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Restoration of the Eggrank bend at the Thur River in Andelfingen ZH

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ABSTRACT: Restoration of the Eggrank Bend at the Thur River near Andelfingen (Canton of Zurich, Switzerland, $HQ_{100} = 1400\,\text{m}^3/\text{s}$) comprises five micro groins of 30 to 50 m length as well as a snail shaped groin. Micro groins are overflowed already at low flow conditions and allow reduction of flow velocities at the outer bank as well as flow diversification. In addition, the inner bank slope was regraded, deadwood was introduced and a new gravel embankment was created upstream of the bend. To gather a maximum of knowledge and conclusions about the functionality and efficiency of the restoration measures at the Eggrank Bend, intensive monitoring is carried out. Monitoring campaigns contain 2D flow velocity recording by Large-Scale-Particle-Image-Velocimetry (LSPIV) from drones and measurement of flow velocities and cross section geometries by 3D Acoustic-Doppler-Current-Profiler measurements (ADCP). First results show a reduction of the bend scour depth from initially around 3.6 m for mean discharge conditions to almost zero. The main flow is not following the outer bank any more but is more equally distributed over the entire cross section.

1 INTRODUCTION

In the framework of the flood mitigation and river restoration project “Hochwasserschutz und Auenlandschaft Thurmündung” the Eggrank Bend of the Thur River in Andelfingen, Switzerland, was restored during winter 2014/15. With the objective of increasing flow diversity and hence morphological variability, an innovative approach consisting of a river bed geometry adaption combined with micro groins was pursued.

Initially, this channelized bend was characterized by unnaturally high flow velocities, a bad connection between the river and the adjacent lands and a lack of flow structuring elements. The river reach presented a pronounced bend scour with flow depths up to four meters at low water discharge. However, due to high flow velocities and the lack of sheltering zones fishes were either drifted already at mean discharge ($MQ = 47\,\text{m}^3/\text{s}$) or the animals had to spend a lot of energy to keep their position.

The excessive flow velocities along the thalweg were caused mainly by the realization of the Thur river correction projects in the past two centuries. The initially meandering river was straightened and restricted to a uniform river with of 50 m, which already lead to an increased mean flow velocity. In the area of the Eggrank Bend, the corrected Thur River enters the very sharp 110°-bend (mean radius $r = 125\,\text{m}$, Figure 1) directly after a 400 m long straight river reach and without transition bend. The main flow upstream of the bend was located already in the center of the cross section and shifted quickly to the relatively smooth protected outer bank. This situation got worse with a river widening in the 1990s, leading to a rising of the river bed and consequently increased bed slope and flow velocities in the upstream reach.

Figure 1. Aerial photo of the Eggrank Bend at mean discharge situation before restoration.

To achieve an ecological enhancement considering the high flood discharges ($HQ_{100} = 1‘400\,\text{m}^3/\text{s}$ at the Andelfingen water level gauge (Horat & Scherrer AG 2000)) the increased structural diversity had to be combined with a reduction of flow velocities.

2 ADAPTION OF RIVER BED GEOMETRY

Wherever possible, ecological enhancements in the restoration project “Hochwasserschutz und Auenlandschaft Thurmündung” should allow and facilitate a

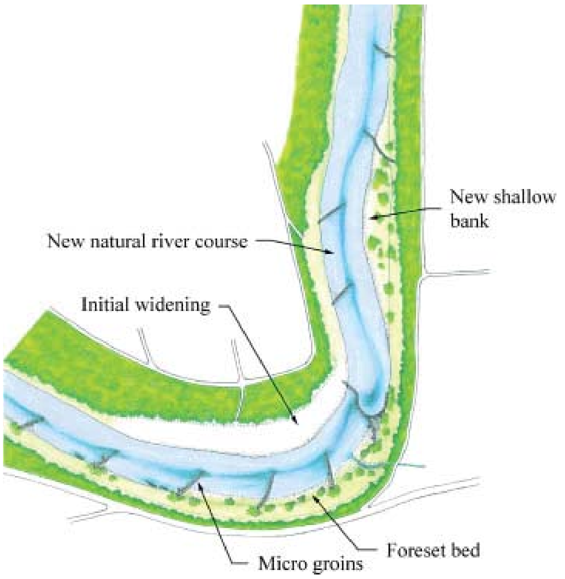

Figure 2. Main elements of the Thur River restoration project at the Eggrank Bend, construction project stage (engineering consortium Bachmann, Stegemann + Partner AG, Staubli, Kurath & Partner AG 2013).

natural dynamic development of the river which generally requires unprotected river banks. However, removing the existing riprap structure at the outer bank of the Eggrank Bend was no feasible option as no change of the road pathway next to the shoreline was allowed. Therefore, constructive measures for river restoration were selected and planned.

2.1 *Initial widening at the inner bend*

The inner bank of the Eggrank Bend was characterized by gravel banks frequented by local tourists for bathing in summer. This recreational use had to be preserved or even improved to concentrate human presence on this particular spot and thus relieve other parts of the wetlands from tourists.

In order to enhance ecological conditions and recreational use, the existing slope crest was moved some 30 to 50 m landwards by forest cleaning and excavation (Figure 2). The main part of the excavated material was used for dumping embankments on the left bank upstream of the Eggrank Bend and for filling the bend scour along the outer bank.

Due to the initial widening of the inner bank new gravel areas were created. However, the sustainability of these gravel surfaces can only be guaranteed if hydraulic loads at the inner bank are increased and prevent sedimentation and scrub growth. Landwards, the gravel areas are followed by the development of a softwood wetland which was partially initiated by planting native grove in the framework of the restoration project.

2.2 *Project progress*

In the construction project and the detailed design, a new additional upstream counter bend was designed which slightly elongates the river reach (Figure 2). At the left river bank, a new 300 m long shallow bank with native woods was planned. Apart from the ecological enhancement, this new naturalized course should lead to increased dynamics in the riverbed (thalweg formation) and thus improve upstream flow conditions and direct the main flow toward the inner bank at its entrance into the Eggrank Bend (Mende et al. 2014).

During the realization phase, some 5,000 m^3 of gravel from the Thur River were dumped along the left bank upstream of the Eggrank Bend. However, the existing outer bank was too high and too steep to allow the development of a shallow bank. Consequently, bioengineering measures for bank protection were omitted and the embankment is now left to natural dynamic development.

To provoke a shift of the thalweg toward the inner bank and thus increase hydraulic loads at the new gravel bank, micro groins were planned and realized. This measure included an increased bend radius from initially some 125 m to about 215 to 280 m. The increased radius allows reducing the transversal secondary currents caused by the curve flow which – interacting with the main flow originally led to increased flow velocity in the thalweg and its shift toward the outer bank (Meckel 1978). With the increasing bend radius, the ecological objective of decreasing flow velocities in the thalweg can be achieved.

After finishing afore described adaption of the river bed geometry and the excavation and dumping works, the micro groins were implemented. The layout and design of the latter are described in Mende et al. (2014). Therefore, this paper only provides a brief introduction on the different groin types applied in the given case and then focuses on the methodology and the findings of the monitoring campaigns.

3 INSTREAM RIVER TRAINING

3.1 *Objectives*

Stream bank protection at the Eggrank bend was initially assured by riprap. The implementation of groins aimed a reinforcement of this protection as well as an improvement of ecological conditions and the preservation of recreational value.

The following sub-goals were defined:

- Reduction of flow velocities at the outer bank to unload the existing riprap protection
- Prevention of sediment deposits at the widened inner bank
- Achievement of natural flow velocities with a correspondent shift of the thalweg to the center of the cross section
- Large-scale increase of flow diversity and morphological variability (scour, substrate sorting, fish habitat, etc.)

3.2 *Micro Groins*

Micro groins are a groin type which is completely overflowed at low discharge conditions (Figure 4). At

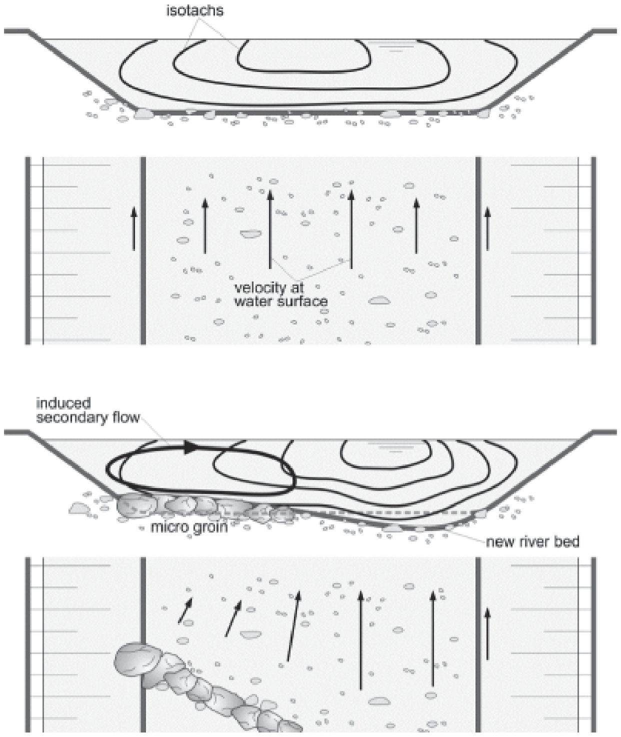

Figure 3. Schematic drawing of flow conditions in a straight river reach without (above) and with an upstream-facing micro groin structure (below, adapted from Sindelar & Mende 2009).

Figure 4. Upstream-facing micro groin at the Mur River in St. Michael/Upper Styria at low flow conditions (Photo courtesy of Otmar Grober).

high discharge, they induce large-scale secondary flow (Figure 3). If built upstream-facing (Figure 3, below), the generated secondary currents direct low flowing water from the river bed toward the groin structure. The fast surface waters are directed away perpendicularly over the groin. This mass and impulse fraction leads to a significant reduction of flow velocity in the groin area. Fine sediment deposits in the backwaters are favored and the bank erosion reduced. In the surrounding areas, flow velocities and consequently also bed erosion increase (Sindelar & Mende 2009).

3.3 *Snail shaped groin*

Additionally to the upstream-facing micro groins, a so called snail shaped groin was constructed at the Eggrank Bend. This specific type of micro groins is generally used at the outer bank as well, but implemented as an isolated element. The snail shaped groin presents a radius which decreases in downstream direction. It is streamed in tangentially which can be provoked by an additional S-sill if necessary (Figure 5). According to the law of conservation of angular momentum velocities are increasing due to the decreasing radius. The surroundings of the snail shaped groin are characterized by an excellent flow diversity triggered by the variety of flow velocities.

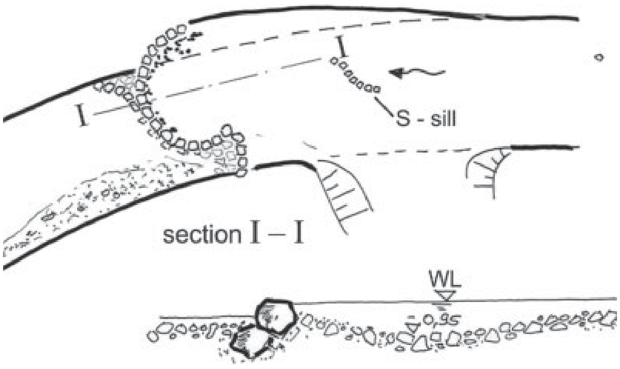

Figure 5. Snail shaped groin at the Wiese River in Maulburg, Germany (source: Erich Linsin).

A part of the flow energy is dissipated by the vortex formation which leads to more convenient downstream flow conditions (Mende 2012). The outer bank is partially unloaded as the groin height slightly decreases in direction of the inner bank and thus concentrates discharge to this part of the cross section.

Monitoring at a snail shaped groin implemented in 2011 at the Wiese River in Maulburg, Germany, revealed large scale upstream scour due to the induced rotating flow (Figure 5). The groin presents a diameter of some 18 m (perpendicularly to the river axis). The area of the created cone-shaped scour hole covers an area of some 250 m^2 and maximum flow depth is about 1.0 m. The Wiese River in Maulburg is characterized by a mean discharge of 10.7 m^3/s and the hundred-years-flood is $HQ_{100} = 260$ m^3/s. Up to now, the constructed snail shaped groin was strained by a maximum discharge of approximately $Q = 100$ m^3/s.

Compared to the Wiese River, the snail shaped structure at the Thur River presents a diameter of some 35 m and thus even larger and deeper scour is expected. In summer, these potholes present excellent bathing opportunities.

3.4 *Micro groin design*

The micro groins in the Thur River were constructed according to the design proposed by Mende (2014) and cover some two thirds of the river bed width, which results in groin lengths of 30 to 50 m. In the zone of the narrowest curve radius, distance between the groins corresponds to approximately 1.8 times the groin length. Further up- and downstream, this distance between the flow structuring elements is getting larger. For all realized micro groins, the crest level at the groin base is located some 50 cm above the mean river bed level (Mende et al. 2014). The crest is

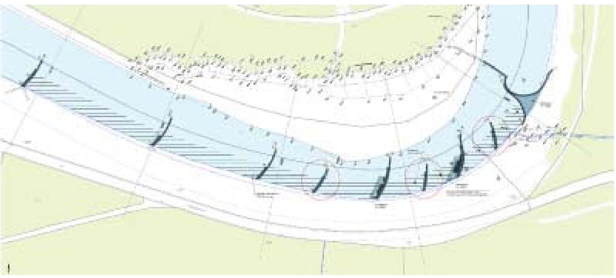

Figure 6. Disposition of groins at the Eggrank Bend, detailed design stage (engineering consortium Bachmann, Stegemann + Partner AG, Staubli, Kurath & Partner AG 2015).

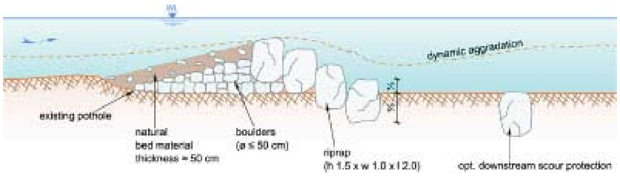

Figure 7. Micro groin design for application in bend scour zone (longitudinal profile in flow direction).

designed with a constant slope toward the groin head, where the level corresponds to the mean river bed level.

To guarantee a maximum stability of the groin structure and to increase flow diversity, the micro groins present an arched layout.

3.5 *Scour protection groins*

In order to increase safety along the outer bank in this particularly narrow bend and with regard to the high flood discharges, three scour protection groins were implemented (highlighted by red circles in Figure 6). They are disposed in the reach of smallest bend radius and in the center between the micro groins. Located some 50 cm lower than the micro groins, they essentially serve for scour limitation between the latter. Usually, the scour protection groins are covered by gravel (bed load), but during flood events they are exposed and become effective.

The first scour protection groin upstream was not planned initially. But in the considered zone, the downstream micro groin could not be built as planned: loose gravel material from the embankment filled the excavation for the groin foundation (Figure 7) and made it impossible to build a deep four-layer micro groin. Instead, a two-layer groin was constructed and the resulting stability loss was compensated by an additional scour protection groin.

4 MONITORING

4.1 *Objectives and approach*

Given their prototype pilot character, the restoration measures of the Eggrank Bend were followed-up by an intensive hydraulic morphological monitoring. On one hand, 2D measurements of flow velocities were carried out applying the Large-Surface-Particle-Image-Velocimetry (LSPIV) from helicopters and drones (Detert & Weitbrecht 2015). On the other hand, flow velocities and cross section geometries were recorded by 3D Acoustic-Doppler-Current-Profiler measurements (ADCP) at ten specific cross sections (Figure 8). Combining these two measurement techniques allowed obtaining quasi-three-dimensional flow characteristics over the entire Eggrank Bend. If possible, LSPIV and ADCP measurements were carried out simultaneously to refer to each other and compare results. Records were always taken during periods of mean discharges between $Q = 40$ and $50\,\mathrm{m}^3/\mathrm{s}$ in order to guarantee comparability. Monitoring during flood events was not possible as the monitoring team and the equipment would have been exposed to very high risk.

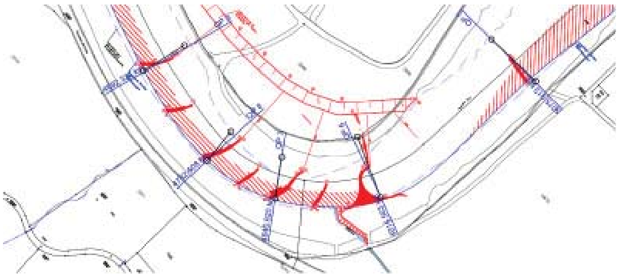

Figure 8. Plan view of the Eggrank Bend with indicated cross sections monitored by ADCP measurements.

Three monitoring campaigns will be effectuated, of which the first two have been realized up to now. The first campaign covered the initial state of the bend, before implementing the restoration measures. As the LSPIV-equipment had to be developed and optimized for the Thur River site conditions these records were advanced to March 2013, while ADCP measurements took place in Mai 2014.

Results of this first monitoring campaign were a key element for the micro groins design as they allowed knowledge on the actual cross section geometry and refining the available data provided by the Swiss Federal Office for the Environment (FOEN). Consequently, levels and layout of the micro groins could be optimized with regard to the given flow conditions and velocities. Further on, comparison of monitoring results with initial state measurements allows interpretation and judgment of the hydraulic morphological development and description of the influence of the implemented instream river training measures.

The second measurement campaign took place in June 2015, some three months after construction completion. Morphology and flow conditions were still influenced by the large movements of bed material during construction works, but first perceptions and predictions about possible future development could be obtained. From this second monitoring period, only ADCP data has been evaluated yet, the LSPIV data is still being treated.

The third and last monitoring campaign will be carried out after a larger flood event ($\geq HQ_5$) leading

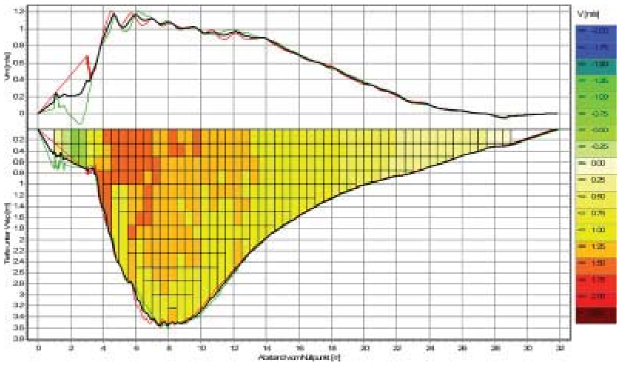

Figure 9. Flow velocities in cross section no. 7, initial state, results from ADCP-measurements.

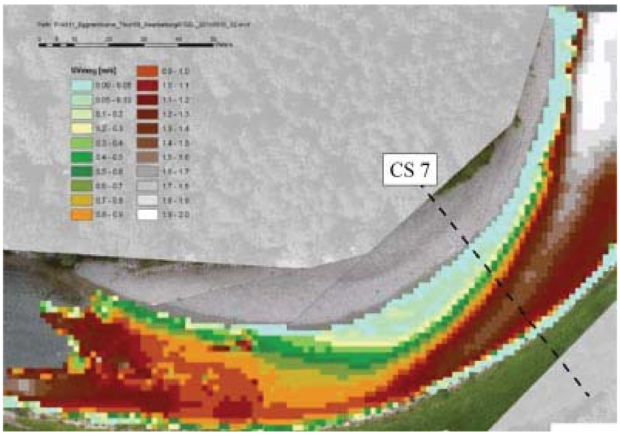

Figure 10. Surface flow velocities at the Eggrank Bend, initial state. Dashed line: approximate location of cross section no. 7 (LSPIV, source: VAW, adapted).

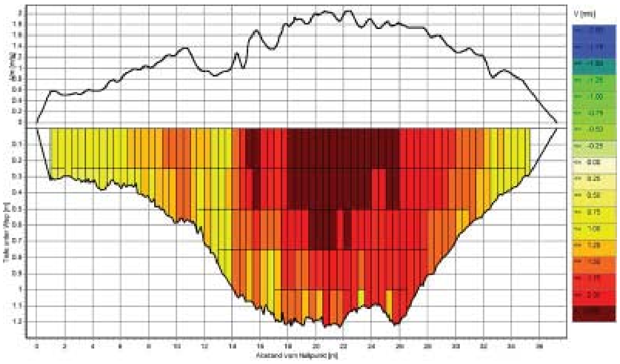

Figure 11. Flow velocities in cross section no. 7, three months after restoration, results from ADCP-measurements.

to morphological changes in the river bed. Comparison with results from the other campaigns will allow derivation of the long-term influence of micro groins on morphology and flow characteristics. It will be possible to evaluate if the objectives of flow diversification, reduction of mean flow velocities and peak flow velocities at the outer bank as well as reduction of scour depths in the bend were achieved.

4.2 *First results*

Based on selected cross sections (ADCP) and plan views (LSPIV), the main findings of the first two monitoring campaigns are discussed.

4.2.1 *Main flow*

Due to the interaction between the main flow and the curve-induced secondary currents, maximum flow velocities shift to the outer bank along the river bend. This leads to bed erosion at the outer bank (bend scour) and to sediment deposits at the inner bank (i.e. Meckel 1978).

Results from the first monitoring campaign (initial state) show that this general statement is entirely matching the flow behavior in the Eggrank Bend. In the curve apex (cross section no. 7, Figure 8) a scour zone of about 3.6 m depth had formed during mean discharge periods and concentrated discharge to this part of the section (Figure 9). Consequently, the water table width is only 31 m and thus considerably smaller compared to a width of some 50 m in the neighboring up- and downstream zones (Figure 1). Flow velocities in the scour area reach between 1.0 and 1.5 m/s at mean discharge, with maximum values close to the left bank, as expected.

ADCP-measurements correlate well with the LSPIV-records. Figure 10 illustrates the flow concentration toward the outer bank and the low flow regime at the inner bank.

The cross section characteristics recorded three months after construction completion reveal fundamental changes in the river bed geometry and the flow velocity distribution (Figure 11). Bend scour does not exist anymore and maximum flow depth at mean discharge is reduced to about 1.2 m. Instead of the pronounced scour, the artificially filled up gravel bank can be observed. Water table width has increased to 37 m and is now about 6 m larger than before restoration. Remarkably, flow velocities have increased to more than 2.0 m/s with maximum values in the center of the cross section. Distribution of flow velocity has become more inhomogeneous which corresponds to increased flow diversity. However, the system is still strongly influenced by the recent construction activities in the river and important changes are expected at mid-term. Especially, it is expected that the wetted cross section will grow larger due to small erosions along the micro groin head as well as erosion at the inner bank. Consequently, flow velocities should decrease.

4.2.2 *Secondary flow*

The shift of maximum flow velocities to the outer bank is provoked by the interaction of the main flow with the curve-induced secondary currents. Figure 12 illustrates the measured transversal velocities at cross section no. 7 for the initial state before restoration. At the surface, transversal currents are directed toward the outer bank while deep currents are pointing toward the inner bank. The resulting secondary flow is drafted by the arrow in Figure 12.

Contrary to the initial state, todays situation does not reveal any important secondary current (Figure 13). This explains the more equilibrated flow velocity distribution over the cross section. Whether

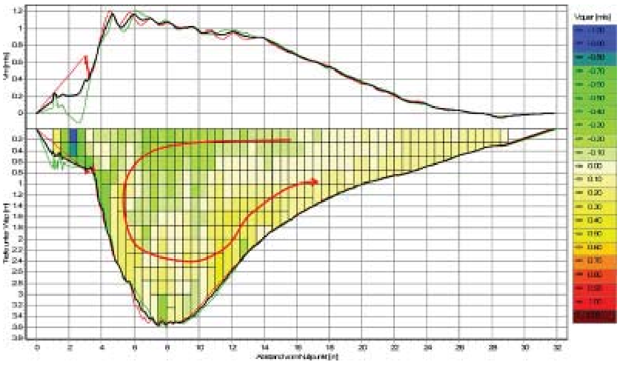

Figure 12. Transversal velocities (measured perpendicularly to the cross section) in cross section no. 7, initial stage; negative transversal velocities are directed to the left, positive ones to the right.

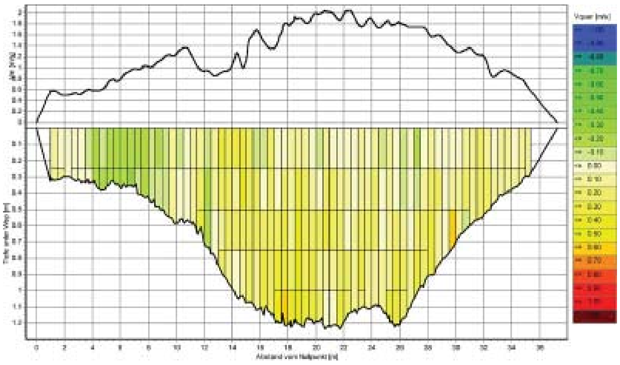

Figure 13. Transversal velocities (measured perpendicularly to the cross section) in cross section no. 7, three months after restoration; negative transversal velocities are directed to the left, positive ones to the right.

this phenomenon is caused by the implemented micro groins or mainly influenced by the large quantities of bed material moved during the construction phase cannot be concluded yet. The third monitoring campaign will provide more detailed information about this aspect.

4.2.3 *River bed and water level*

Bed geometries recorded by ADCP during the first two monitoring campaigns – before and right after the realization of restoration measures – were compared for each cross section to illustrate the development of the bed level. Furthermore, the upper edge of the micro groins is represented.

Figure 14 reveals the bed geometry development at cross section no. 5 located at the upstream end of the Eggrank Bend in the area of the new embankment along the left shoreline (about 5,000 m^3, Figure 2). The river bed has only marginally developed compared to the initial state. Even in the area of the filling, the river bed level is only some 50 cm higher than before. This leads to the conclusion that a main part of the embankment has already been eroded during minor flood events since the end of construction works.

Apparently, the bed material deposited in the area of the snail shaped groin (cross section no. 6, Figure 15). This section presents deposits in the outer bank zone

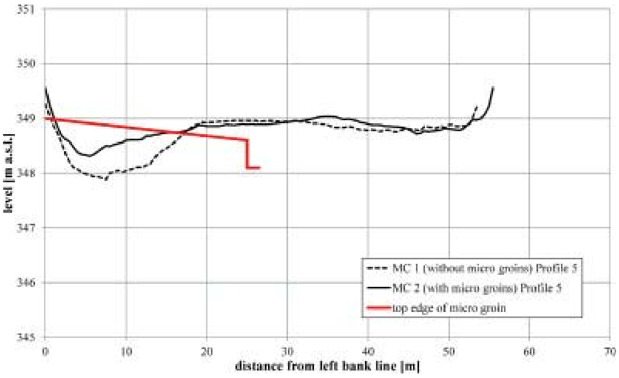

Figure 14. River bed geometry at cross section no. 5, recorded by ADCP before (dashed line) and after restoration (continuous line). The bold continuous line represents the upper edge of the implemented micro groin.

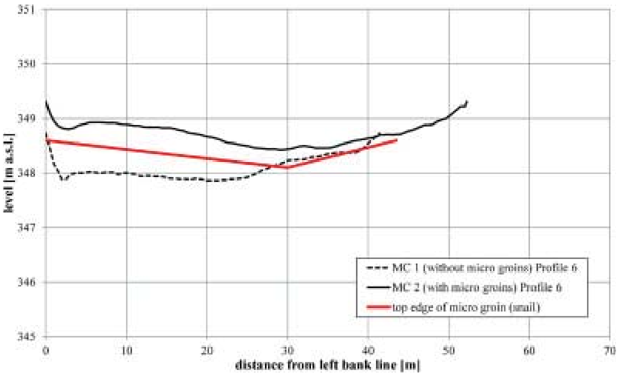

Figure 15. River bed geometry at cross section no. 6, recorded by ADCP before (dashed line) and after restoration (continuous line). The bold continuous line represents the upper edge of the implemented micro groin.

of almost 1.0 m which lead to a complete cover of the snail shaped groin.

In the area of the initially deepest bend scour (cross section no. 7), the river bed is now located up to 3.5 m higher than before restoration (Figure 16). The thalweg has shifted by some 15 m toward the center of the cross section. Due to the filling in the scour zone combined with the material transported downstream from the upstream embankments, the micro groin is mostly covered by gravel. However, it is expected that it will be quickly exposed during major flood events and thus becomes an active flow structuring element.

Besides cross sections with river bed levels, a longitudinal profile of the water surface level was generated based on ADCP data (Figure 17). As discharges during the two monitoring campaigns were very similar, a good comparability between water levels before and after construction is assured. After restoration, the water level in the considered area has increased by up to 60 cm. This is mainly due to the big amount of new additional material in the river.

In the initial bend scour zone which was characterized by a lower slope of the water surface table, the slope has considerably increased which explains the high flow velocities. However, it is expected that future

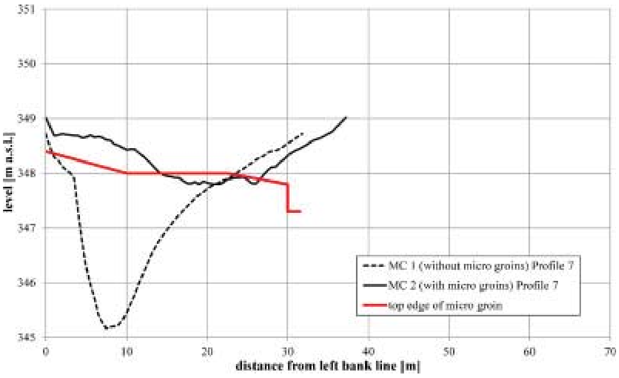

Figure 16. River bed geometry at cross section no. 7, recorded by ADCP before (dashed line) and after restoration (continuous line). The bold continuous line represents the upper edge of the implemented micro groin.

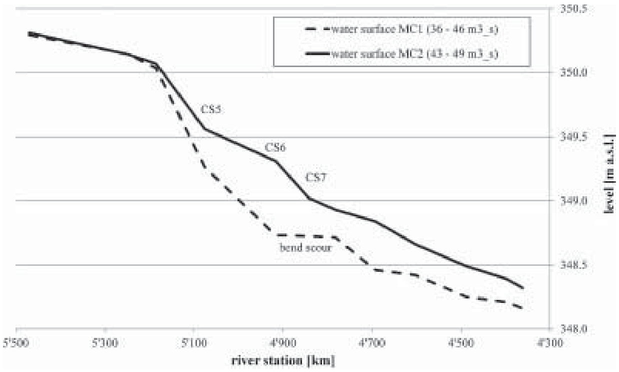

Figure 17. Longitudinal profile of the water level, recorded by ADCP before (dashed line) and after restoration (continuous line).

water surface tables reach similar levels as in the initial state once the bed material transport has stabilized.

5 CONCLUSIONS

Like in other river restoration projects, the Thur River is – some months after completion – still influenced by the just terminated construction works and the related material movements and forest clearings. Development of vegetation and morphological changes requires time and, in case of the morphology, the occurrence of flood events.

Since the end of construction works in March 2015, three minor flood events have occurred ($Q = 370 \div 510\,\mathrm{m^3/s}$), corresponding to return periods of less than two years. These events provoked minor morphological changes such as deposits at the inner bank and erosion of the new embankments along the left bank upstream of the Eggrank Bend. The effects were revealed by the results of the monitoring campaigns.

Major parts of the constructed micro groins are gravel-covered today and only partially visible (Figures 18 and 19). This is due to the important quantity of new material in the river which already was redistributed during minor flood events.

Figure 18. Aerial photo of the Eggrank Bend in April 2015, after restoration.

Figure 19. View in downstream direction at cross section no. 10 (micro groin and correspondent flow conditions).

Depending on flood dynamics the initial river bed level is expected to be regained relatively quickly. Consequently, the micro groins will develop their full flow structuring effect. Today's high flow velocities at the outer bank will be reduced and flow diversity enhanced.

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