Bed load management at the River Lech – A physical model

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ABSTRACT: The Tyrolean river Lech is one of the last near-natural Alpine riverine ecosystems of Austria. The flood event in August 2005 led to large flooding in the Reutte area caused by the extreme discharge and a river bed aggradation due to the high bed load from the upstream catchment. The reason for the latter is mainly a reduced bed slope of the Lech resulting in a halved bed load transport capacity despite a canalised river reach upstream of Reutte. A sustainable solution both ecologically and hydraulically satisfying was developed using a physical model test. The physically modelled river was divided into two channels approaching to the natural, braided river morphology. One channel worked as a bed load entrapment only for high discharges. The second channel forwarded the bed load according to the sediment transport capacity of the downstream river reach and remains untouched by the dredging.

1 INTRODUCTION

The Tyrolean Lech Valley with the river Lech and its tributaries is one of the last near-natural Alpine riverine ecosystems of Austria and because of its size and character one of the most important for whole Central Europe. The valley is mostly untouched by flood protection measures which was the reason for defining the whole Tyrolean Lech Valley as a Natura 2000 reserve (Birds Directive 1979, Habitats Directive 1992). This resulted in a particular protection of the whole area. Usually, a Natura 2000 reserve entails a limited anthropogenic utilisation within the concerned area due to the fact that any ecological deterioration is prohibited. Any technical engagement must always be seen in this context and is permitted only in cases of jeopardy of life. Thus, each river training measure has to consider this specific situation.

The flood event in August 2005 in Western Austria led to large flooding in the Reutte area caused, on the one hand, obviously by the extreme discharge with a return period of at least 200 years, and on the other hand, by a river bed aggradation due to the high bed load from the upstream catchment. The reason for the latter is mainly a reduced bed slope of the Lech resulting in a halved bed load transport capacity despite a canalised river reach upstream of Reutte. In the past years, this aggradation tendency regularly entailed large, ecologically disputed bed load dredgings. Since each bed load dredging also means unfavourable effects on the river ecosystem, notably in an ecologically valuable area, a sustainable solution both ecologically and hydraulically satisfying was needed.

2 BASIC CONCEPT

The bed load transport capacity in the Reutte area and downstream of it amounts to 50,000 m^3/y, while it reaches the double amount in the upstream area. Thus, to achieve a morphological dynamic equilibrium in the downstream river reach an amount of about 50,000 m^3/y on the average could be dredged. To achieve a solution which, on the one hand, minimises human influences on the river ecosystem and does not interrupt the flow continuum, and, on the other hand, also approaches to the natural, braided river morphology, the river is planned to be divided into two channels (Hanisch et al. 2005). One channel works as a bed load entrapment only for high discharges. The second channel, forwarding the bed load according to the sediment transport capacity of the downstream river reach, works like a bypass to the deposition zone and remains untouched by the dredging. Hence, the concept achieves both the morphological dynamic equilibrium of the downstream river reach and reduced human influences on the river ecosystem. The bed load entrapment was planned to be situated upstream of the endangered aggradation area (Fig. 1).

On the upstream and downstream end, the bed load entrapment is bordered by two ramps. The second channel – the diversion channel – starts upstream of the upper ramp and meets the river Lech again downstream of the second ramp (Fig. 2). Thus, the length of the diversion channel arises to almost 1000 m. The upper ramp situated at km 183.397 provides a stable head water level for the inflow into the diversion channel. The lower ramp situated at km 182.775, bordering the bed load entrapment at the downstream end,

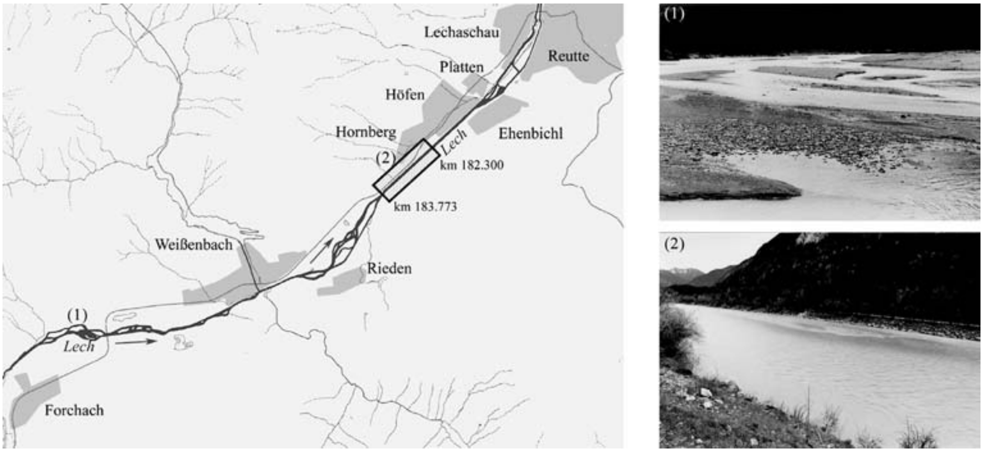

Figure 1. Tyrolean Lech Valley with the river Lech: (1) a natural river stretch upstream of Weißenbach and (2) the constricted river stretch at the location of the planned bed load entrapment.

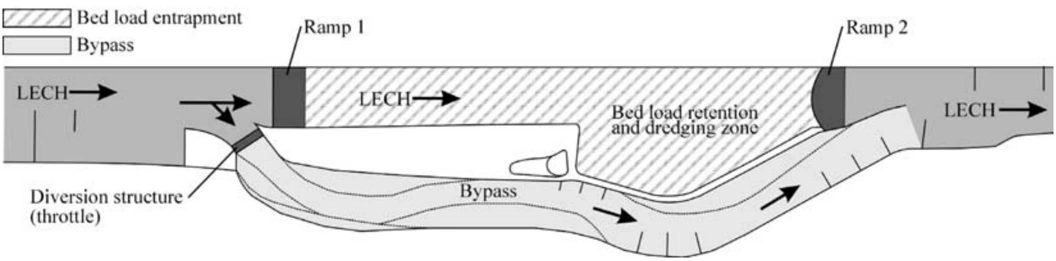

Figure 2. Scheme of the physical model.

reduces the flow velocity inside the entrapment area which leads to a controlled bed load deposition. The river bed widening between the two ramps additionally reduces the flow velocity and the bed shear stress and, thus, increases the retention area.

The inflow into the diversion channel is limited by a discharge throttle (Fig. 2). Discharges lower and equal to the mean flow are forwarded solely to the diversion channel. Discharges higher than the mean flow corresponding to high bed load also flow through the bed load entrapment. Since the bed load entrapment runs dry during low water periods the dredging can be limited to these periods causing only little unfavourable effects on the river ecosystem. These periods mainly occur during the winter, when the whole discharge flows through the diversion channel.

The whole design of the bed load entrapment is based on an optimal discharge and bed load distribution between the two channels. This discharge and bed load distribution mainly depends on the crest height of the upper ramp, on the dimensions of the discharge throttle as well as the position of groynes to direct the flow of water and sediment. Since all these influencing variables were expected to cause highly complex interactions, it was decided to highlight the problem by conducting a physical model test. The model, amongst others, focused on possible control elements such as the discharge throttle or dikes and groynes to influence the discharge and bed load distribution and transport depending on the geomorphologic boundary conditions.

3 PHYSICAL MODEL

The modelled river section had a length of 1573 m and a width of 220 m in nature. According to the available space of the laboratory flume with a length of 25 m and a width of 3 m, the scale factor of the physical model was fixed at 1:80 applying the Froude's law.

The physical model was built with a movable river bed. This scale factor does not allow quantitative but qualitative assessments of morphological results, since the morphological transport processes in nature do

Table 1. Characteristic grain sizes in the physical model compared to the nature sizes.

	Physical model [mm]	Nature [mm]
d_m	52	35
d_{90}	75	95

Figure 3. Development of alternate bars in the physical model at the bed-forming discharge.

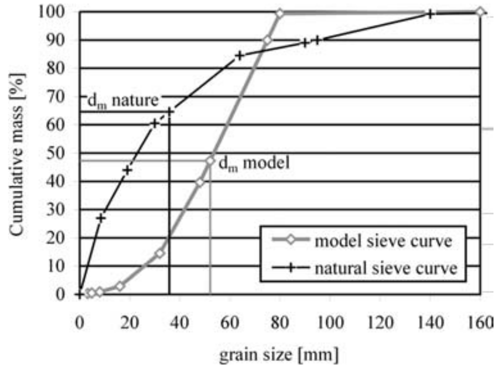

Figure 4. Natural and model sieve curve (both full-scale data).

Table 2. Characteristic discharges.

	Nature [m³/s]	Physical model [l/s]
MQ	45	0.8
BBQ	147	2.6
HQ1	245	4.3
HQ10	439	7.7
HQ30	570	10.0
HQ100	762	13.3

not exactly correspond to transport processes in the physical model. The reasons are as follows:

– The sieve curve of the bed material could not be reproduced entirely since grain sizes lower than 0.2 mm might agglutinate.
– Bed forms such as dunes, ripples or bars in the physical model differ from natural ones for high scale factors.

To transfer morphological assessments from the physical model to nature it is important to physically reproduce the grain sizes especially between the mean diameter d_m and the d_{90} (Tab. 1). The grain size was scaled down geometrically. In this case, the model sieve curve sufficiently agreed with the natural sieve curve to derive qualitative assessments of the observed morphological processes (Fig. 4).

Model tests investigating the morphological behaviour of the current situation of the river Lech provided a basis for the comparison of current and planned situation. The characteristic morphological behaviour was derived from steady state experiments for different discharges and compared to natural bed forms. Air photographs from the canalised river reach of the Lech show alternate bars with a mean distance of 260 m. In the physical model, similar bars with a mean distance of 225 m could be observed (Fig. 3) which serves as an example for the qualitative agreement of the morphological behaviour in the physical model and in nature. Since bed load transport mainly occurs in terms of alternate bars for the present hydraulic and morphological boundary conditions, an analogous bed load distribution between main and bypass channel can be assumed for both physical model and nature.

In the physical model, the river-adjacent areas were made from concrete and the river bed was a mobile sand bed. The roughness of both the river banks and the river-adjacent areas was simulated by stones of a mean weight of approximately 1000 to 2000 kg per stone which means a stone size of d = 11–14 mm in the physical model (Figs 3, 6). The discharge throttle consisted of a slit PVC-plate which could easily be changed in case of unfavourable results. Thus, different slot sizes could be tested.

The bed load entrapment was optimised within more than 20 experiments varying the crest height of the ramps and ramp heights, the size and height of the slot of the discharge throttle as well as position and layout of different measures to direct the flow and the bed load upstream of the diversion structure.

4 BOUNDARY CONDITIONS

The gauge in Lechaschau was used to define the representative discharges (Tab. 2) for the concerned river reach. The duration curve was calculated from the discharge hydrograph 1996–2001 which serves as a basis for defining the bed forming discharge BBQ by superposing the duration curve and the sediment transport capacity depending on the discharge (Fig. 5).

The experiments were conducted either as steady state or unsteady state experiments with bed load input into the model inflow. The amount of bed load was calculated according to Meyer-Peter & Müller (1949) using a mean diameter of $d_m = 52$ mm according to the sieve curve of the material used in the physical model (Fig. 4).

5 PROPOSED SYSTEM

The main components of the optimised system (Fig. 6) which yielded the best results concerning the most favourable dividing of flow and bed load between the

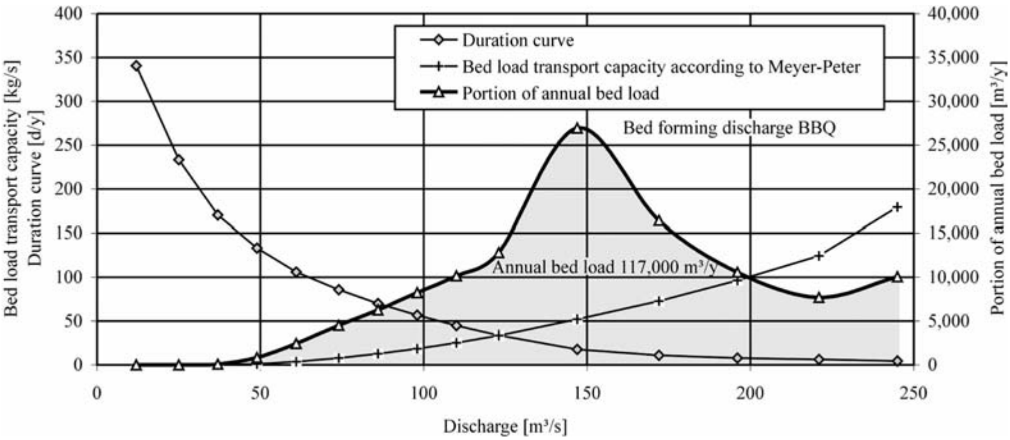

Figure 5. Calculation of bed-forming discharge.

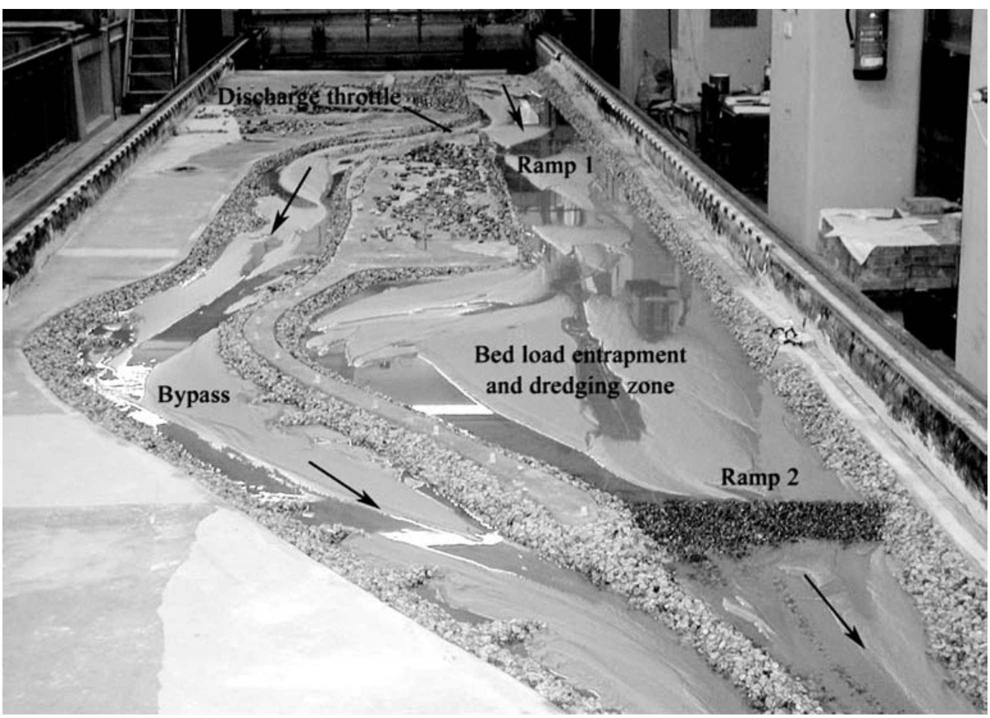

Figure 6. Physical model of the bed load entrapment including the bypass and the dredging zone.

main channel, i.e. the bed load entrapment, and the bypass can be described as follows. The proposed catalogue of measures provided a dynamic equilibrium (Jäggi 1992, Stephan et al. 2003) in the bypass channel, the upstream as well as the downstream river reach and an appropriate bed load supply of the bed load entrapment.

5.1 *Ramps*

The bed load entrapment was situated in the main channel between two ramps. Since the bypass channel started upstream of the upper ramp the crest height of this ramp served as a decisive factor for dividing flow and bed load between the main and the bypass channel. The best results were gained for a crest height being 1.8 m higher than the bed level of the current river bed. Due to the local situation an appropriate flood protection could be guaranteed despite the raised bed level. The crest of the lower ramp had the same height as the base of the upper ramp. The ramp height of the upper ramp was 3.0 m and of the lower ramp 3.4 m. Both ramps had a width of 55 m and a ramp slope of 1:8. Since the upper ramp is expected to be mostly covered with bed load material this ramp was planned as a plane ramp. The lower ramp at the downstream end of the bed load entrapment was planned as a synclinal ramp according to Schauberger (1973). Stone sizes as well as length and size of the bed protection downstream of the ramps were calculated according to Platzer (2000). The stone size of both ramps was fixed to $l_m = 1.5$ m as a mean stone length which means a mean stone weight of approximately 1500 kg.

5.2 *Bed load entrapment (BLE)*

The river section between the two ramps, which served as a bed load entrapment, had a total length of 600 m (Fig. 2). The river width of the upper half of the section being 55 m remained unchanged. The width of the other half of the section was widened up to 130 m which resulted in a reduced flow velocity and, thus, in a favoured bed load deposition within this area. No additional measures to direct flow and bed load between the ramps such as groynes were needed.

5.3 *Discharge throttle*

The slot size of the discharge throttle as shown in Figure 7 was fixed to 15.0 × 1.5 m. To direct flows lower or equal to the mean flow into the bypass channel the bottom line of the throttle had to be 1.7 m below the crest height of the upper ramp. For high discharges the water flowed not only through but also over the discharge throttle. Thus, the river bed had to be protected by a riprap section in front of and behind the throttle to avoid scouring.

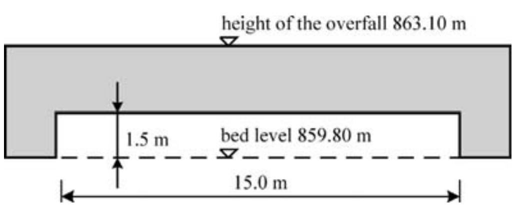

Figure 7. Discharge throttle.

5.4 *Bypass*

The bypass channel showed a slightly curved course with a width ranging from 30 m to 40 m. Alternately situated fields of groynes reduced the channel width by 50% to approximately 15 m for discharges equal and lower than the mean discharge which resulted in the formation of an additional narrower, secondary channel inside the bypass (Fig. 8). It was important to keep the throttle free from deposited bed load material and free flow through the throttle had to be available for every discharge especially for low discharges. Thus, no aggradations should occur in the bypass channel. Best results were obtained for a channel width of 15 m and a bed slope of 0.3%. At discharges larger than 50 m^3/s the groynes were overflowed and, thus, the whole bypass width was available for higher flows decreasing also the sediment transport capacity.

River training structures as well as alternate fields of groynes supported a morphological diversity which strongly enhances also an ecological diversity.

5.5 *Upstream river reach*

Due to the crest height of 861.5 m of the upper ramp, the bed level of the upstream river section was increased by an amount of 1.8 m. This measure was needed to direct low discharges into the bypass, but had also be combined with measures to regulate the bed load input into the bypass channel. Experiments without control measures such as groynes entailed high bed load transport into the bypass resulting in bed load

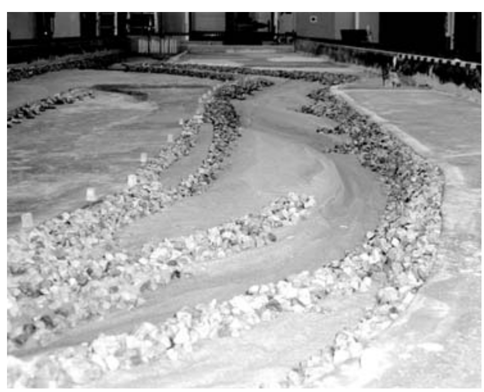

Figure 8. Bypass channel (view in downstream direction).

Table 3. Test programme for the optimised solution.

Experiment		Maximum discharge [m^3/s]	Bed load input [m^3]	Bed load output [m^3]	Deposited material [m^3]	Deposition in the bed load entrapment [%]
Run 1	HQ1, steady and unsteady state	245	32,873	10,982	21,890	66.6
Run 2	HQ1, unsteady state	215	4099	1946	2153	52.5
Run 3	snowmelt, BBQ, steady state	147	21,806	10,330	11,476	52.6
Run 4	HQ30, unsteady state	570	46,202	13,453	32,750	70.9
Run 5	100 m^3/s, steady state	100	3279	112	3167	96.6
Run 6	HQ100, unsteady state	762	50,728	10,355	40,373	79.6
Run 7	BBQ-MQ, unsteady state, falling limb of the hydrograph	147	2209	0	2209	100.0
Run 8	HQ1, unsteady state	245	5952	2522	3430	57.6
Sum			167,148	49,700	117,448	70.3

deposition close to the discharge throttle and in the bypass. Groynes on the left hand side of the main channel had the same effect on the bed load input into the bypass causing an unfavourable aggradation. The best results were gained by placing two groynes 198 m and 243 m, respectively, upstream of the discharge throttle on the right hand side of the main channel. Thus, especially for high discharges the major part of the bed load material was forwarded into the bed load entrapment avoiding depositions close to the throttle. The groynes being 15 m long were situated right angled to the river bank and were overflowed at a discharge with a return period of one year. In case of changes of the bed load supply from the upstream catchment, design and location of the groynes can easily be adapted to the actual situation. This means a great advantage in meeting changed boundary conditions.

5.6 *Downstream river reach*

The river section downstream of the confluence of bypass and main channel turned out to be endangered by aggradation due to the sudden river widening which, for some cases, proceeded in upstream direction. Hence, to avoid unfavourable bed load depositions behind the confluence the river width had to be reduced locally which was realised by a spur dike and by a single groyne on the right hand side of the river directing the bed load coming through the bypass into the main channel (Fig. 2). Alternately situated fields of groynes in the main channel additionally reduced the river width and, thus, increased the shear stress. They also supported an increased structural variety of the currently canalised river reach since the slightly curved course of the river entailed sequences of bends and fords in longitudinal direction. These measures resulted in a mean bed level 0.3 m lower than the current bed level which still lays within acceptable limits.

6 RESULTS

The optimised solution was investigated by means of a detailed test programme (Tab. 3) with different scenarios and representative flood events from the discharge hydrograph 1996–2001. By comparing bed level measurements of the bypass and the main channel before and after each experiment, bed level changes could be summarised to a cumulative volume describing bed load transport through bypass and main channel, respectively. Table 3 shows eight steady and unsteady state experiments with varying discharges. Five experiments simulating characteristic or extreme scenarios are described more in detail to highlight tendencies of erosion and/or aggradation in bypass and main channel.

The upper chart of the following figures shows the hydrograph of the experimental run (a) and the lower chart presents the deposited area as well as the cumulative volume for both the main (BLE) and the bypass channel (b). All data are converted into full-scale data.

6.1 *Run 1*

The hydrograph of Run 1 consisted of four small flood events approximately corresponding to a discharge with a return period of one year, to the bed-forming discharge and the mean discharge, respectively (Fig. 9). The duration of the first three events was calculated from the duration curve, the fourth curve corresponded to a real flood event of September 2000.

As it can be seen from the deposition curve of the main channel, i.e. the bed load entrapment, adding up the bed level changes of all four flood events, the bed load material was mainly deposited in the widened river section upstream of ramp 2. The bed load material was partly transported to but not over ramp 2.

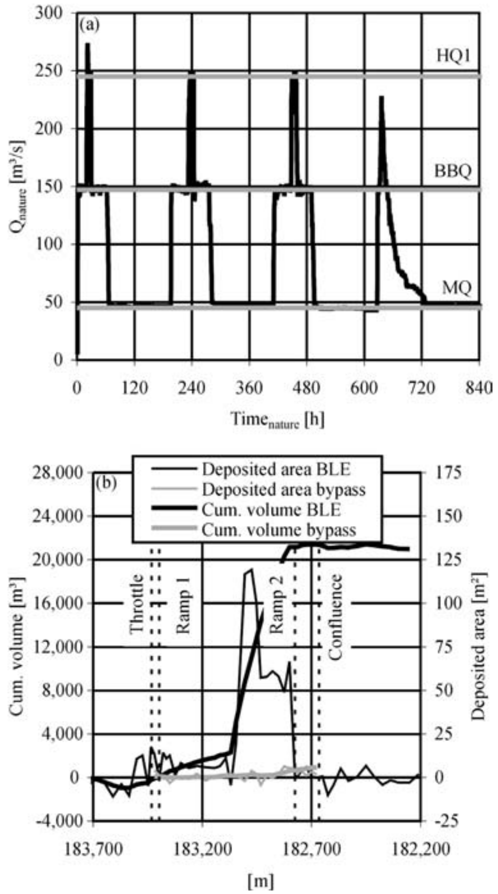

Figure 9. Run 1 – hydrograph (a), deposited area and cumulative volume (b).

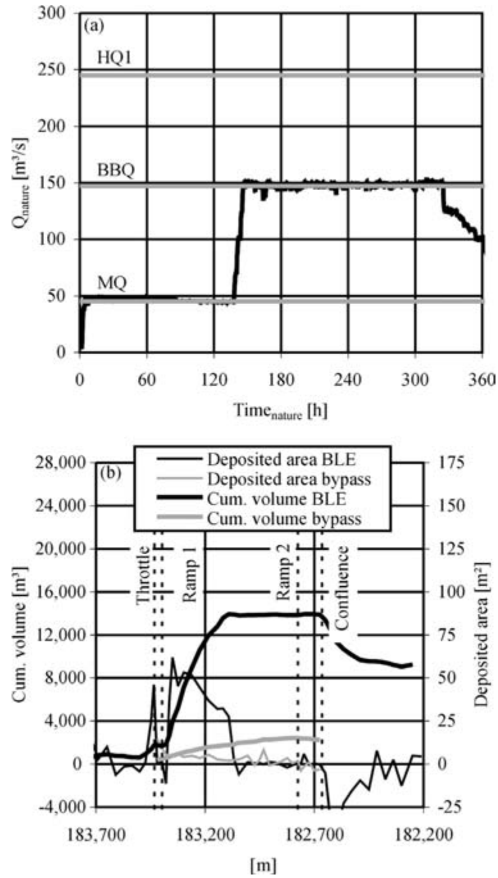

Figure 10. Run 3 – hydrograph (a), deposited area and cumulative volume (b).

Behind the confluence of bypass and main channel neither aggradation nor erosion could be observed which points out a dynamic equilibrium of the downstream river reach. Upstream of ramp 1 the curve reveals a slight tendency of erosion.

The bypass bed levels showed only minor aggradations upstream of the confluence which resulted from alternate fields of groynes. As mentioned above, the groynes reduced the width of the bypass to 15 m for discharges lower than 50 m^3/s and, thus, increased the transport capacity which, finally, resulted in the development of an additional narrower, secondary channel inside the bypass. This secondary, slightly deeper channel enabled discharging of low flows through the bypass whereby the bed load entrapment ran dry. The bed load material deposited near the confluence in the bypass channel was removed again by higher discharges. Thus, the results demonstrate continuous bed load transport into the downstream river reach.

6.2 *Run 3*

The hydrograph of the river Lech in Figure 10 simulated a rather typical scenario during spring time – the snowmelt. Usually, the low flow period during the winter time passes into a long period of higher discharges typically in the range of the bed-forming discharge. For this case, approximately half of the discharge flowed through each of the channels.

Depositions could be observed in front of the discharge throttle and behind the upper ramp 1. The latter seems to be astonishing since the deposition in the main channel did not appear in the widened part of the bed load entrapment but in the narrow part with higher transport capacity. This indicates that the transport capacity related to the remaining discharge in the main channel was too low for the high amount of bed load forwarded over ramp 1 even in the narrow part of the bed load entrapment.

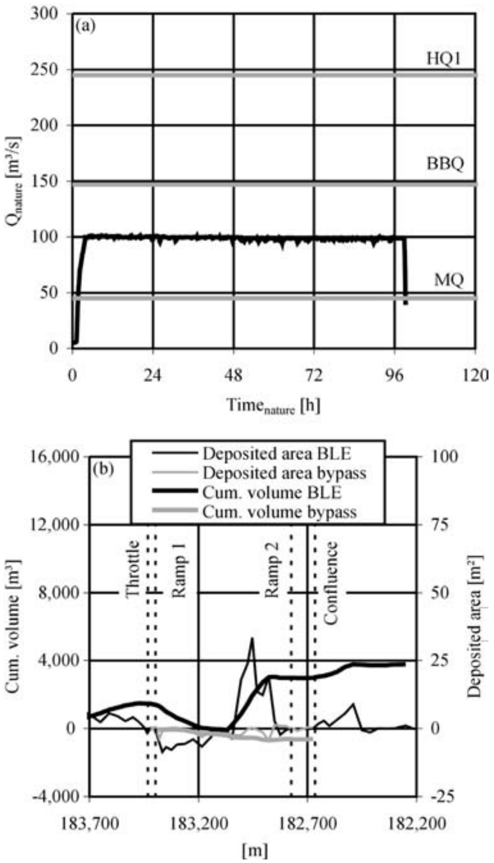

Figure 11. Run 5 – hydrograph (a), deposited area and cumulative volume (b).

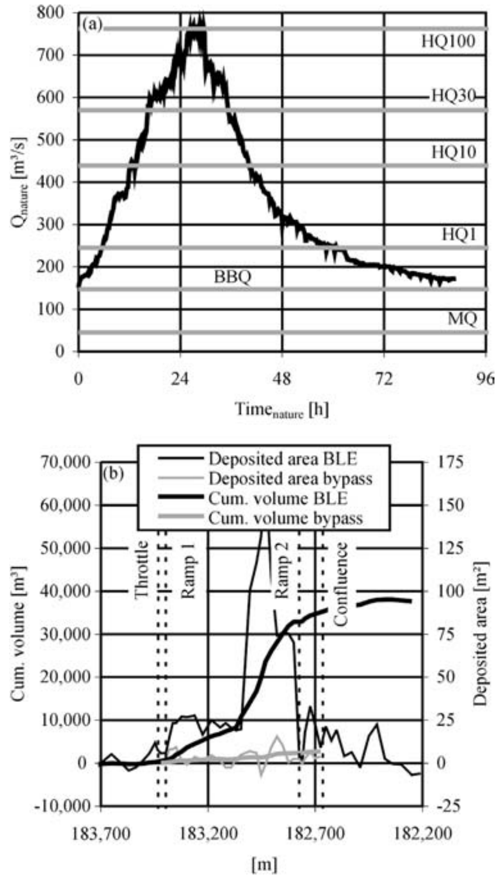

Figure 12. Run 6 – hydrograph (a), deposited area and cumulative volume (b).

Depositions also appeared in the bypass channel, but can be explained by the comparatively high discharge at the end of the experiment. The discharge was not low enough to enable the formation of the additional secondary channel which would accelerate the re-mobilisation of deposited material.

The downstream river reach showed an erosion tendency which resulted from aggradation in both the bypass and the main channel which can be explained by the lack of sediment transport from upstream.

6.3 *Run 5*

To investigate a wide range of different discharges one of the experiments was conducted with a steady state discharge of 100 m^3/s being between the mean and the bed-forming discharge.

Figure 11 exhibits that depositions appeared in both the upstream and the downstream river reach despite a comparatively low discharge. During the experiment, no bed load material was transported over ramp 2 and, thus, depositions occurred in the widened section of the bed load entrapment. The depositions in the downstream river reach resulted from bed load transport through the bypass which indicated minor erosions proving the functional ability to forward the bed load into the downstream river reach especially for low discharges.

6.4 *Run 6*

Figure 12 shows the simulation of a 100 years flood event beginning and ending with the bed-forming discharge.

The river reach upstream of the upper ramp 1 exhibited neither aggradation nor erosion but remained almost unchanged. As also shown in Figure 9, the bed load material was mainly deposited in the widened river section upstream of ramp 2. But aggradation also appeared between ramp 1 and the widened river section and, to some extent, also in the river reach downstream of ramp 2. This can be explained by the high amount of bed load material mobilised by the high discharge which was also transported over ramp 2. Added up to the bed load material coming from the bypass channel, the total amount of bed load exceeded the transport capacity of the downstream river reach and, thus, caused depositions behind the confluence of main and bypass channel.

The bypass channel also showed a slight tendency of aggradation. This can easily be traced back to the experiment ending with a discharge not lower than the bed-forming discharge. Again, the discharge was not low enough to enable the formation of the additional secondary channel which would enhance the re-mobilisation of deposited material caused by a higher discharge.

6.5 *Run 7*

To investigate the function of the bypass channel during the falling limb of a hydrograph, Run 7 continued Run 6 simulating the falling limb of a flood event beginning with the bed-forming and finishing with the mean discharge (Fig. 13). This scenario led to depositions behind ramp 2 and behind the confluence of bypass and main channel, but not in the bedload entrapment or in the bypass. The bypass even showed an erosion tendency which proofed the re-mobilisation of deposited bed load material after a flood event due to the development of a secondary channel with a higher transport capacity.

6.6 *Summary*

Figure 14, finally, summarizes the bed level changes of all experiments done (see also Tab. 3). The graph demonstrates major depositions of bed load material in the bed load entrapment, especially in the widened section upstream of ramp 2. Only minor depositions can be observed in the bypass channel. But a re-mobilization of this material is to be expected for low flow periods. Both, the upstream and the downstream river reach remain unchanged which is important especially for the downstream river reach. The capacity of the bed load entrapment proved to match very well with the reduced transport capacity of the downstream river reach.

The percentage of deposited material in the bed load entrapment related to all investigated discharges is shown in Figure 15. The linear regression exhibits that the sediment retention in the bed load entrapment increased with higher discharges. For an average year the deposited material amounted to approximately 55% of the total bed load. For extreme flood events even 75% of the total bed load were entrapped in the dredging zone.

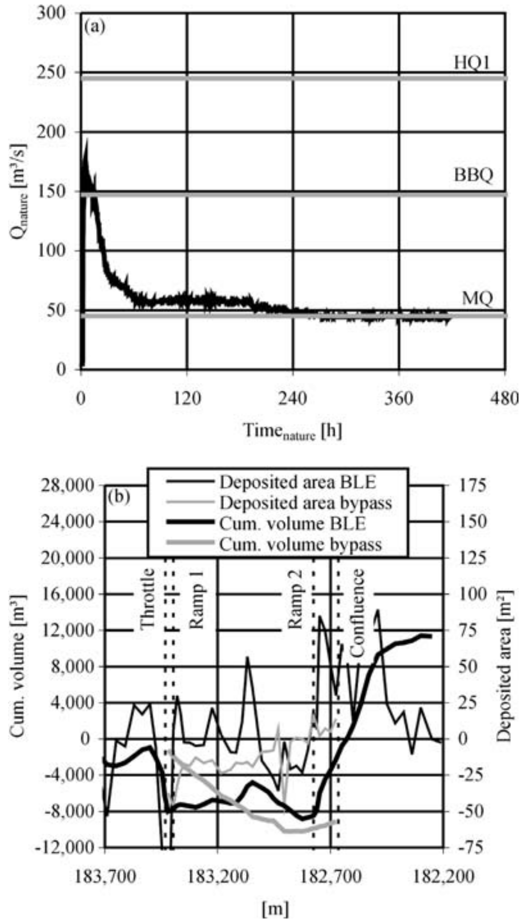

Figure 13. Run 7 – hydrograph (a), deposited area and cumulative volume (b).

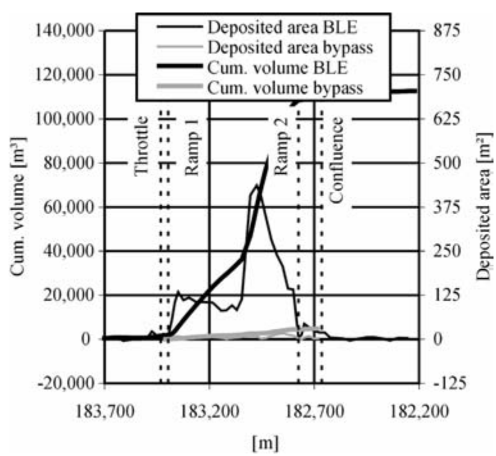

Figure 14. Summarizing Run 1–8 – Deposited area and cumulative volume.

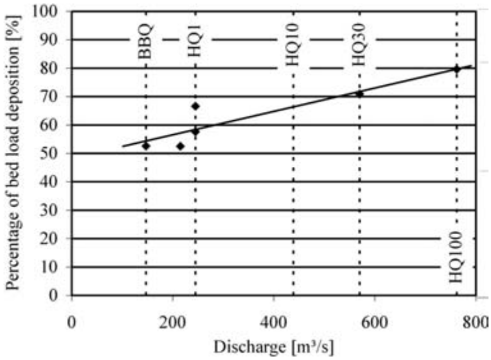

Figure 15. Percentage of bed load retention related to the discharge.

7 CONCLUSIONS

The Tyrolean river Lech is one of the last near-natural Alpine riverine ecosystems of Austria. The valley is mostly untouched by flood protection measures which was the reason for defining the whole Tyrolean Lech Valley as a Natura 2000 reserve. Thus, each river training measure has to consider this special situation. In the Reutte area, a reduced bed slope of the Lech resulting in a halved bed load transport capacity despite a canalised river reach often causes unfavourable aggradations increasing the danger of flooding. A sustainable solution both ecologically and hydraulically satisfying was developed using a physical model test. The physically modelled river was divided into two channels approaching to the natural, braided river morphology. One channel – the main channel – worked as a bed load entrapment only for high discharges and ran dry for discharges lower than the mean discharge. This channel section was bordered by two ramps at the upstream and downstream end. The width of half of the section was enlarged to concentrate the depositions within this channel section by reducing the sediment transport capacity. The second channel – the bypass – forwarded the bed load according to the transport capacity of the downstream river reach. The model results indicated that the deposited material amounted to approximately 55% of the total bed load for an average year. This means that 45% of the total bed load material satisfied the transport capacity of the downstream river reach since the model results adding up all experiments exhibited bed levels being in a morphological dynamic equilibrium. However, the experimental runs provided valuable findings concerning the interplay of deposition and erosion of bed material in both the main and the bypass channel varying with discharge.

The physical model "Lech – Bed Load Entrapment Hornberg-Ehenbichl" was essential for assessing the interaction of the different components and for testing the reliability of the complex site layout in the most efficient way. The model furthermore proved its value in optimizing the design and evaluation of operation and maintenance guidelines. However, stochastic factors like discharge regime or saturation level of the sediment transport capacity affect bed load transport and deposition processes.

Hence the permit planning is complemented by a complex river bed stability and bed load monitoring program, the results of which will be presented in the near future.

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