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# Physical and numerical modeling of sediment transport in the river Salzach

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ABSTRACT: The paper describes the results of a physical model test which aimed at improving the sediment transport through the backwater of a hydropower plant to reduce the flood risk of the town of Hallein. In addition, some of the results were compared with results of a three-dimensional sediment transport model applying the sediment transport formula by Wu et al. (2000). The numerical results when using the default values for the transport formula show a good agreement for the main erosion and deposition pattern but not for the absolute bed levels. A parameter variation slightly improved the numerical results.

*Keywords: Sediment transport, Hydropower plant, Physical modeling, Numerical modeling*

## 1 INTRODUCTION

In the town of Hallein (Salzburg/Austria) the river Salzach is divided into two arms with an interjacent, flood-free island. A hydropower plant is located approximately 190 m downstream of the confluence of these two branches. The sill was originally built to stabilize the degrading river bed of the river Salzach and had a free flow over the construction. In a second step, the hydropower plant was erected on the sill. The current transport capacity of the upstream river reach is too low which resulted in continuous bed aggradations in the two river arms during the past years. The flood risk continuously increased over the years and, finally, led to a flooding of Hallein during the 80-year flood in 2002. Thus, it was decided to develop a morphological sustainable solution for the river reach upstream of the power plant, on the one hand, by optimizing the measures to direct the bed load material to the weir and, on the other hand, by partly lowering the weir crest of the hydropower plant. Both measures were intended to improve the sediment transport through the hydropower plant by increasing the transport capacity and, hence, also the flood protection of the town Hallein by lowering the mean bed level in the two arms. Due to the complex geometric and hydraulic situation the measures were optimized by applying a hybrid model combining a physical model, a two-dimensional numerical flow model and a three-dimensional numerical sediment transport model. The paper explains the main results of the physical model (Figure 1) and compares some of these results with the three-dimensional sediment transport model.

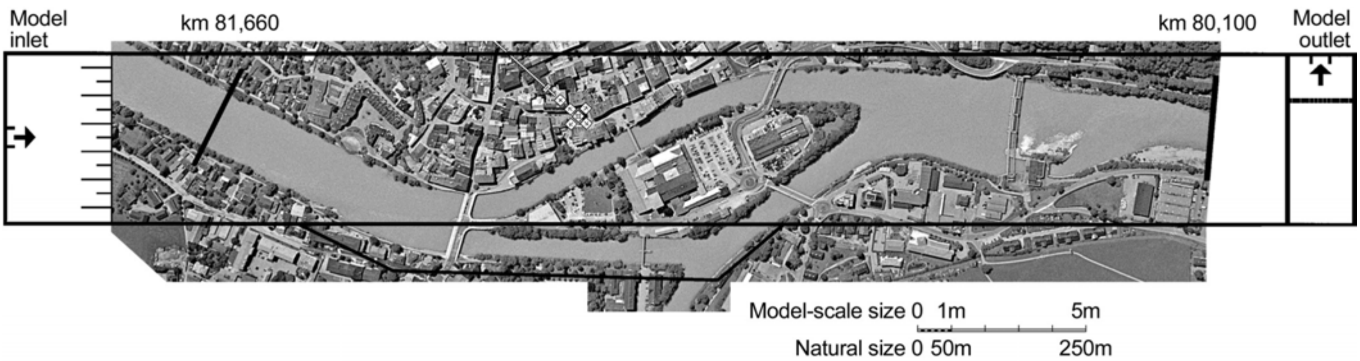


Figure 1. Schematic of the physical model.

## 2 PHYSICAL MODEL

### 2.1 *Geometry, grain size and discharges*

The physical model ran from km 81.660 to km 80.100 and, thus, reproduced a river section of 1560 m. The maximum width of the section was 333 m. The hydropower plant was located in the downstream part of the modeled river section. Thus, the river section was divided into a reach upstream of this power plant with a length of 1260 m and a downstream reach being 300 m long. The hydropower plant consisted of four weir fields, each with a width of 25 m and with a weir crest height of 438.0 m ü.A. (Figure 1).

The physical model was scaled 1:50 applying the Froude's law. This resulted in a total model length of 39 m (including model in- and outlet) and a model width of 6.66 m (model-scale sizes).

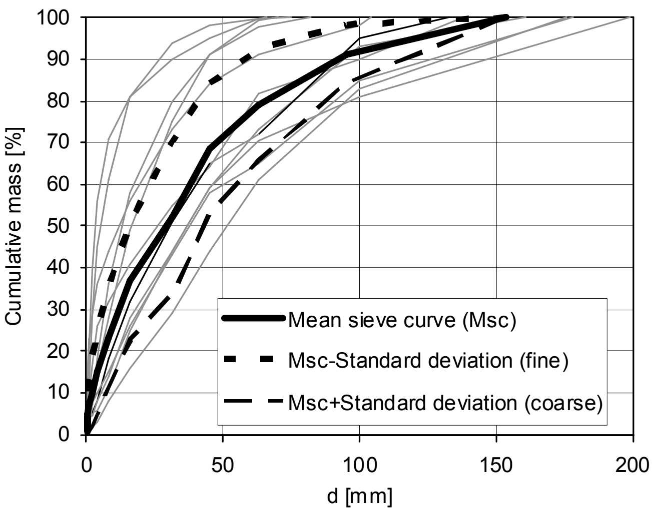

Figure 2. Natural sieve curve.

The physical model was built with a movable river bed. The sieve curves of 10 samples taken from the concerned river reach provided the basis for the model sieve curve. From these samples both a mean sieve curve and the standard deviation were calculated (see Figure 2). To transfer morphological assessments from the physical model to nature and to get comparable transport processes the calculated mean sieve curve was

Table 1. Characteristic discharges

| | Nature [m³/s] | Physical model [l/s] |
|---|---|---|
| MQ | 142 | 8.0 |
| HQ1 | 520 | 29.4 |
| HQ10 | 1065 | 60.2 |
| HQ30 | 1325 | 75.0 |
| HQ100 | 1690 | 95.6 |

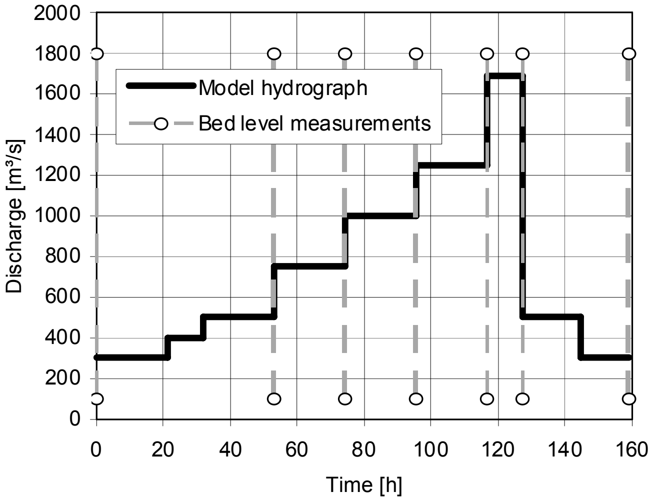

Figure 3. Model hydrograph.

modified on the basis of the transport formulas of Hunziker (1995) and Zanke (1999) and of incipient motion of the grain depending on the grain Reynolds number (see also Cao et al. 2006). From this procedure the following characteristic grain sizes were derived for the physical model: $d_{30}/d_m/d_{90}$ = 5.9-26.0/23.9-52.9/57.7-116.4 mm.

The model hydrograph (Figure 3) was derived from the duration curve of the river Salzach and the characteristic discharges (Table 1).

### 2.2 *Current situation and proposed system*

The current design (Figure 4) generally directs the approaching flow of the right river arm to the left hand side of the river to increase the distance between the powerhouse and the obvious sediment bank resulting from the curve geometry of the right river arm. The consequences are a slightly retarded flow and, hence, also a reduced bed load transport in the left river arm and this finally led to a flooding of the town in 2002.

The proposed system aimed at both the reduc-

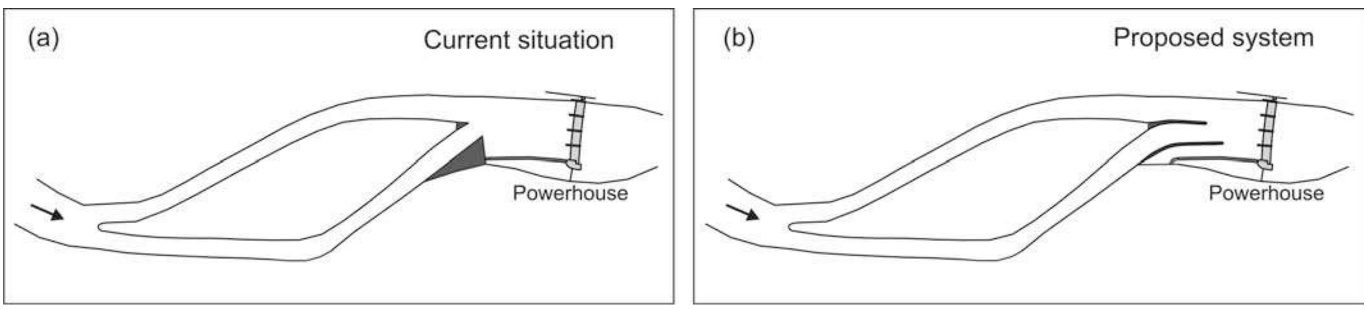

Figure 4. Current situation (a) and proposed system (b) of the sediment directing measures

tion of the sediment deposition in the inside curve at the right hand river side and the reduction of the backwater in the left river arm. The measures (Figure 5) leading to the best results can be summarized as follows:

1. Lowering of the weir crest height of the two middle weir fields of the power plant by 2.0 m;
2. Extension of the island by a flow dividing structure (rough wall) which divides the flow of the two river arms until a 10-year flood and, thus, was expected to reduce the backwater in the left river arm and to improve the approach flow to the power plant;
3. Training structure to prevent sediment depositions at the powerhouse inlet;
4. Rip-rap section as a scour protection at the outside curve of the right river arm along the dividing structure and along the right training structure.

Figure 5. Proposed, optimized system.

## 2.3 *Results*

The results of the bed level development due to these measures after all experimental runs with different discharges are explained by means of the mean bed level changes in two characteristic control cross sections, P4 and P5 (see also Figure 8), respectively. As shown in Figure 6, an erosion process could be initiated in both river arms due to the changed sediment control system. The backwater effect in the left river arm was reduced remarkably since the mean bed levels exhibited an erosion process at least for discharges equal and higher than 1000 m³/s. For the maximum discharge (1690 m³/s) the erosion trend stopped due to a high amount of sediment arriving from the upstream river reach. But these highly mobile sediment depositions were removed even by the following low discharges. The sediment transport in the right river arm was increased to an even higher extent which resulted in mean bed level changes up to -0.8 m.

Thus, these results proved the suitability of the proposed measures for both an improved bed load transport in both river arms and a reduced flood risk for the town Hallein.

# 3 NUMERICAL MODEL

In recent years, several 2D and 3D numerical morphodynamic models have been developed, for predicting bed deformation and, in some cases, sorting processes for graded sediment size distributions (e.g. Minh Duc et al. 2004, Zeng et al.

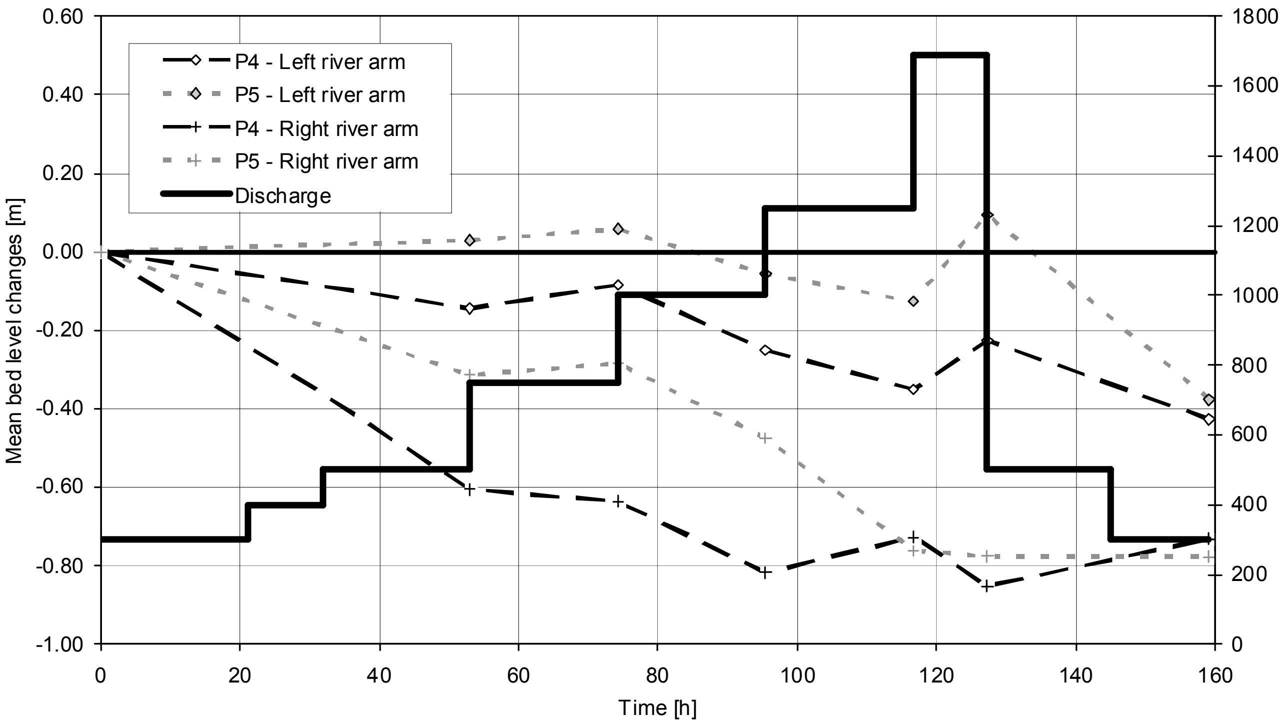

Figure 6. Mean bed level changes in the control cross sections P4 and P5 depending on the discharges.

2005). In this study, the semi-implicit numerical model SSIIM (Olsen 2002) was applied to compute bed changes over time. For spatial discretization, a finite volume method with a non-orthogonal, structured and adaptive grid in vertical direction was used.

The model has several options to calculate the sediment transport. For the present study, the sediment transport formula for bed load according to Wu et al. (2000) was chosen which was implemented to the 3D model by Fischer-Antze (2004) and successfully applied to the Danube near Vienna/Austria. In this transport formula, a correction factor accounts for the hiding and exposure mechanisms assuming to be a function of the hidden and exposed probabilities. According to Wu et al. (2000) the hiding and exposure correction factor considers not only the influence of sediment particle size but also the bed material gradation. To model armouring processes a two layer concept of the model with an active upper layer (layer thickness = $d_{max}$) and a lower inactive layer was implemented in the program.

The grid geometry was constructed according to the proposed optimized system (Figure 4b) and consisted of 213 cells in longitudinal, 70 cells in transversal and 10 cells in vertical direction. The complex geometry was reproduced by outblocking parts of the grid (e.g. island). The mean sieve curve (Figure 2) divided into 7 fractions was used as the model sieve curve. The model roughness was calculated from the $d_{90}$ of the sieve curve (Manning's $n = d_{90}^{1/6}/26$) and used as a uniform value for the whole bed except the rip-rap sections.

## 4 COMPARISON OF THE RESULTS OF PHYSICAL AND NUMERICAL MODEL

Often transport formulas are developed for a specific problem and are limited to a given range of applicability due to their empirically determined parameters. For practical applications of numerical models it is of utmost importance that transport formulas are applicable to a wide range of situations. If a numerical model is a useful planning tool it, after all, depends on the effort for calibrating the model, i.e. on the applicability of the default values of the empirical parameters for specific problems. Thus, the model was applied by using the default values for the exponent of the correction factor ($m = -0.6$) as well as the non-dimensional critical shear stress ($\theta_{crit} = 0.03$) as derived by Wu et al. (2000).

The main erosion and deposition pattern especially due to the curve geometry of the right river arm and after the confluence of the two river arms

Table 2. Parameter variation of the transport formula

| | m | $\theta_{crit}$ |
|---|---|---|
| Run1 | -0.6 (default value) | 0.03 (default value) |
| Run2 | -0.6 (default value) | 0.045 |
| Run3 | -0.3 | 0.03 (default value) |

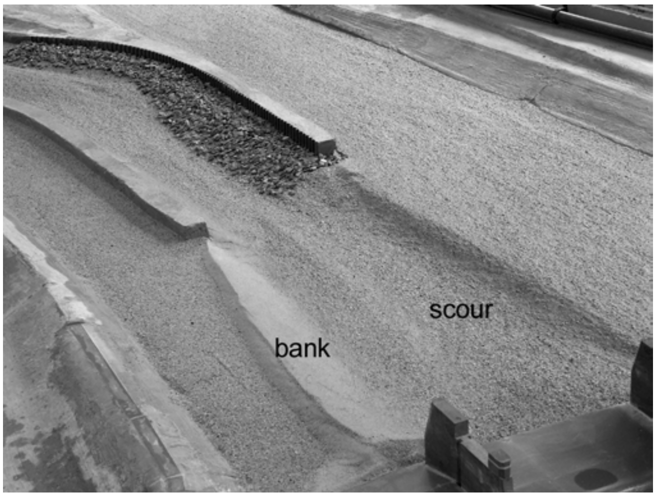

Figure 7. Bed level changes in the physical model after a discharge of Q = 500 m³/s.

could be well reproduced by applying the default parameters (see Figure 7 and Figure 8). But the actual bed heights were over or under predicted. As shown in Figure 9, the default parameters (Run1) overestimate the mobility of the grain causing deeper scours and higher sediment banks than measured.

Therefore, two other tests varying m (-0.6/-0.3) and $\theta_{crit}$ (0.03/0.045) were conducted to analyse their influence on bed deformation (see Table 2). Reducing the absolute value of m results in a weaker consideration of the hiding-exposure effect. Therefore, small grains are less protected by larger ones which led to reduced bed changes and a slightly better agreement of measured and calculated results. Increasing the threshold value to $\theta_{crit} = 0.045$ for incipient sediment motion, as also derived by Meyer-Peter and Müller (1949), has the same effect on bed deformation as reducing the absolute value of m. A higher value for the non-dimensional critical shear stress considers armouring processes but, in the present study, also reduced the grain mobility considerably. Therefore, it is to be expected that $\theta_{crit} = 0.045$ will not give satisfying results for higher discharges too when armouring processes have less importance.

These numerical tests expect to give the best results for the parameter combination of $m = -0.3$ and $\theta_{crit} = 0.03$ (default value) when modelling the bed deformation also for higher discharges according to the model hydrograph. However, each model calibration results in a specific parameter set representing specific transport processes. These transport processes might be changed due to higher discharges or an altered model geometry.

Thus, these numerical results demonstrate the importance not only of a model calibration but also of a model verification to prove the model applicability for a wide range of transport phenomena.

## 5 CONCLUSIONS

A physical model test was conducted aiming at an improved sediment transport through the backwater of a hydropower plant to keep the bed levels low, since the current low sediment transport capacity in the river reach upstream of the hydropower plant caused the flooding of the town Hallein in 2002. Several measures such as training structures for sediment and flow to increase the sediment transport capacity were optimised within the model test. In addition, the morphodynamic 3D model SSIIM was applied to this case in order to investigate if a 3D model may reproduce erosion and deposition pattern for such a complex situation. The numerical results were compared to some results of a physical model test. Although the main erosion and deposition pattern could be well reproduced by the numerical model, the absolute bed levels did not agree with the measured results satisfyingly. Further tests with parameters deviating from the default values of the used transport formula slightly improved the calculated results.

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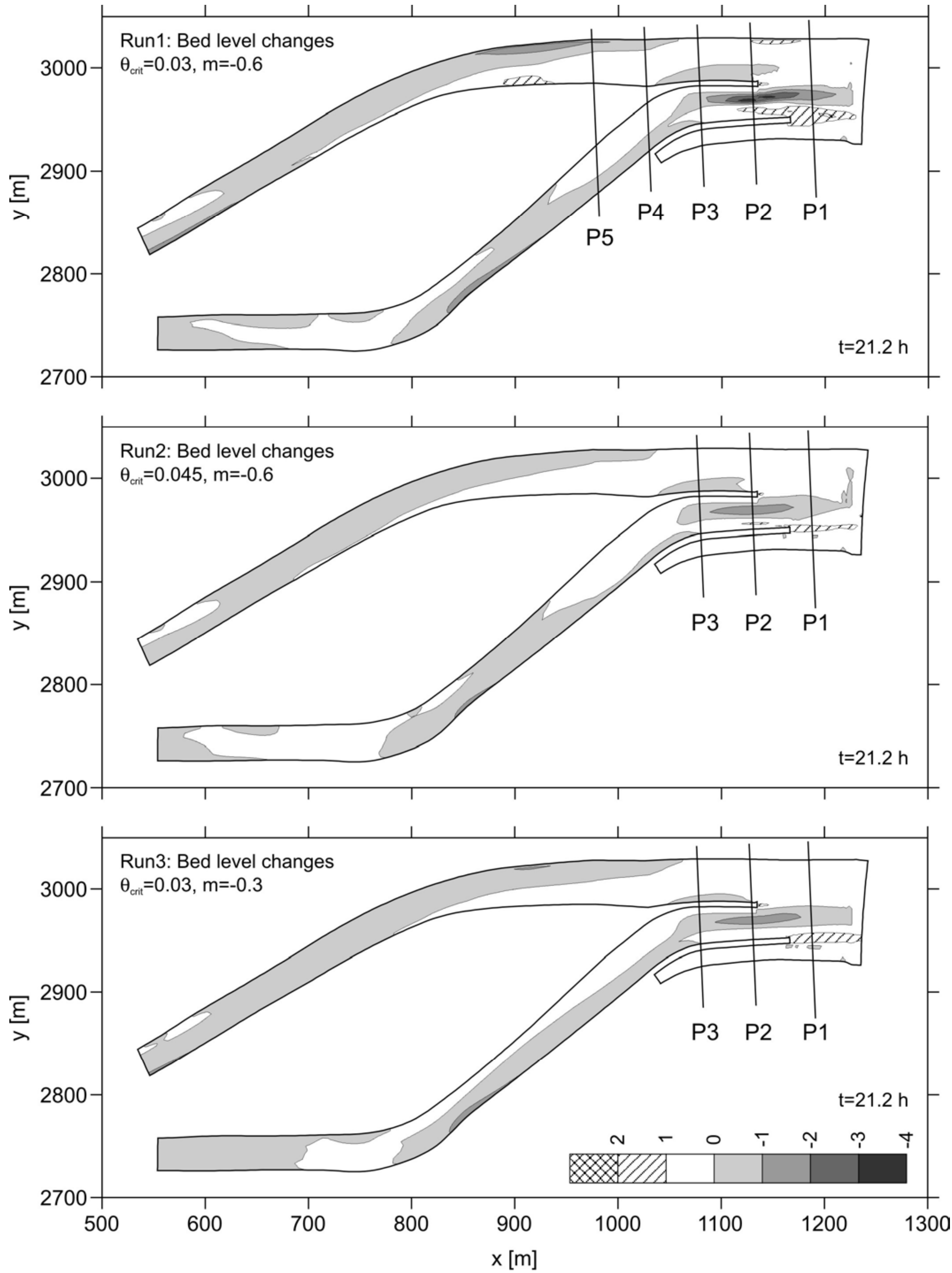


Figure 8. Bed level changes [m] in the numerical model after a discharge of Q = 500 m³/s.

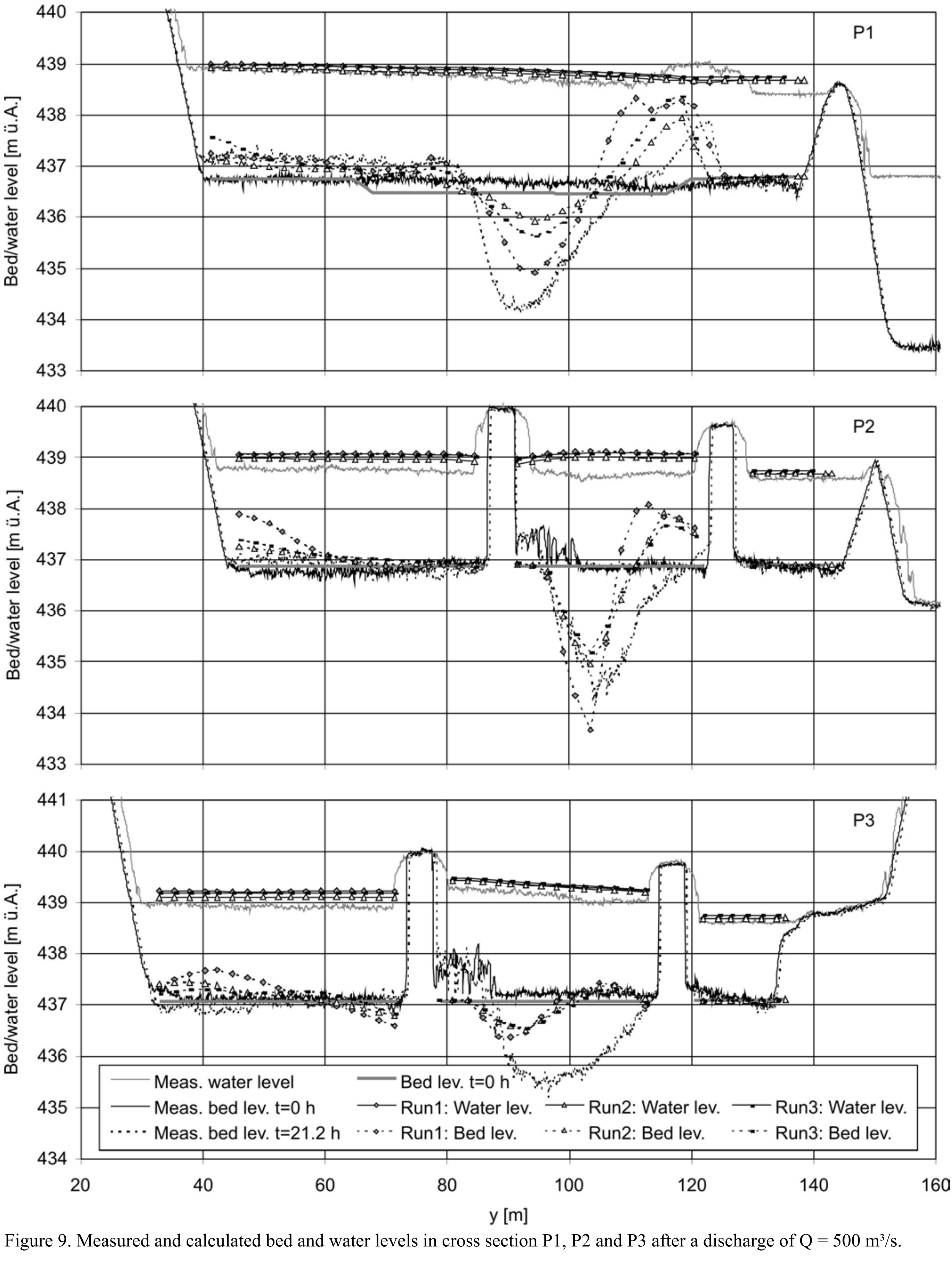


Figure 9. Measured and calculated bed and water levels in cross section P1, P2 and P3 after a discharge of Q = 500 m³/s.