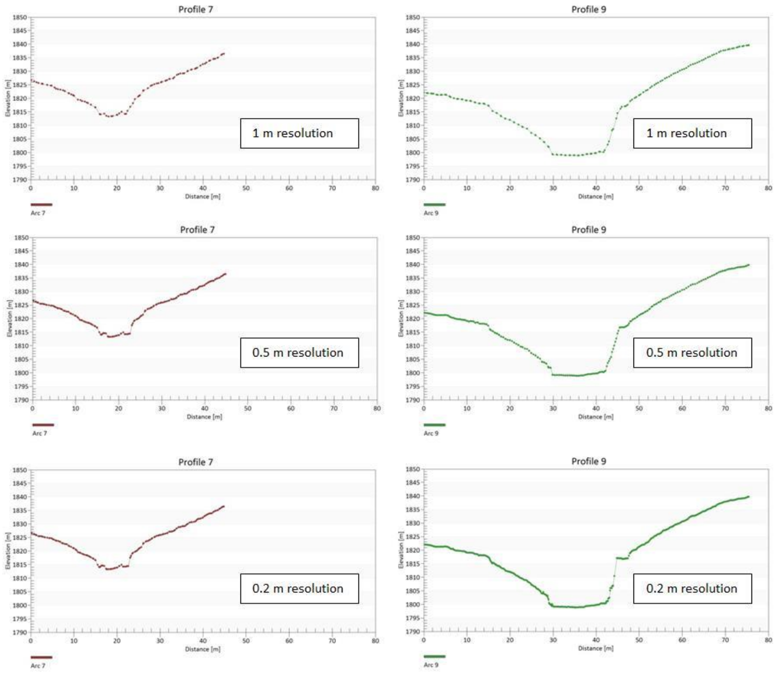


Figure 4: Cross sections derived from terrain models of different resolutions for two different transect.

Even though the cross sections originate from a small region of the stream, they show a noticeable variability in their shape. **Figure 5** displays a sequence of cross sections extracted from the terrain model with a resolution of 0.2 m. **Figure 6** shows the location of the cross sections in the channel in a plan view.

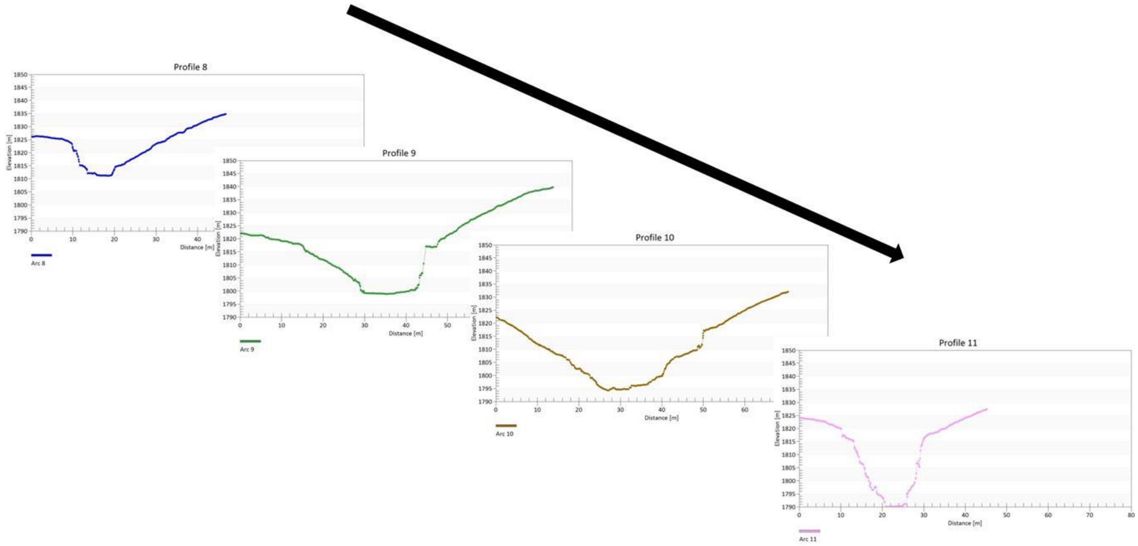


Figure 5: Sequence of cross sections along a river reach derived from a terrain model with a 0.2 m resolution.

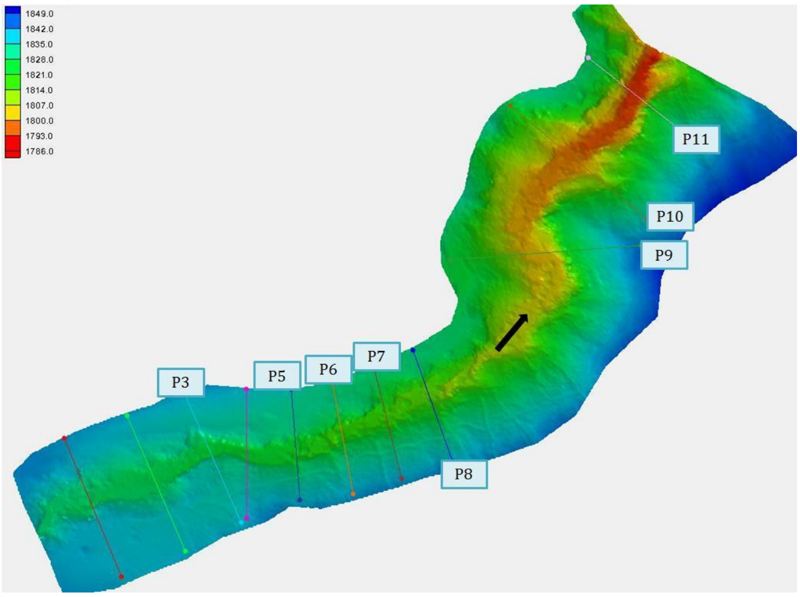


Figure 6: Location of the cross sections.

For the calculation of flow velocities and accordingly also flow depths at a certain discharge, knowledge of the flow cross section or even the flow conveyance is necessary. The flow conveyance, additionally to the flow area also takes into account the channel slope between cross sections (Jarrett, 1984). Simplifications, interpolation or assumptions that become necessary due to a lack of information are likely to underrepresent a channel shape's variability and accordingly affect the results of flow depth calculations.

Bathurst (1985) defined a roughness area to allow for the assessment of the influence of mesoscale flow features on the resistance to flow in mountain streams. The roughness area is the ratio of the area of mesoscale roughness features to the total area of the cross section (Bathurst, 1985). He used this ratio to derive an empirical relationship for the assessment of flow resistance. Extensive information on such mesoscale roughness features is mandatory for a through use of this method. **Figure 7** shows a sketch that illustrates the idea of a roughness area. The mesoscale features are shaded. The detailed assessment of such features through terrestrial surveys is, if at all possible, very time consuming. **Figure 8** shows in two examples how AHM derived terrain data can be used to assess roughness areas for an arbitrary number of cross sections within a reach.

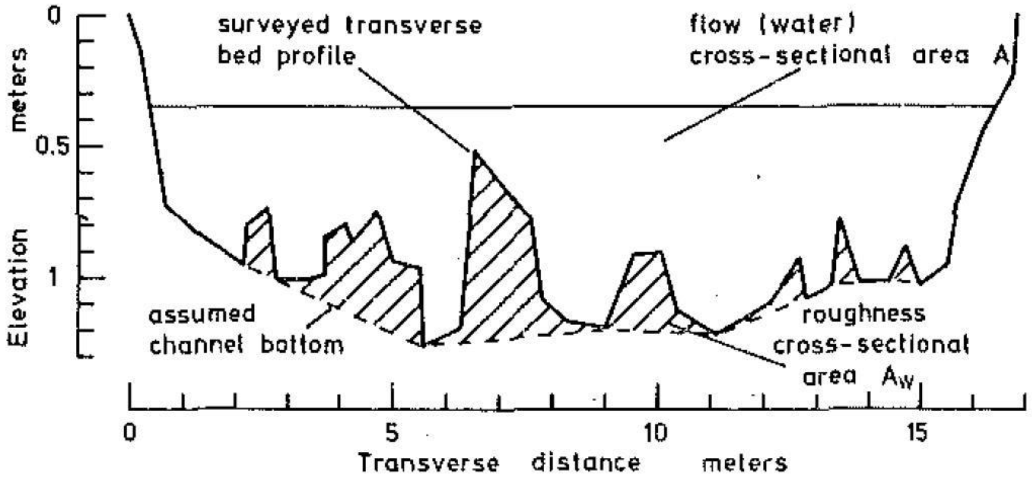


Figure 7: Definition of the roughness area (Bathurst, 1985).

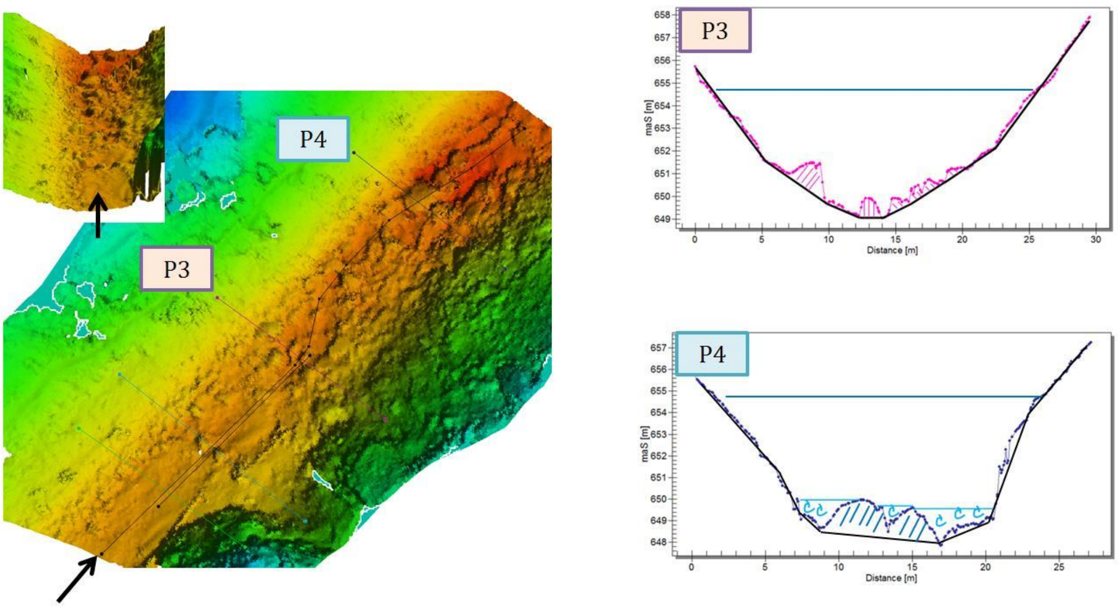


Figure 8: Roughness area derived from AHM data in two cross sections.

Longitudinal profiles extracted from the terrain models in **figure 9** and in **figure 10** show that river bed data at this resolution allows the detection of steps or pools within the river course. Significant obstructions to the flow, as for example large boulders, can be identified. It can be noted that also the slope of the river bed is strongly variable, even though only a short stretch of the river is displayed. Variability in the slope that cannot be detected due to a lack of data from riverbed features clearly affects the calculation of flow conveyance and accordingly the calculation of flow depths and flow velocities (Jarrett, 1984). **Figure 11** shows the location of the longitudinal profiles in the channel in a plan view.

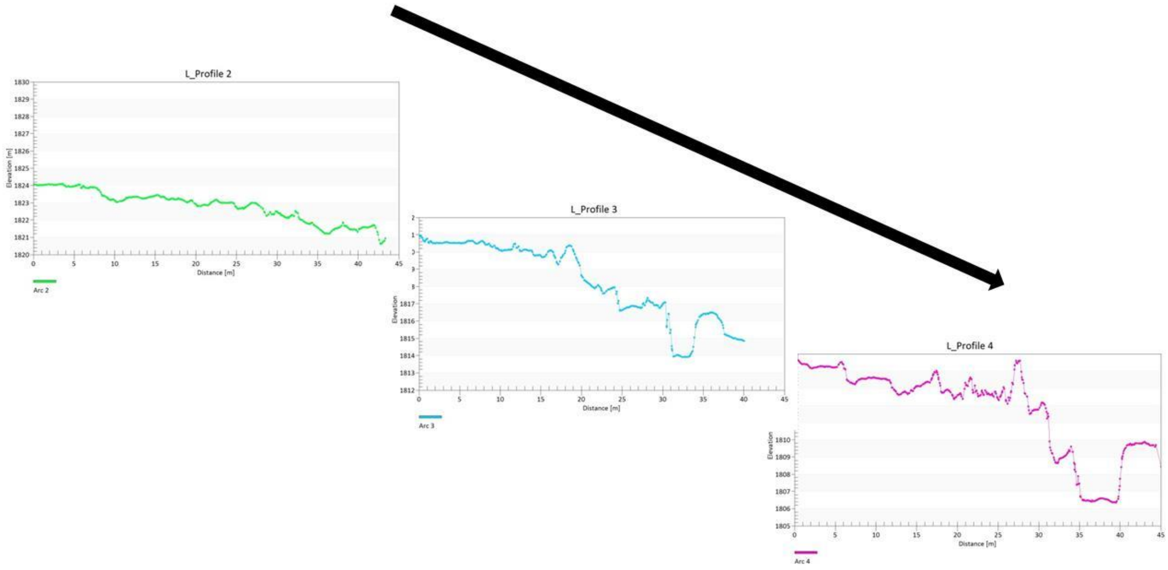


Figure 9: Sequence of longitudinal profiles along a river reach derived from a terrain model with a 0.2 m resolution.

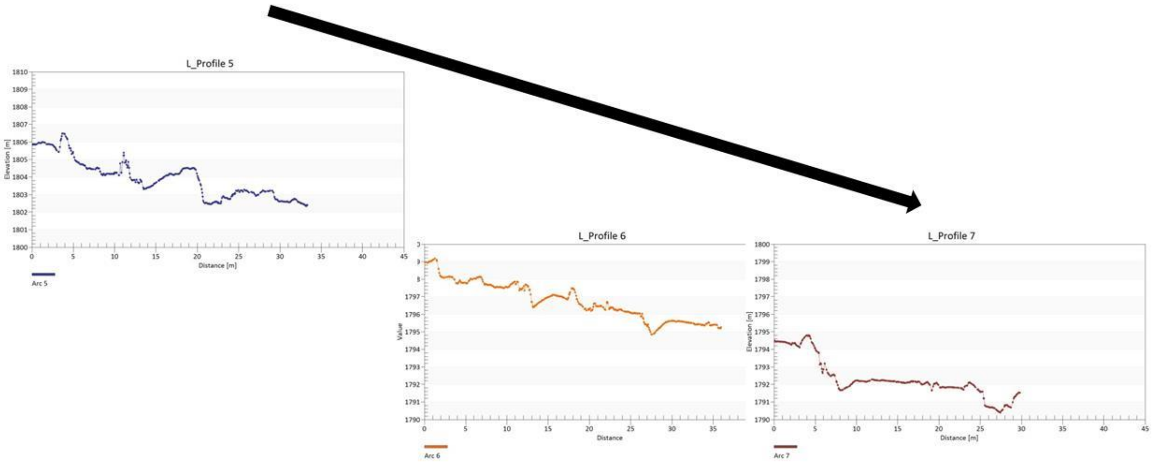


Figure 10: Sequence of longitudinal profiles along a river reach derived from a terrain model with a 0.2 m resolution.

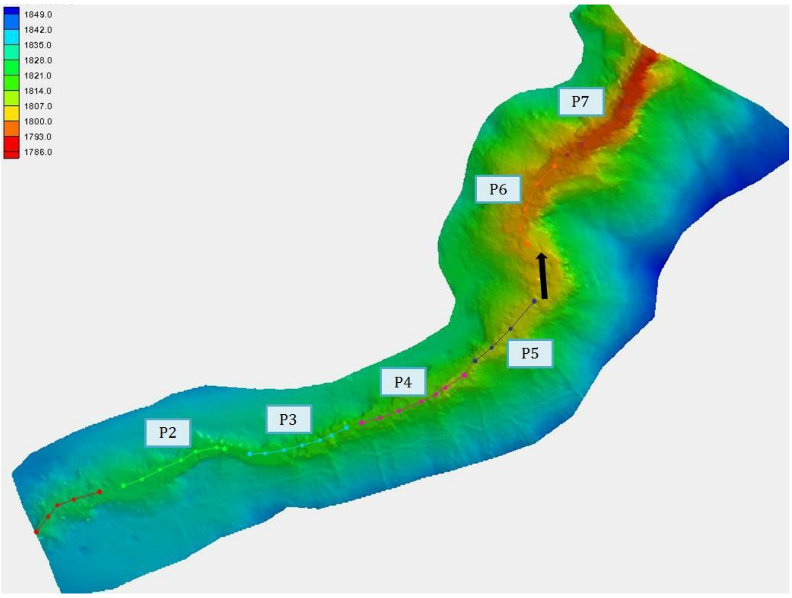


Figure 11: Location of the longitudinal profiles.

Aberle and Smart (2003) empirically derived channel roughness for flow calculations from the standard deviation of elevations along a longitudinal profile of the riverbed. **Figure 12** shows longitudinal cross sections, displayed at two different resolutions (1 m and 0.2 m) that were all derived from AHM data. Different resolutions will provide different results. The availability but also the resolution of the representation of detailed information on the shape of riverbeds is mandatory to successfully derive the flow resistance.

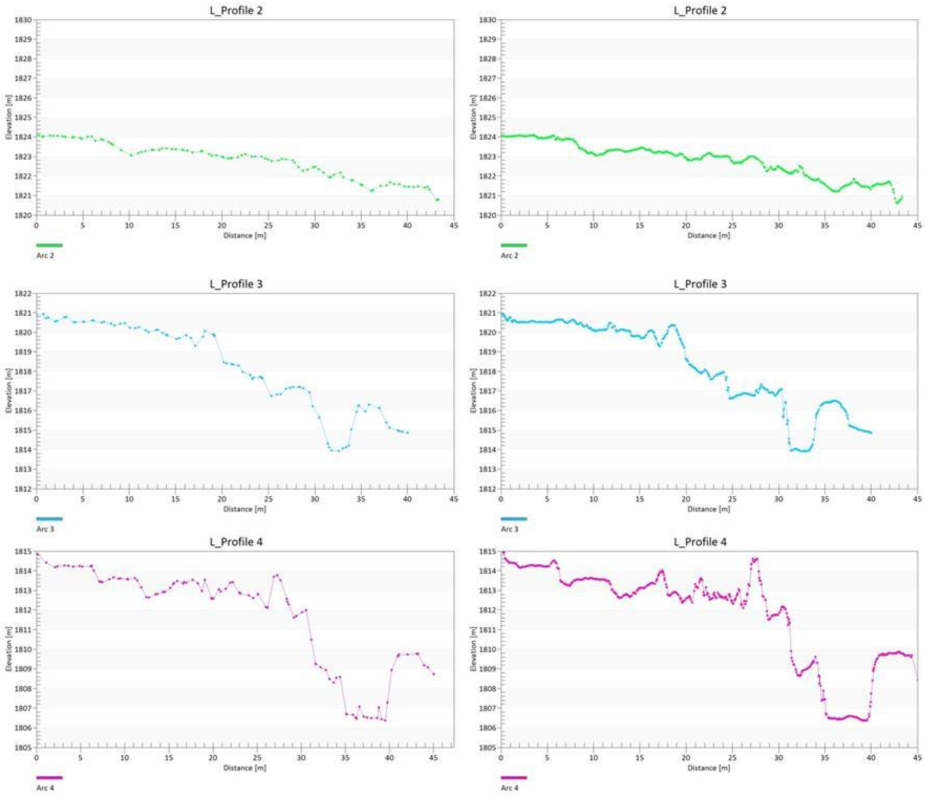


Figure 12: Location of the longitudinal profiles.

6. Conclusions

Fluid mechanics and the calculation of their important parameters, flow velocities and flow depth are important for the dimensioning of structures, for stream restoration or for protection and hazard assessments in river engineering. Especially in mountain streams flow parameters are difficult to assess as a result of highly variable stream geometries which result in strongly variable flow patterns. Especially the flow resistance, which represents the link between a certain discharge and the flow velocities and flow depth that establish as a reaction on the stream morphology, varies especially strong in steep mountain streams.

1D, 2D and 3D formulae are available for stream flow calculations. They differ in their representation of the flow field and accordingly are differently taking flow resistance into account. Care has to be taken in terms of their suitability for the calculation of the flow parameters in a specific river. Especially in 1D approaches, which are of a strong empirical character, and partly also in 2D approaches, it is not unlimitedly possible to transfer formulae between streams of different characteristics. 3D calculations provide the best replication of the actual physical processes related to the flow, which might make them the most suitable solution for detailed flow calculations in mountain streams. However, this, apart from the need of immense computational power, comes along with also the highest demands on the accuracy of the geometrical input data, on which the calculations are based on. Only on a very accurate representation of the actual form of the riverbeds, also the detailed 3D representations of the flow can make sense.

While detailed assessments of flow resistance and the use of high resolved calculations were so far limited by the availability of information about the shape of riverbeds, especially on the meso- and microscale, the use of green laser sources in airborne laser scanning now makes the geometry of riverbeds more accessible. The established methods to estimate flow characteristics such as flow depths, flow velocities and flow resistance need to be reevaluated with this better resolved data and possibly new methods to allow its best use need to be developed.

A quick introduction into flow hydraulics with an emphasis on mountain streams was provided. The laser scanning technique called Airborne Hydromapping, which uses a green laser source to scan through water, was shortly explained. Data examples were shown to provide few examples of the data’s potential for flow hydraulic calculations and flow assessments.

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