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Fig. 1
Artificially placed boulders acting as form roughness elements in the river Wutach, Germany

THE ROUGHNESS OF WATERWAYS

Environmental hydraulics is a sub-branch of environmental fluid mechanics that deals with the movement of water and transport processes in both natural water bodies and engineered waterways. Techniques developed to evaluate flow resistance in man-made conduits can be successfully applied to natural waterways.

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Environmental hydraulics emerged from fluid mechanics and traditional hydraulics due to the increased environmental awareness of modern society. The discipline seeks to provide professionals working in water-related areas with the knowledge and technology needed to better secure clean water and water resources for upcoming generations. Moreover, it focuses on fundamental hydraulic phenomena and their interactions with environmental processes on multiple scales. This includes the investigation of physical, chemical, and biological aspects of flowing water that are important for the protection, restoration, and management of environmental quality – as for example required by the European Water Framework Directive and defined by the UN Sustainable Development Goals.

Roughness in natural channels

A key challenge when dealing with flowing water is adequately assessing the retardance of the flow caused by the frictional resistance of water along the wetted boundaries, as well as the resistance imposed by objects directly exposed to the flow (Figures 1 and 2). These are the main ingredients of the so-called flow resistance. Flow resistance results in energy losses, thereby determining the bed shear stress, i.e. the frictional force of the water along the river-bed and banks, flow velocities and turbulence characteristics, water levels and hence the conveyance capacity. This means, in more general terms, that an increase in roughness for any given channel geometry, slope and water discharge results in an increase in flow resistance, so that a higher water level and slower flow will be observed compared to a smoother case. On the other hand, for a channel with a given roughness, slope and cross-sectional geometry, the flow resistance depends on discharge. For such a case, flow resistance typically decreases with increasing discharge once the roughness elements are completely submerged.

Such considerations are important for the design of nature-based solutions or hydraulic structures aiming to, for example, reduce flood risk, improve the ecological status of water bodies, or control sediment transport and the morphological development of rivers and streams. It is also worth mentioning that all aforementioned parameters represent the basis for scientific studies and practical applications in environmental hydraulics.


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Fig. 2
A trained section of the Kirchenbach stream, Germany, where the flow resistance in the main channel is governed by surface roughness

Roughness scales

Roughness is typically subdivided into two different types: surface or particle roughness, and form roughness (see Figures 1 and 2). The energy losses due to the latter are associated with large-scale roughness elements and the related form drag. Riparian vegetation, bridge piers, morphological features such as step-pool systems and bed forms (dunes and ripples) or even individual large boulders (see Figures 1–4) are examples of large-scale roughness elements causing form resistance. On the other hand, the energy losses due to surface/grain roughness are associated with

Fig. 3
Examples of form roughness: a trunk exposed to the flow and the associated wake


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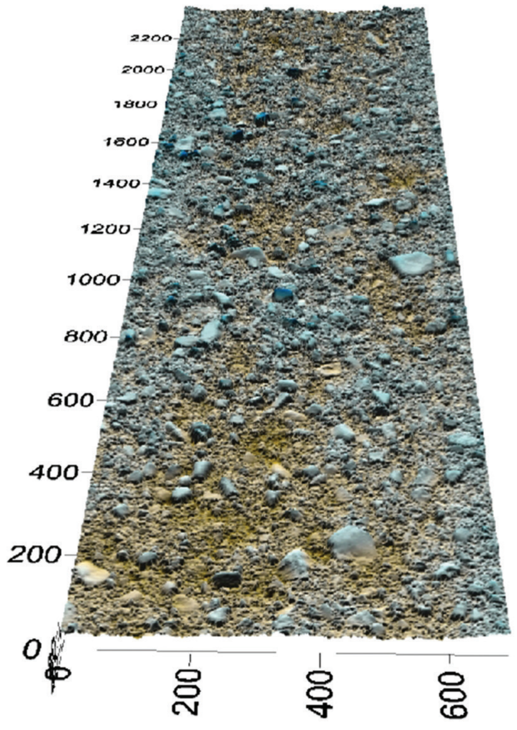
Fig. 4
A step-pool system in the Black Forest, Germany

both viscous drag on the bed surface and form drag due to small-scale roughness elements, such as the grains that form alluvial beds or channels (Figure 5). A distinction is also drawn between hydraulically smooth and hydraulically rough regimes, which are connected via a transitional regime showing features of both. A flow over a hydraulically smooth bed is not directly affected by roughness elements, since they are small compared to the size of the viscous sublayer. The latter is a thin fluid layer characterized by laminar flow (fluid flow in layers with no or little mixing between the layers) that is associated with the flow velocity equal to zero at a non-moving solid boundary (no-slip condition); outside of the viscous sublayer, the flow is turbulent (flow characterized by irregular fluid motion). The hydraulically smooth regime is typically observed in engineered flows over smooth surfaces (e.g. steel pipes, glass surfaces or concrete) or in alluvial flows over beds composed of (very) fine particles. The flow in the hydraulically rough regime, on the other hand, is observed where particles protrude through the viscous sublayer along the wall. This means that the particles are directly exposed to the flow and the corresponding energy losses depend to a large extent on the size, shape, and arrangement of the particles on the surface (Figure 5).

Quantification of roughness

A key question that arises in many applications in hydraulic engineering and environmental hydraulics is how conduit roughness can be adequately described. Manning's n (or the Strickler coefficient k_{St}) has, to date, probably been the most widely used roughness coefficient in practical hydraulic engineering and environmental hydraulics applications. However, it has often been criticized because of its "non-physical" dimensions of $[s/m^{1/3}]$ and hence its empirical nature, reflected in the well-known fact of its dependence on the water level stage. In modern applications of Computational Fluid Dynamics (CFD), it is often used as a fitting parameter in the model calibration process, i.e. it is adjusted so that the measured, known water levels or/and discharges are met by the representative simulation results. There are only few empirical approaches that have directly linked the Manning's coefficient values with physically measurable roughness characteristics of alluvial and engineered waterways. Examples include rigid emergent vegetation elements (e.g. tree trunks with a known diameter and defined spacing) or alluvial beds, for which this coefficient may be estimated from a characteristic grain diameter of the bed surface by an empirical relationship. Note, however, that Manning values are interrelated with the other commonly used roughness coefficients, i.e. Chézy's C and Darcy-Weisbach's friction factor f.

Of these two, the latter dimensionless friction factor f is perceived as more physical, hence it is preferred in scientific applications. Moreover, it can be combined with the so-called "law of the wall," which is based on the assumption that the temporal mean velocity of a turbulent flow at a certain point is proportional to the logarithm of the distance of this point to the wall. For the aforementioned hydraulically rough regime, the roughness coefficient used in the logarithmic "law of the wall" is the equivalent sand roughness k_s, which originates from the fundamental results of Nikuradse's experiments in sand-roughened pipes. Note that, despite its physical background, the



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Fot. 5
A digital elevation model of a gravel bed at the LWI laboratory

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Fig. 6
A view into a rock-blasted unlined hydropower tunnel investigated in the *Tunnelroughness* project

applicability of the log-law is restricted (e.g., it is only valid for large relative submergences and up to 20% of the water depth), and that k_s represents a hydraulic roughness parameter that may differ from geometrically derived roughness parameters used to describe the vertical extent of the roughness elements. Therefore, k_s is often assumed to correspond to a vertical geometrical roughness height multiplied by a constant factor, so that many existing resistance laws need to be interpreted as semi-empirical.

Digitalization opens up new possibilities

The accurate determination of geometrical roughness is not always straightforward due to the stochastic nature of roughness in natural streams, i.e. the spatial heterogeneity of river beds (see Figures 3 and 4). Methods for quantifying the roughness of fluvial beds can be divided, for example, into discrete-component vs. random-field approaches. In the former approach the bed surface is assumed to consist of individual particles or morphological elements and the corresponding roughness is often described in terms of a characteristic grain-size of the surface layer. Such a roughness descriptor does not consider the surface structure, which also depends on further parameters such as particle orientation, packing, imbrication, and protrusion. This means that even if the full grain-size distribution of the surface material is known, unambiguous determination of the surface roughness is still not possible, as the very same material can be arranged in various ways.

A characterization of the surface structure, on the other hand, becomes achievable in the random-field approach, which harnesses recent technical developments in close-range photogrammetry and laser scanning to generate high precision digital elevation models (DEMs), which can then be analyzed in detail by statistical methods. Thus, the roughness of a bed or wall is considered as a random field of surface elevations, making the derivation of scales possible not only for vertical but also for horizontal roughness features, leading to an improved description of roughness. It should be mentioned that corresponding techniques were already developed in the previous century but have not yet been incorporated into adequate flow resistance laws. The need for such developments can be highlighted by the following example of ongoing research activities at the LWI, illustrating how joint consideration of seemingly different topics can lead to further advancements in the description of roughness in environmental hydraulics applications.

What do hydropower tunnels and block ramps have in common?

This question seems to be rather awkward as, at first glance, hydropower tunnels have nothing to do with block ramps (engineering structures used for river bed stabilization). However, in terms of environmental hydraulics, they do share an important feature: both are characterized by rough walls and the roughness plays a key role in the design of both structures.

Hydropower tunnels are an important component in many hydropower systems. To a large extent, friction is what determines how much water can be conveyed by such a tunnel. The *Tunnelroughness* project, hosted by the Norwegian University of Science and Technology (NTNU), focuses on energy losses in Norway's generally unlined hydropower tunnels, i.e. tunnels where the walls are left rough after excavation or blasting (see Figure 6). They are used for

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Fig. 7
An unstructured block ramp built for re-establishing the ecological connectivity of river reaches. The design of such structures requires the assessment of both form and particle roughness

both to transport water from reservoirs to the powerhouse for energy production and to facilitate the controlled release of flood flows from reservoirs into downstream areas. The friction caused by such tunnel walls is generally quantified by empirical formulae, tabulated values or photographic methods. In other words, it is estimated rather roughly, not based on the analysis of real roughness patterns. This is the issue tackled by *Tunnelroughness*, which aims to improve the analytical, experimental and numerical methods used to determine the friction losses of flowing water in rock-blasted unlined hydropower tunnels.

Using laser-scanning data of real tunnel systems to construct scale and computer models (see Figure 6), it became possible to collect high resolution flow data from laboratory and numerical experiments. These data will be used to determine the energy losses, which will then be related to the structure of the tunnel's wall roughness. The latter will be assessed based on statistical analyses of the laser-scanning data. As the final results of the project will allow for the assessment of energy losses in unlined tunnels from laser-scanning data, they are of high relevance for the hydropower industry and other end-users. Moreover, the properties of the near-wall flow field will be further investigated by applying the so-called Double-Averaging Methodology (DAM), which represents an innovative framework to investigate spatially heterogeneous flows based on the double-averaged (in space and time) Navier-Stokes Equations (equations describing the motion of viscous fluids).

Interestingly, these same methods can also be used to describe the spatially heterogenous flow in rough mountain streams (see Figure 4) or artificial block ramps (Figure 7). The latter structures are especially of interest in re-establishing the ecological connectivity between river reaches that have been disconnected from each other by enabling fish passage over barriers. However, establishing fish migration corridors is no trivial task, as they are three-dimensional structures characterized by local geometric and hydraulic conditions, to be designed for different fish species and fish sizes. This means that migration corridors require a design guaranteeing adequately moderate flow velocities and sufficient water depths. As is apparent from the above considerations, the flow velocities and water depths depend on the roughness characteristics, which need to be properly assessed within the design process.

These two examples, taken together, represent an *applied summary* of this article. They point to objectives for further investigations and developments to characterize the effect of complex roughness on the flow field, i.e. to investigate how hydraulic roughness can be related to bed topography.

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