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Channel bed adjustment of a large sand-gravel bed river to an intermitted sediment sink

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ABSTRACT: A large mixed-bed alluvial stream (Vereinigte Mulde near Bitterfeld, Sachsen-Anhalt, Germany) with a riffle-pool bed was investigated for bed form morphodynamics. The study focused on flood-associated processes. It is based on bathymetric monitoring of selected channel reaches and systematic bed material sampling. Evaluation increased the understanding of undulating channel beds, their maintaining processes and channel bed adaptation to a sediment deficit. A sediment sink divides the stream into an undisturbed upstream and a disturbed downstream reach. Channel changes downstream of the sink were for the first time systematically surveyed and analysed. Amplitudes of longitudinal channel profiles proved to be a significant morphometric parameter of the surveyed type of stream. High bed amplitudes indicate pronounced scour of pools and fill of riffles during floods. Maximum aggradation of riffles and degradation of pools lagged behind peak discharges. During these periods the channel bed is mobile. With flows falling under a threshold value, bed amplitudes decrease and bed mobility is restricted to downsloping stretches of the channel bed. These changes are closely related to flood events. Higher values of bed amplitudes were permanently observed at the downstream reach and are interpreted as an indicator for the sediment deficit there. The results of detailed morphometric analysis show that permanent degradation of the disturbed, downstream channel bed affects the downstream pools selectively. Riffles appear to be unaffected. An approach to estimate bed stability based on the comparison of the two reaches is introduced. It corroborates the survey analysis and explains that an apparent general channel incision downstream is pretended by a larger wetted cross section due to a smaller river gradient. The findings give rise to the hypothesis that form roughness is increased by greater bed amplitudes, be it periodically, flood-associated or permanently induced by a sediment deficit.

Keywords: Channel bed adjustment, Form roughness, Riffle-pool dynamics, Alluvial river, Sediment deficit

1 INTRODUCTION

Channel bed adjustment to sediment deficit is not only a question of stream management but also a question of scientific concern. Within the scope of a project to monitor and analyse flood-associated bed morphodynamics (riffle-pool maintaining processes) the contribution focuses on the question whether there is evidence for a bed degradation under sediment deficit conditions.

A permanently flooded former mining pit divides the stream into an undisturbed upstream and a disturbed downstream reach since 1975. Estimated 80% of the fluvial load is deposited in the reservoir. The disturbed, downstream reach is expected to be incised and degrading.

This expection is fed by a greater channel depth downstream as the scatter of width and depth data shows (Figure 1). The data were compiled by geodetic surveys during comparable flows. The range of width values shows no discernible difference between the two reaches, but depth is generally and clearly greater downstream. However, there have been no systematic studies on change and stability of the affected downstream reach.

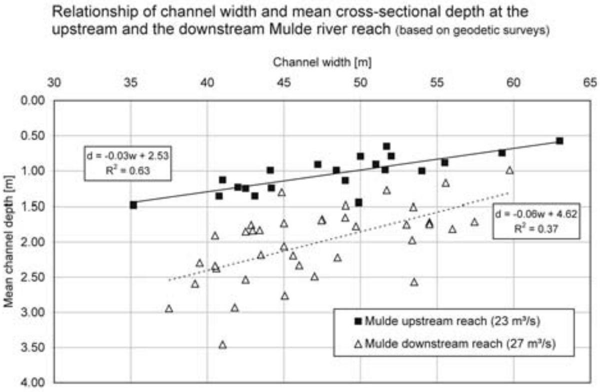

Figure 1. Scattergram of cross-sectional width and depth data.

2 THE INVESTIGATED RIVER

The Mulde river is a large meandering floodplain river and one of the large tributaries of the Elbe river in Germany (width 40 – 60 m, catchment area 6200 km^2, MQ = 64 m^3s^{-1} at gauge Bad Düben, slope 0.018 – 0.029%, bed material medium sand to coarse gravel).

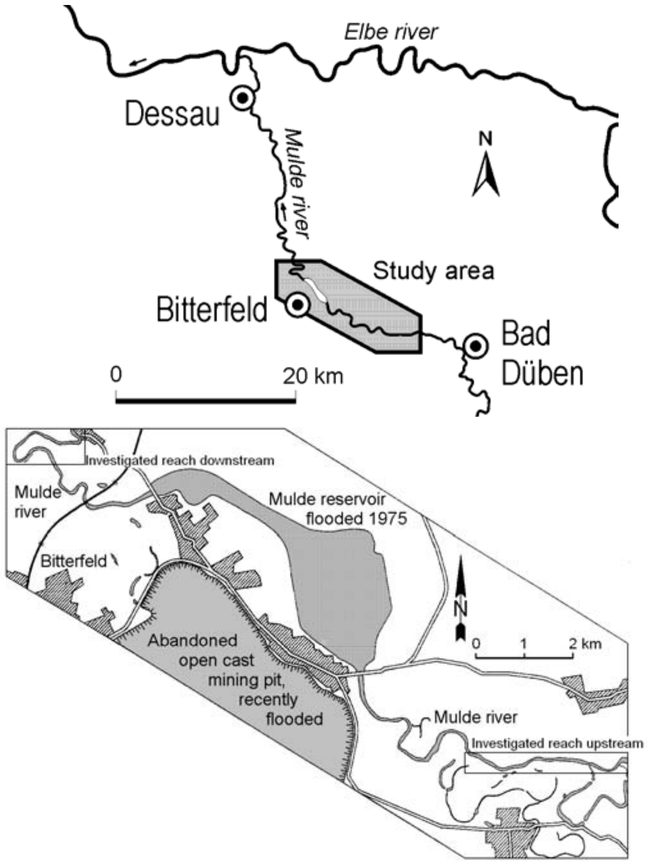

Figure 2. Location and overview of the study area.

The difference in river gradients is caused by weirs along the downstream reach that cut the drop of the river from 18.30 m to 8.30 m on a 42 km long reach. The floodplain consists of 1 - 3 m loamy Holocene deposits over Pleistocene gravel.

Human impact on the Mulde river and its floodplain have been and still are comparably limited. The Mulde river is unsuitable for navigation and there was only sporadic maintenance and reinforcing of the banks.

However, there has been significant man-made impact on the fluvial system in the highly industrialized region close to Bitterfeld (Figure 2). An artificial lake (Mulde reservoir) formed in 1975 when an abandoned open-cast mining pit was flooded by a permanent diversion of the river. The reservoir is a sediment sink with a total volume of app. 100 mio. m^3 which is reduced by an annual deposition of app. 80% of the solid load equalling 400000 m^3.

3 METHODS

Flood-associated bed changes were monitored systematically with hydrographic equipment (echosounder and realtime differentially corrected NAVSTAR Global Positioning System) comprising subsequent stages from antecedent low stages over almost bankfull to falling stages. They comprised longitudinal center profiles along two selected reaches upstream (river mileage 60,450 m to 57,030 m, Figure 3) and downstream (40,300 m to 36,570 m, Figure 4) of the Mulde reservoir as well as cross-sectional surveys at selected riffles at 58,650 m and 38,236 m and pools at 58,500 m and 38,048 m. River mileage in Meters, decreasing from source to mouth, is used as a spatial reference for bed form and sampling locations.

Determining absolute, geodetic water level altitudes and thus realtime water level gradients was beyond the precision of the employed GPS-equipment. Water depth values refer to water level generally and have to be considered to be relative.

Quasi-equidistant geodetic surveys of channel cross sections at low flows (external data) were evaluated along the reaches that were covered by own longitudinal surveys. Their evaluation yielded high-precision river gradient data as an input parameter for hydraulic estimations. Official discharge data were provided by a official gauge nearby (Bad Düben).

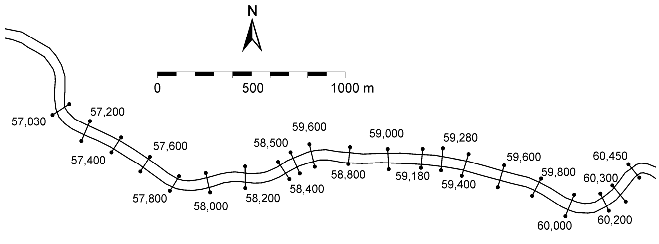

Figure 3. Cross sections of the investigated upstream reach.

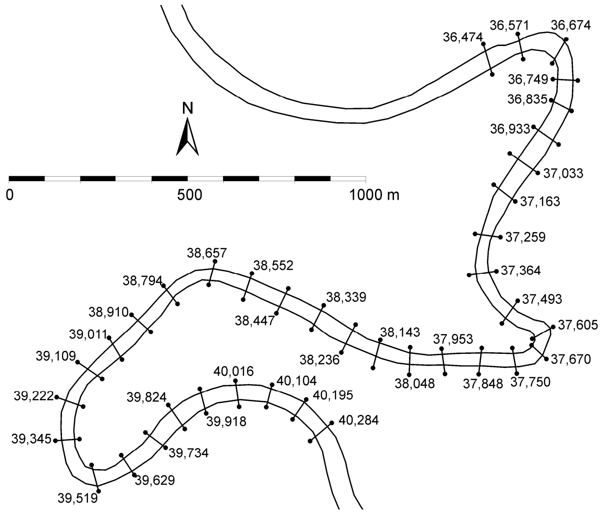

Figure 4. Cross sections of the investigated downstream reach.

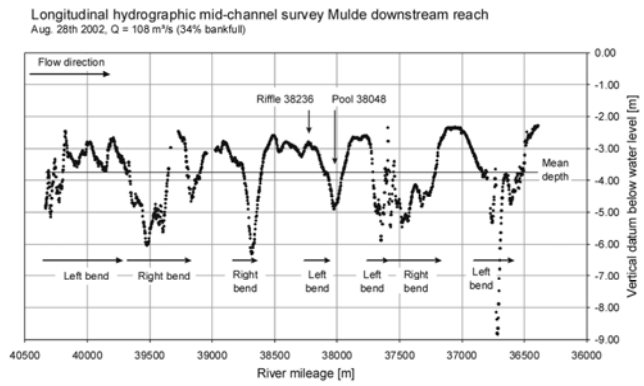

Figure 5. Longitudinal section of disturbed downstream Mulde river reach.

Bed material samples were collected simultaneously with hydrographic surveys mainly from riffles' tops (riffles 58650 and 38236), pools' bottoms (pools 58500 and 38048). The sampling technique, employing a sediment scraping device, provided approximately 20 kg of sample weight for each sample selectively from upper bed layers.

Realtime navigation both for bathymetric surveys and bed material sampling was strongly aided by GPS in realtime differential correction mode. The hydrographic equipment is described in closer detail by Vetter (1999) and Vetter (2008).

Particle size D and grain size distributions, mean channel depth d_m, channel width w, hydraulic radius r_{hy}, mean flow velocity v_m, wetted perimeter P, cross-sectional area A, mean cross sectional shear stress τ, dimensionless shear stress or Shields mobility number Θ were collected or calculated synchronously in order to monitor the riffle-pool sequences consistently with process-associated changes.

The undulating riffle-pool topography is parameterised by the standard deviation of water depth along representative center profiles. In this study 3.5 km upstream and 3.8 km downstream comprising 6 and 7 riffle-pool sequences, respectively, were surveyed (Figure 3, 4, and 5).

Mean bed altitude is a first order polynomial regression of geodetic bed altitudes. Richards (1976) denoted it as zero-line. Removing this trend from the data leaves riffles as positive and pools as negative anomalies in a quasi-rhythmic alignment acc. to Richards (1976). The standard deviation of the detrended dataset is a measure for the height of the riffles above and the depth of the pools below the zero-line. In case riffles are aggraded and pools are scoured, the standard deviation increases. Bathymetric datasets refer to water level which is parallel to the zero-line in case of steady-state conditions. For this reason bathymetric data need no detrending.

4 RESULTS

4.1 *Flood stage bed morphodynamics*

Figure 6 displays the flood-associated changes of bed undulation intensities. Upstream values are clearly smaller than downstream during low flows (0.42 vs. 0.86 m) in Oct. 2001, approaching the downstream values during high stages (0.83 m vs. 0.90 m) at Feb. 6th 2002 and decreasing again towards the pre-high stage values after the flood (0.72 m vs. 0.84 m) in March and April 2002. The development is similar in February 2004.

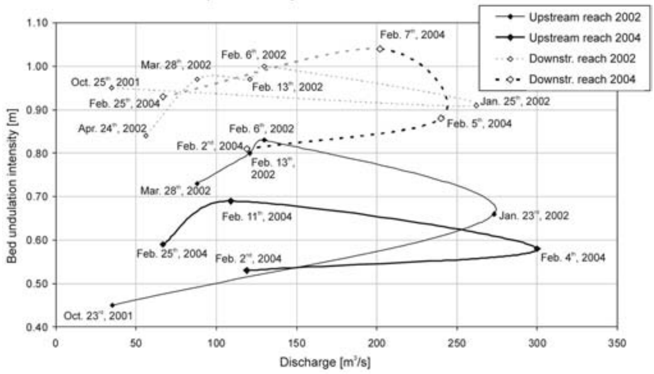

Figure 6. Bed undulation intensity vs. discharge at the Mulde river during floods.

Mean bed undulation intensities generally increase during the course of floods. A counter-clockwise hysteresis is observed in all cases. The pre-peak increase is generally less than the post-peak increase. After peak flows the bed amplitudes continue to increase. It has to be noted that highest monitored flows are not necessarily flood peaks but highest monitored discharges. Only at Feb. 4th 2004 was a peak flow monitored. Increase of the bed undulation intensity during falling flows is greater than during rising flows.

After peaks flows at a discharge of app. 41% of the bankfull discharge Q_{bf} (= 320 m^3s^{-1}), bed amplitudes start decreasing. This threshold discharge for attenuating bed undulations is repeatedly observed. In February 2004 at the lower reach, the maximum bed amplitude appears to have been reached at $Q = 200\ m^3s^{-1}$. Since no surveys were performed between Q = 200 and 70 m^3s^{-1} the development during falling flows between Feb. 7th and Feb. 25th 2004 is not known on the basis of data. It may well be assumed that after Feb. 7th 2004 ($Q = 200\ m^3s^{-1}$) the bed undulation intensity increased further than the interpolation in Figure 6 suggests.

It is further assumed that bed form accentuation starts at approximately the same threshold discharge. Due to the generally short period of stage rise this assumption could not be corroborated by monitoring results. Interpolation between Oct. 23rd 2001 and Jan. 23rd 2002 is misleading because there is no continuous rise of the bed undulation intensity during the whole low flow period but only during rising flows in late January 2002.

Bed form accentuation is inevitably linked to sediment mobility. Only when bed material is mobile throughout all subsequent stretches can pools be degraded and riffles be aggraded. Mobility then includes the upsloping stretches from pools to riffles which may be as steep as 3% (Figure 5). This implies that the threshold discharge for mobile bed morphodynamics ($Q = 41\%\ Q_{bf} = 131\ m^3s^{-1}$) equals the critical discharge for bed form maintenance. If bed form accentuation starts with bed mobility, Q_{cr} for the maintenance of riffles and pools equals the critical discharge for mobile bed.

Beds remain mobile during falling flows until Q becomes less than Q_{cr}, as the large post-peak increases of bed undulation intensities suggest. The long duration of the post-peak discharges obviously is a stronger control for bed form accentuation than a short occurrence of high stages. There is apparently no difference of the value of Q_{cr} between the undisturbed and the disturbed reach.

The large difference of bed amplitude s between upstream and downstream values is interpreted as morphometric evidence for channel bed adjustment to the sediment deficit downstream. Above critical discharge, bed material is removed from the pools if available and transferred to the riffles. Given a sufficient sediment availability, pool scour and riffle aggradation is great resulting in a great difference between low stage and flood stage bed amplitudes and vice versa. If less material is available both pool scour and riffle fill are less pronounced. Material availability thus controls the high flow bed form accentuation and subsequent low flow attenuation. According to this analysis, the disturbed Mulde reach exhibits a flood stage morphometry even at low flows because it has been depleted of much of the transportable sediment. It is assumed that the major removal occurred during few floods after the Mulde reservoir came into operation.

At falling sub-critical flows (< 41% Q_{bf}) accentuation of bed forms is reversed into attenuation, riffles are being degraded, pools are being aggraded and, as a consequence, bed amplitudes decrease. During this phase, bed mobility is restricted to the downsloping stretches from riffles to pools. The term of disconnected mobility appears appropriate for this phase. Post-mobility attenuation starts at both reaches below the same threshold.

4.2 *Medium term change of selected bed forms*

Figure 7 shows the change of morphometric parameters of a riffle and pool cross section between the years of 1996 (geodetic survey) and 2002 (hydrographic survey). Visual evaluation of cross sections yielded differences only for the pool and only on flood-event base but not for the period from 1996 until 2002. At the riffle cross section no trend or difference was discernible either on the event scale or on the medium term (1996 until 2002).

Since flood-associated changes of morphometry exceeds medium term rates of change, the datasets need to be strictly comparable. Discharge is not the only measure by which stages should be referred to each other, but also by the history of preceding floods. Due to the lag of morphometric changes behind flows, morphometric parameters of cross-sections may still change at low flows under conditions of disconnected mobility. In this of case flood-associated changes may veil or pretend medium-term changes.

The comparison shows no degradation at the riffle cross section during the monitored time interval. In case of the pool, there is a total scour of 18 cm in six years which equals an average scour of 3 cm/year. Water level altitude decreased 1 cm/year in average. This is in fair accordance with the difference in mean longitudinal water depths upstream and downstream of the Mulde reservoir of 1.25 m. If this is considered the total change between 1975 and 2002, the average degradation rate would be 4.6 cm/year.

In 1996, a long period of low flows preceded the survey whereas in 2002 active flows occurred only 6 weeks prior to the survey. Beside the smaller discharge, this may account for the apparently shallower riffles in 2002.

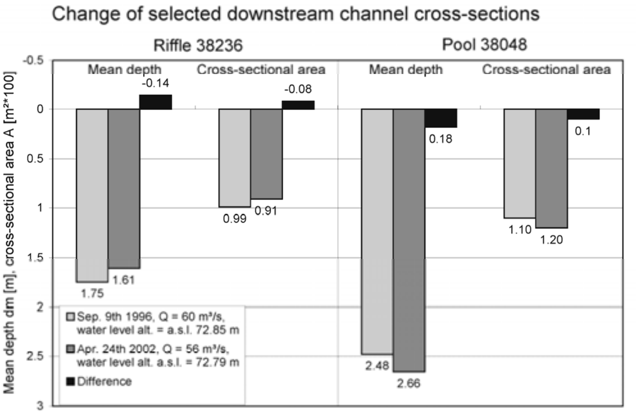

Figure 7. Change of selected channel cross sections from 1996 to 2004.

4.3 *Long term change of longitudinal morphometry*

Longitudinal hydrographic surveys of stretches of 3.5 and 3.8 km length with a bathymetric sampling resolution of few meters were evaluated in respect to channel morphometry changes. Figure 8 displays frequency distributions of high stage center channel depth values. Mean depth values of both bedforms and channel stretches are marked. It is assumed that the upstream bed represents undisturbed morphometry.

Upstream and downstream distributions are quite similar among themselves but differ from each other in three aspects:

- Downstream (disturbed) distributions are shifted to greater depths with an offset of app. 0.5 m.
- Downstream distributions are less peaked.
- Downstream distributions are broader, extended at depths greater than 5.70 m.

The rightward offset of the downstream distributions accounts only for the minor part of the extension. Comparing disturbed beds reduced by this offset, only an average downstream (disturbed) channel deepening of 0.1 – 0.2 m remains. However, there is an obvious selective scouring of the pools. This is consistent with previous findings and is explained with the observed riffle-pool dynamics.

After accentuating flows, bed sediment that was temporarily stored on riffles is removed into the pools, re-aggrading the pools to a limited extent. Re-aggradation is determined by the availability of disposable sediment. Under sediment deficit conditions the extent of re-aggradation is reduced and, as a consequence, high stage morphometric characteristics are preserved throughout low stages. Riffles are not affected by degradation since they are degraded to approximately the same degree to which they were aggraded at flood stages.

4.4 *A combined hydraulic-morphometric approach to estimate bed stability*

In order to consider the effect of the smaller river gradient at the downstream reach, an approach was developed that integrates the continuity equation, the Darcy-Weisbach equation and stage-dependant morphometric parameters of both channel reaches. As a prerequisite it is assumed that the upstream reach is in an equilibrium state and does neither aggrade nor degrade on the long run.

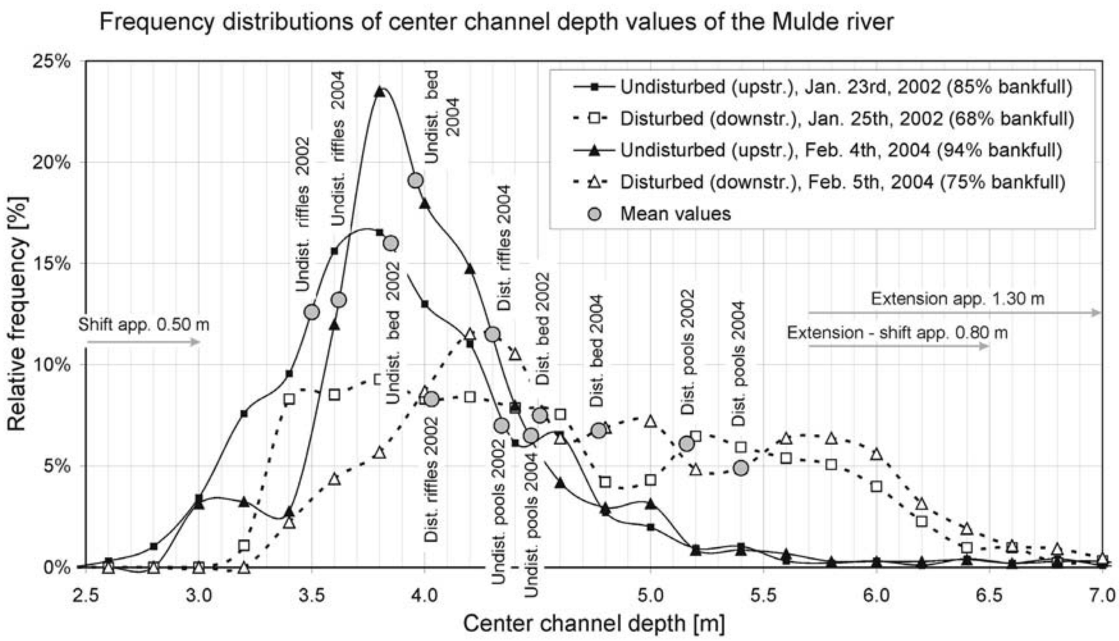

Figure 8. Frequency distributions of center channel depths

In the Darcy-Weisbach equation, v_m is substituted according to

$$v_m = \frac{Q}{A} = \frac{Q}{d_m \cdot w} \tag{1}$$

where
v_m is mean flow velocity
Q is discharge
A is cross sectional channel area
w is channel width and
d_m is mean channel depth.

For every reach and flow follows that

$$Q^2 = 8g \cdot R \cdot S \cdot w^2 \cdot d^2_m \cdot \lambda^{-1} \tag{2}$$

where g is acceleration due to gravity, R is the Hydraulic Radius, S is energy line gradient, λ is the Darcy-Weisbach friction factor.

For every reach and flow stage individual equations based on eq. 2 are formed. For equal flows the equations for the reaches may be equaled. After further transformation it follows that

$$\frac{S_d}{S_u} = \frac{w_u^2 \cdot d_{m,u}^2 \cdot R_u \cdot \lambda_d}{w_d^2 \cdot d_{m,d}^2 \cdot R_d \cdot \lambda_u} = SR_{crit} \tag{3}$$

where
S_u, S_d is the energy line gradient upstream, downstream resp. (from geodetic surveys), S_u = 0.029%, S_d = 0.018%,
w_u, w_d width upstream, width downstream resp.,
$d_{m,u}$, $d_{m,d}$ mean water depth upstream, downstream,
R_u R_d hydraulic radius upstream, downstream resp.,
λ_u, λ_d is the Darcy-Weisbach friction factor upstream (λ_u = 0.04) and downstream (λ_d = 0.05) resp. calculated by inserting field data into the Darcy-Weisbach formula.

In order to simplify the relationship, constants S_u, S_d, λ_u and λ_d may be summarized as SR_{crit} according to

$$\frac{S_d \cdot \lambda_u}{S_u \cdot \lambda_d} = SR_{crit} = 0.05 \tag{4}$$

Given the gradients, friction factors and the assumption, that the upstream reach is in grade, SR_{crit} is supposed to be 0.50 if the downstream bed is stable. SR_{crit} values < 0.50 indicate bed instability downstream.

The morphometric parameters d, R, w and A are measured by or derived from hydrographic surveys at synchronous stages. Values of Q were provided by the official gauging station (Bad Düben).

The ratio was calculated for three observations. Table 1 lists the results.

Table 1. Stage dependant values of gradient ratios for friction factors λ_u = 0.04 and λ_d = 0.05.

Date Discharge	Feb. 6^{th} 41% Q_{bf}	Feb. 13^{th} 38% Q_{bf}	Mar. 28^{th} 27% Q_{bf}
Riffle	0.51	0.55	0.43
Pool	0.36	0.40	0.44

Critical threshold is SR_{crit} = 0.50

Riffle values are greater than pool values except on March 28^{th}. The other riffle values indicate stability whereas all pool values are clearly smaller than the threshold. This confirms the morphometric evaluations. The values of March 28^{th} are contradictory in so far that there is no significant difference between riffle and pool and that even the riffle bed is indicated as being instable. On March 28^{th} discharge was as low as 27% Q_{bf} on the falling limb of a long flood season. Stable conditions are expected to occur at that very stage. Although results are not perfectly consistent the approach is expected to be generally applicable, because it integrates commonly accepted hydraulic laws and data from real systems. It calls for testing a larger record of appropriate data.

4.5 *Interpretation of the results*

Greater bed amplitudes occur both during high flows and under sediment deficit conditions. This suggests on the one hand side that during late floods sediment availability decreases. On the other hand form friction increases as indicated by the bed undulation intensity. Similar suggestions were made by Yang (1971) who compared meandering with undulating bed topography, Keller & Melhorn (1978) who denoted the riffle-pool topography as vertical meandering. Miller & Wenzel (1985) interpreted non-uniformity of flow as an element of friction and Thompson (1986) assumes the same processes for the generation of riffle-pool sequences and meanders. Meanders are long term forms without a mechanism for flexible short-term adjustment. The riffle-pool topography may adjust during floods, which is within days. The mechanism of generating higher friction by increased bed undulation can be a short term adaptation to an imbalance between driving and resisting forces in a gravelbed fluvial system. In case of a permanent disturbance the system attains another state indicated by a higher range of form friction. Variability within this range is caused by long floods with mobile bed.

The standard deviation of bed amplitudes was first proposed by Squarer (1970) as a parameter for form friction. A number of authors, among them Aberle (2002), De Jong & Ergenzinger (1998), Dittrich (1998), Karim (1995), Smart et al. (2004) confirmed the applicability of standard deviations of bedform altitudes or related measures. Ergenzingers's roughness coefficient K3 "represents vertical bed height differences derived from three lateral measurements at 10 cm intervals along the cross section" (Ergenzinger, 1992, 422). It is the greatest difference of a floating set of three adjacent water depth measurements and correlates closely with the standard deviation of the same dataset. Lee & Ferguson (2002) summarised that bed form amplitudes as well as Ergenzinger's (1992) K3 are appropriate measures to parameterise roughness by morphometric properties. Although the cited studies span a number of years, different types of channels and bedforms, there is a broad consensus that form roughness is related to bedform amplitudes. In case of gravel-bed rivers this is the bed undulation intensity of the riffle-pool sequence. However, the standard deviation was not applied to macro-scale bedforms to large gravel-bed rivers so far nor has there been an attempt to quantify it for further application.

5 SUMMARY AND OUTLOOK

Morphometric evidence suggested degradation of the disturbed downstream channel bed as a consequence of a severe reduction in bed load since 1975. The preliminary findings were improved by systematic analysis of morphometric and hydraulic data. Firstly, a certain degree of apparent incision is due to a smaller bed gradient downstream. Secondly, degradation is restricted to pools according to the study. Thirdly, main pool degradation is hypothesized to have occurred during a limited number of floods after the Mulde reservoir came into effect, and has later decelerated to lesser rates. This is consistent with flood-associated riffle-pool dynamics where most of the pool scour occurs during high flows. Fourthly, high longitudinal bed amplitudes were observed particularly during late flood stages (Vetter 2008, Vetter 2010) and under sediment deficit conditions. This strongly suggests that an increased bed amplitude is an adaptation to reduced sediment input. In the disturbed downstream channel, the flood bed is preserved during low stage periods due to the sediment deficit. Hence, it is hypothesised that sediment starving conditions also may occur in equilibrium channels during late floods as well, and that macro-bed undulations constitute a major component of form roughness. Correlation between bed undulation intensity and overall roughness appears promising. This hypothesis should be tracked in further research.

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