Ripple dynamics over various microtopographical roughness elements and their implications for river management

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Funding information
Austrian Federal Ministry for Digital and Economic Affairs; the National Foundation of Research, Technology and Development of Austria; National Foundation of Research, Technology and Development of Austria; Austrian Federal Ministry for Digital and Economic Affairs

Abstract
Specific problems in connection with the sediment regime have arisen in the granite and gneiss area in the northern part of Austria due to the increased sediment supply of coarse sand and fine gravel as a product of rock weathering. One of the physical characteristics of these sediments is their high mobility in form of ripple bedforms along the surface. In these rivers, the microtopographical structures of the bed surface are hydraulically active, especially in the initial stages when ripples have not overtopped the largest elements of the bed’s roughness elements. There is a lack of detailed studies of the impacts of these microtopographical structures on ripple dynamics. Thus, the aim of the present study was to investigate the impact of various microtopographic roughness elements on ripple movement. This study was performed using a 1:1-scaled physical laboratory experiment. The results showed, in all repetitions of the experiment with variable grain sizes, that the higher the microtopographical variability of the river substrate and turbulence was, the higher the measured transport velocities of the ripples were. The expected hidden impacts on sediment transport were not documented. Important implications for sediment management were discussed, as river sections with high accumulation rates of coarse sand and fine gravel are prone to additional degradation as downstream transport decreases over smooth ripple-dune morphologies. Additionally, structural elements such as exposed rocks may increase the downstream transport due to the increased variability in turbulence.

KEYWORDS
morphology, physical experiments, ripple dynamics, river management, roughness

1 | INTRODUCTION

Due to the granite- and gneiss-dominated old mountain range (formed 300 million years ago in the Devonian and Permian), the northern part of Austria shows (a) some specific characteristics in river morphology and grain-size distribution and (b) some specific problems in sediment management compared with much younger alpine streams (Hauer, Unfer, Habersack, Pugl, & Schnell, 2013; Höfler, Gumpinger, & Hauer, 2016). Long stretches of the river systems correspond to the so-called “plane-bed type” (Montgomery & Buffington, 1997) without significant longitudinal structuring (e.g., riffle-pool sequences) or no gravel bars along the banks (Hauer, Unfer, Holzmann, Schmutz, & Habersack, 2013).
The typical microtopography of the riverbed surface (cf. Morvan, Knight, Wright, Tang, & Crossley, 2008) is characterized by its bimodal grain-size distributions (Bunte & Abt, 2001; Figure 1a and 1c). The coarser parts of the grain-size distributions belong to cobbles ($d_c = 64–256$ mm) and boulders ($d_b > 256$ mm; Wentworth, 1922) with only a slight degree of the roundness of sediments (Hauer, Unfer, Holzmann, et al., 2013). The occasionally low bankfull discharge capacity of these rivers hardly enables the breakup of the surface layer due to the low bed shear stresses, even in terms of exceptional flood events (e.g., with hundred-year recurrence intervals; Hauer, Unfer, Tritthart, & Habersack, 2011). Furthermore, suitable spawning gravel ($d_s = 2–5$ cm; Obruca & Hauer, 2016) deposited in the subsurface layer is limited and largely unavailable for the reproduction of salmonids ($Salmo trutta$ and $Thymallus thymallus$; Hauer et al., 2011).

Moreover, specific problems in connection with the sediment regime arise via tributaries in the granite and gneiss area, enforced by the increasing entry of coarse sand and fine gravel as a product of rock weathering ($d_s = 1–10$ mm; Hauer, 2015), which, in this paper, are labelled as fine bedload (Figure 1b). In particular, the deposition of this fine sediment part of the bimodal grain-size distribution (Figure 1a) results in the continuous and sustainable degradation of the riverbed and its associated habitat features (Figure 1c,d). For example, in the Aist (Upper Austria), field studies have shown that in the areas completely covered by fine bedload, a decrease in the macroinvertebrate biomass of >80% was found compared with reference sites (Leitner, Hauer, Ofenböck, Pletterbauer, & Schmidt-Kloiber, 2015). In addition to the ecological problems, there are also critical issues in terms of flood protection, which especially arise in river sections with a decrease in energy slope (e.g., the transition between the highlands and the Danube basin). By reducing the necessary flood discharge capacity in artificial river widenings by the deposition of transported material (e.g., discharge designed for a hundred-year recurrence interval), there is an additional risk in such areas of a continuous increase in the damage potential.

One of the physical characteristics of these fine parts of the bimodal grain-size distribution, however, is their high mobility (cf. Hjulström, 1935), even under low-flow conditions (Hauer, 2015). In rivers with a high supply rate of fine bedload, the morphological and sedimentological features reflect the so-called dune–ripple type (cf. Montgomery & Buffington, 1997; see also Figure 1c). Here, the ripples are almost constantly moving on the surface layer, even in low-flow conditions, partially covering the coarser grain-size fractions of riffle pool or plane-bed sections by various decimetres in height. Thus, misclassifications of natural channel patterns may be possible in terms of the overforming of plane-bed or riffle-pool sites by the excessive supply of fine bedload (Hauer, 2015).

Studies of ripples and ripple movements are manifold (e.g., Ashley, 1990). It is commonly observed that sand beds (or even gravel beds) do in fact deform into persistent arrays of ripples, dunes, and antidunes, collectively termed as bedforms (Kennedy, 1969). The
formations of ripples and dunes on erodible beds have been studied in both laboratory experiments (e.g., Richards, 1980) and field studies (e.g., Collinson, 1970; Jackson, 1976). The stability (McLean, 1990) and the mechanics of ripples (Nelson & Smith, 1989) have been described, including the development of bedload equations for ripples and dunes (Simons, Richardson, & Nordin, 1965). In particular, the morphodynamics of ripples (e.g., Carling, Williams, Golz, & Kelsey, 2000) are of great importance, as they are responsible for the low abundance of macroinvertebrates in the area of interest (Leitner et al., 2015). Various macroinvertebrate species have adapted to coarse sand and fine gravel (e.g., Circomidae and Oligocheten; Graf et al., 2016) but not to high mobile bedforms. However, in contrast to the idealized boundary conditions in physical laboratory studies (e.g., Baas, 1994), the ripple movements in studied granite/gneiss rivers have been found to be variable, partially in terms of the coarse surface layer grains of the characteristic bimodal grain-size distribution (cf. Figure 1). These microtopographical structures of the bed surface are hydraulically active, especially in the initial stages, when the ripples have not overtopped the largest elements of the microform bed roughness elements. However, detailed studies of the processes of these microtopographic impacts are missing.

The geomorphic and hydromorphologic impacts of bedforms on instream hydraulics have been frequently studied (e.g., Maddux, McLean, & Nelson, 2003; McLean, Nelson, & Wolfe, 1994). However, the influence of microform bed roughness elements on flow and sediment transport is limited. Hassan and Reid (1990) concluded that pebble cluster spacing tends towards an equilibrium that is regulated by a feedback process involving sediment transport rates and that the spatial concentration of these microforms will adjust to the point where they induce maximum flow resistance. In general, microform/microtopographical roughness elements are responsible for the definition of hiding and exposure in sediment transport (e.g., Sutherland, 1992; Wu, Wang, & Jia, 2000). Here, correction factors were developed to account for the hiding and exposure mechanisms in sediment transport (e.g., Mosselman, 2005). However, until now, it has not been determined how ripple movements interact with coarser substrates and thus various microtopographic roughness conditions, which are given in the area of interest.

Thus, the aim of the present study was to investigate the impact of various microtopographic roughness elements on ripple movement. Knowledge about this relationship is important for river management, especially of how transported sediments as well as mobile bedforms interact with variable river substrate sizes as an important boundary for river restoration. The research was set up in a 1:1-scaled physical laboratory experiment at BOKU University. The hypothesis for this experiment was, in line with the hiding-exposure results, that the coarser the microtopography is, the lower the transport velocities of ripples are, thus reflecting the impact of hiding processes on ripple movement.

2 | METHODS

To analyse the sediment transport processes, a physical model with a 1:1 scale was constructed in a hydraulic flume at the BOKU University (width = 300 mm). The model was divided into three sections with different microtopographic roughness values: section “A” with a mean grain-size $d_m = 140$ mm, section “B” with $d_m = 70$ mm, and section “C” with $d_m = 30$ mm, as well as steady-state discharge conditions. The experimental setup in the longitudinal perspective is presented in Figure 2. The total length of the experimental setup was 7.5 m, and each section of variable microtopographic roughness was 2.5-m long. For detailed analysis, four subsections were determined in every section ($n = 3$) with a total length of 0.625 m, labelled as A1 to A4, B1 to B4, and C1 to C4 (Figure 2). To avoid boundary disturbances on flow and sediment transport, presections and postsections (1.25 m in length) with smooth surfaces (plywood) were implemented in the experimental setup. The flume was connected to the central water cycle of the laboratory, and the flow was controlled via frequency-controlled pumps with $Q$ discharges of up to 55 $\text{ls}^{-1}$. The accuracy of the discharge measurement was ±0.1 $\text{ls}^{-1}$.

On the basis of the volumetric samples ($n > 600$) of rivers in the granite and gneiss region and the follow-up particle-size analyses (Hauer et al., 2015), two particle-size fractions ($d = 2$ mm and $d = 4$ mm) were selected as experimental material (cf. Figure 1b). Hence, the experimental test runs included two scenarios of variable grain sizes with three repetitions each. An overview of the test series is given in Table 1. Due to the hydraulic similarities of the two scenarios, nearly the same $Fr'$ (densimetric particle Froude number) could be achieved. Sediment was supplied continuously at 40 kg per hour (~0.67 $\text{kg min}^{-1}$).

Moreover, in the longitudinal axis of the flume, 14 vertical profiles were defined to measure the flow velocity. With respect to the microtopographic variability, a total number of eight profiles (A1 to A-8) in section A, four profiles (B1 to B-4) in section B, and two profiles (C-1 and C-2) in section C were established (Figure 2). Each vertical profile consisted of maximum seven different elevations over the bottom of the flume, where the streamwise velocities were recorded over time to determine the velocity distribution over the entire water depth. Recording the flow velocity profiles several times

![FIGURE 2](image-url)  Experimental setup in the laboratory flume, including the definition of the various sections with variable microtopography (a–c), the various subsections (length = 0.625 m; A1–C4), and the points of measuring velocity profiles (A1–C-2) [Colour figure can be viewed at wileyonlinelibrary.com]
over the flume bottom at the same coordinates allowed for the quantitative evaluation of changes in flow velocity due to variations in microtopographic conditions and during various stages of sediment deposits.

For the point velocity measurements, a hydrometric measuring blade ZS25 (18) (in a “rod” version) from Höntzsch was used. The measurement data from the measuring vane were recorded directly via a data acquisition system in order to evaluate the individual pulses of the four-vane impeller (four speed values per turn). The measurement duration at each point was 60 s, and (a) the mean value \( \langle V_m \rangle \) and (b) the turbulence intensity \( (T_u = \frac{V_{\text{std}}}{V_m} \times 100\%) \) were evaluated, where \( V_{\text{std}} \) represents the standard deviation of the velocity. The systematic error caused by the flow speed-dependent impeller rotation speed was taken into account in the statistical evaluation.

To record the microtopographic roughness of the flume and different stages of ripple movement (after passing the various subsections A1–C4), a laser profile sensor from Leuze© was used. This is based on the triangulation measurement principle. At each location in the longitudinal direction \( (x) \), a bed profile \( (y, z) \) was measured. The displacement in the direction of \( x \) was recorded by means of a friction wheel with an incremental encoder with a resolution of 0.5 mm. The raw data, that is, the individual measurement profiles \( (y = \text{spanwise direction and } z = \text{vertical direction}) \) with a resolution of <1 mm, were averaged, interpolated, and transferred to a regular grid \((x, y, z)\) with defined distances. With this method, a precise 3D digital elevation model was achieved, as shown, for example, in Figure 3. Three topographical stages of the flume bottom were measured: (a) the variable microtopographical characteristics without sediment supply (pre-experimental stage), (b) the surface during sediment transport and ripple movement (experimental stage), and (v) the topography after achieving an equilibrium status following the end of sediment supply (Figure 3; Table 2). The experiment setup with the constant water depth of 0.3 m for \( Q = 4.5 \text{ l s}^{-1} \) over the variable microtopographic roughness elements reflects hydraulic conditions in the river of interest, which are influenced and determined by downstream bathymetric highs—such as riffles or transversal obstructions. In the experiment, this was achieved by using the flap gate of the flume to control the water depth and energy slope.

### RESULTS

Here, results are presented for two different subheadings to test the hypothesis of the study: (a) changes in the surface topography during various experimental stages \((n = 3)\) of laser bathymetry measurements and (b) the results of flow velocity measurements in relation to ripple transport velocities.

### TABLE 1

| Scenario  | VR-I         | VR-II        |
|-----------|--------------|--------------|
| Grain size| \( d_s = 2 \text{ mm (coarse sand)} \) | \( d_s = 4 \text{ mm (fine gravel)} \) |
| Discharge | \( Q = 0.045 \text{ m}^3 \text{s}^{-1} \) | \( Q = 0.055 \text{ m}^3 \text{s}^{-1} \) |
| Specific discharge \( q = \frac{Q}{B} \) | \( q = 0.150 \text{ m}^2 \text{s}^{-1} \) | \( q = 0.183 \text{ m}^2 \text{s}^{-1} \) |
| Slope     | \( I = 0.3\% \) | \( I = 0.5\% \) |
| Water depth| \( H = 0.3 \text{ m} \) | \( H = 0.3 \text{ m} \) |
| Shear wall \((1)\) | \( \tau \equiv 3 \text{ N/m}^2 \) | \( \tau \equiv 5 \text{ N/m}^2 \) |
| Grain Froude number \( Fr^* = \frac{Fr}{Fr_{\text{ref}}} \) | \( Fr^* = 0.30 \) | \( Fr^* = 0.28 \) |

### TABLE 2

| Stage          | Description                                                                 |
|----------------|-----------------------------------------------------------------------------|
| Pre-experiment | Rough surface without sediment cover and sediment supply                    |
| Experimental phase | Surface with moving sediment layer, continuous sediment supply            |
| Postexperiment | Equilibrium status after stopping sediment supply and partially downstream wash out of deposited sediments |
| Reference      | Smooth surface (plywood)                                                   |

FIGURE 3

Visualization of the digital elevation model in the flume in the various sections A, B, and C (1-m length) comparing the scenarios (a) pre-experimental and (b) experimental stages. The coloured labelling determines absolute terrain height of the experimental surface compared with a reference value. Digital elevation model—data of the pre-experiment are presented in the left column, and data of the postexperiments (after establishing of an equilibrium status) are presented in the right column [Colour figure can be viewed at wileyonlinelibrary.com]
3.1 | Changes in surface topography during various experimental stages

Figure 4 shows the cumulative distribution of the bed levels ($z$) of the flume topography acquired by the laser scanning of the experimental flume section. The diagrams show both test series (VR-I and VR-II) for (a) the pre-experiment conditions, (b) during the experimental stage, and (c) after achieving the equilibrium status (postexperiment). During the ripple movement, the microtopographic surface was partially covered with the transported sediments, and consequently, the distribution curves shifted to larger $z$ values. After the sediment supply was stopped, a portion of the addition was eroded, and the bottom of the flume surface achieved an equilibrium status (reduction in $z$ values). In all sections, however, approximately 30 mm of the deeper roughness elements remained permanently filled with the fine bedload sediments (cf. Figure 3). On the basis of the results presented in Figure 4, it can be seen that the thickest layer of the fine bedload concerns section C. In the coarse-grained sections with the highest microtopographical roughness (section A), however, the fine bedload deposits are not that evident; deeper roughness element spaces with $Z = 0$ to 30 mm remain filled, and maximum heights of up to $Z = 100$ mm were documented. The deposited sediment volumes for the various microtopographical sections and the final state are summarized in Table 3. The lowest deposits took place in section A. In contrast, the downstream section C, with comparatively low microtopographic variability, contained volumes of deposition that were approximately five times higher. The bed surface in section B contained obviously fine bedload deposits after the ripples passed this section. Nevertheless, the final state exhibited almost the same quantitative numbers as those of the microtopographic section A (Table 3).

FIGURE 4 Cumulative distribution of the $z$-ordinate of the (a) pre-experimental microtopographical variability and (b) silted surface as well as (c) postexperimental microtopographical conditions (after achieving an equilibrium status of the bed surface (defined in Table 2) [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 (a) Mean flow velocity profile ($V_m$), and (b) turbulence intensity ($T_u$) depict for the various sections ($n = 3$) and various stages of the experiment ($n = 3$) [Colour figure can be viewed at wileyonlinelibrary.com]
3.2 | Flow velocity measurements in relation to ripple transport velocities

As a central part of the presented study and in order to address the formulated hypothesis, the sediment transport dynamics were evaluated by determining the magnitude of the transport velocity of ripples (Table 4). Interestingly, it turned out that the highest roughness in section A exhibited the fastest (e.g., 3.24 m hr$^{-1}$) and section C the slowest transport velocities (e.g., 1.05 m hr$^{-1}$) of the ripples (scenario VR-I). However, all experiments ($n = 6$) exhibited the same results concerning the differences in the downstream transport velocities of ripples (Table 4). This contrasted with the expected impact of hiding effects of higher microtopographical elements on transported sediments; thus, the hypothesis of the presented study had to be rejected.

In Figure 5, the flow velocity and resulting fluctuations of the flows in the form of turbulence and its variance are presented. In the diagrams, the normalized profile height $Z_{n}$ ($z$/water depth $H$) is shown, where $Z_{n} = 0$ at the bottom of the flume and $Z_{n} = 1$ corresponds to the water level (plotted to a maximum of $z/H = 0.4$). The analysis of these three flow-related parameters should allow for the identification of the driving factors of the ripple transport velocity. Figure 5a presents the mean velocity profile over the variable microtopography sections in the (a) pre-experimental, (b) experimental, and (c) postexperimental stages (cf. Table 2). Interestingly, in addition to the similarities in magnitude, the second largest velocity gradient (from the bottom to $z/H = 0.4$) was recorded in section A (high microtopographic variability), and the smallest was recorded in section C. Furthermore, the mean velocity distribution was similar in sections B and C; section A contained approximately the same gradient but with slightly higher velocities (<0.1 m s$^{-1}$) than the two other sections B and C (Figure 5a).

| Flume sections | Experimental stage (L/m$^{2}$) | Final stage (L/m$^{2}$) | Difference (%) |
|----------------|-----------------|-----------------|----------------|
|                | VR-I             | VR-II            | VR-I          | VR-II          | VR-I | VR-II |
| A              | 9.6              | 13.2             | 5.5           | 9.0            | -43  | -32   |
| B              | 19.8             | 18.2             | 4.7           | 10.5           | -76  | -42   |
| C              | 57.5             | 54.7             | 27.5          | 43.8           | -52  | -20   |

Abbreviation: L, litre.

4 | DISCUSSION

In recent years, the roles of turbulence and fluctuating parameters, such as instantaneous velocities, pressures, and drag and lift forces, in terms of sediment transport have been widely acknowledged (Celik, Diplas, & Dancey, 2013; Diplas et al., 2008; Schmeeckle, Nelson, & Shreve, 2007; Sindelar & Smart, 2016). In physical laboratory studies, analyses of sediment transport dynamics (e.g., incipient motion, delta formation, and deposition) have been conducted based on critical turbulent forces and impulse (Celik et al., 2013), critical local approach velocity (Schmeeckle et al., 2007), and grid turbulence imposed on the flow (Wan Mohtar & Munro, 2013). However, the contributions of turbulent processes are not reflected in the commonly used sediment transport formulas. In addition, they were derived from flume experiments and often correctly fail to predict sediment transport rates at the 1:1 scale. In the presented study, we implemented a 1:1-scaled physical experiment with a focus on the impacts of microtopographic roughness on small-scale flow fluctuations and sediment transport dynamics. The results very clearly showed the impact of turbulence and especially the variability in turbulence on sediment transport dynamics in the form of ripple transport velocity. Although the microtopographical characteristics caused a minor deviation in the mean flow velocity distribution of part A in the flume experiment (compared with B and C with similar numbers; Figure 5), the turbulence intensity ($T_{u}$), resulting in higher flow velocity peaks at the near bottom, could be clearly identified as the driving force of the transport velocity of the ripples of the various roughness elements ($n = 3$). This is in line with Biron, Robson, Lapionte, and Gaskin (2004) who suggest the turbulent kinetic energy, that is, the sum of the squared turbulence intensities, as an estimate for bed shear stress. However, these findings are in contrast to the assumption that coarser grains (increased

The near-bottom flow velocities, however, varied from 0.53 m s$^{-1}$ (section A) to 0.43 m s$^{-1}$ (section B) and 0.31 m s$^{-1}$ (section C).

Furthermore, Figure 5b shows the turbulence intensities of the local flow velocities ($T_{u}$ [%]) and exhibits very low values (about 7%) and almost no variability for section C from the flume bottom to $z/H = 0.4$. Comparing the relative differences between the microtopographical sections (Figure 6) in terms of their mean flow velocity (Figure 5a) and turbulence intensity ($T_{u}$), Figure 5b reveals that significant differences were not only observed for the near-bottom areas. In section A, high variations in the velocity profile were detected up to $T_{u_{max}}$ = approximately 55%; in section B, $T_{u_{max}}$ = approximately 23% or 12% (after achieving equilibrium status); and in section C, $T_{u_{max}}$ = approximately 10% or 5% (after achieving equilibrium status). In the smooth surface section $T_{u_{max}}$ was approximately only 1%. Thus, based on the conducted experiment and comparing the ripple movements to the various parameters of Figure 5, the turbulence intensity ($T_{u}$) resulting in higher flow velocity peaks at the near bottom, was detected as the driver for the transport velocity of ripples, in contrast to the expected hiding impact of larger microtopographical elements.
FIGURE 6  Visualization of the different stages of the experiment ($d = 2$ mm) showing the bed surface for different time periods; flow direction from left to right, various sections (A–C) highlighted [Colour figure can be viewed at wileyonlinelibrary.com]
microtopography) induce hiding effects (cf., e.g., Sutherland, 1992; Wu et al., 2000) and thus reduce sediment transport velocity \( (v_t) \). Thus, the hypothesis of this study could not be proved.

Furthermore, Stoesser, Braun, García-Villalba, and Rodi (2008) stated that the geomorphological origins of ripples and dunes are believed to lie in the presence of coherent structures, which are the driving mechanisms for sediment transport and thus for channel processes. This finding cannot be directly supported by the presented study, as only turbulence (variability) and not coherent turbulent structures have been analysed. Per their definition, turbulent flows are complex multiscale and chaotic motions that must be classified into more elementary components, which are referred to as coherent turbulent structures. Coherent flow structures are vortex systems that vary in size and time and are key features for understanding the aspects of turbulence production and turbulence transport (Stoesser et al., 2008). Hence, using the same experimental setup with particle image velocimetry (PIV) technology to visualize and determine coherent structures (cf. Schobesberger, Lichtneger, Hauer, Habersack, & Sindelar, 2018) to validate the impact of coherent structures on ripple dynamics is required.

Natural fluctuations in bedload transport (Bunte, 1992; Cudden & Hoey, 2003; García, Laronne, & Sala, 2000; Habersack, 2001; Paige & Hickin, 2000) due to the high quantity of influencing parameters (e.g., flow turbulence, bed topography, sorting, hiding, and surface heterogeneity, such as bedforms, bedform migration, flow discharge and flow hysteresis, and sediment supply) are well known. Natural fluctuations lead to the stochastic nature of bedload transport (Einstein, 1937; Hamamori, 1962; Millar, 2005; Turowski, 2010) as well as the initiation of bedforms over plane beds (cf. Lopez & Garcia, 2001). Moreover, the effects of different flow conditions on velocity profiles above homogenous rough beds have been examined in several studies (e.g., Nowell & Church, 1979; Wohl & Ikeda, 1998), but few have investigated the differences in the spatial characteristics as flow conditions change (e.g., topographic variability; Buffin-Bélanger, Rice, Reid, & Lancaster, 2006). Additionally, the present study could also determine the role of boundary conditions in the form of microtopographical variability on ripple dynamics. Although all three sections of flume experiments (A, B, and C) are labelled in the rivers of the Bohemian Massif as plane bed, the variability in absolute roughness height had a clear impact on the transport velocity, and it is thus an important aspect that must be considered in sediment transport modelling. The findings, however, somewhat contrast with the conclusions of Clifford (1996), who suggested that the variations in mean velocity and turbulence intensity are lower when the relative roughness is high.

From a sediment management perspective, an important interpretation of the derived results is possible and required. The variability in the microtopographic roughness used here reflects the different stages of sediment conditions and bed surface development in rivers. In particular, scenario C contains almost smooth plane-bed conditions, similar to the topographic features of the dune–ripple type (Montgomery & Buffington, 1997). Here, the lowest transport velocities occurred due to the lowest variability in turbulence. Thus, this means that for the problematic situation of an increased sediment supply of fine bedload (cf. Hauer, 2015), deposits with increasing grain size \( (d = 1-10 \text{ mm}) \) lead to a lowering of the transport velocity of fine bedload transport in the form of ripples through these sections (compare also with the deposition volumes of Table 3). Thus, this process accumulates the problems of increased fine bedload deposits (cf. Figure 1c), with all of their negative consequences for aquatic ecology (Leitner et al., 2015), as well as flood security aspects (Hauer, 2015). The higher the stage of accumulation is and the lower the microtopographical variability is, the lower the transport rates are.

Moreover, in a one-dimensional hydrodynamic numerical sediment transport model, the results of the flume experiment were implemented (Holzinger, 2015)—It turned out that for an annual flood event at the Aist River, the transport distance of ripples decreased by 80% with the decrease in microtopographic variability from scenario A to scenario C. These are important points of discussion for the application of sediment management in such river systems, as there is a strong need for mitigation. For the discussion of mitigation measures, a flume experiment could also be used to determine that a reduction or end of sediment supply would lead to the significant improvement of habitat properties (heterogeneity) of the riverbed. This, however, would take longer in the river sections that already contain a high degree of accumulated fine bedload (dune–ripple type) compared with the stretches where the microtopography is exposed on the surface, creating local turbulence. Thus, artificially deposited roughness elements such as boulders may lead to an increase in turbulence and especially variance in turbulence, with positive impacts on the velocity of downstream sediment transport. These issues are important for future management where the possibility of self-dynamic improvement/remediation by means of measures in the catchment area (e.g., the reduction of material input due to land use change) is targeted.

5 | CONCLUSIONS

The 1:1-scaled flume experiment on ripple dynamics exhibited the clear relationship between microtopographical variability and ripple dynamics. Although the expected impact of hiding and thus the expected reduced transport velocities were not observed, the results showed, in all repetitions of the experiment \( (n = 3) \) with variable grain sizes \( (n = 2) \), that the higher the microtopographical variability of the river substrate is, the higher the turbulence intensity is, and the higher the transport velocities of ripples are. These findings include some important implications for river management; namely, that river sections with accumulation rates of fine bedload are prone to the accumulation of sediments as downstream transport decreases over smooth ripple–dune morphologies. However, there is still a lack of understanding of how turbulence characteristics change at different scales and, subsequently, how turbulent processes control sediment transport and particle entrainment in natural rivers. Physical models are typically scaled models because of space restrictions and limitations regarding the maximum available discharge. However, in
medium- and small-scale models, bedload transport and incipient motion processes are not modelled correctly. Thus, there is still a need for large scale or 1:1 experiments under controlled conditions.

ACKNOWLEDGEMENTS

The financial support by the Austrian Federal Ministry for Digital and Economic Affairs and the National Foundation of Research, Technology and Development of Austria is gratefully acknowledged.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.

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How to cite this article: Hauer C, Lichtneger P, Holzinger J, Schobesberger J, Habersack H, Sindelar C. Ripple dynamics over various microtopographical roughness elements and their implications for river management. River Res Applic. 2019;35:601–610. https://doi.org/10.1002/rra.3437