Paper 166 - Environmental friendly solutions to improve the navigation fairway of the Danube in Serbia

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ABSTRACT: Conceptual designs of environmentally friendly river training works have been prepared to improve the navigation conditions at 24 critical sectors located in the Danube in Serbia and Croatia. Six critical sectors were further developed into main designs using a 2-D morphological model (MIKE 21C). The morphological model was setup to optimize the layout of river training structures and to mitigate adverse morphological effects. The morphological model has been calibrated to observed sediment transport rates and bathymetrical changes. The main designs have been prepared for a total of eight structures in combination with dredging at three critical sectors while at three other critical sectors dredging appeared to be the optimal design solution.

1 INTRODUCTION

A consortium consisting of Witteveen+Bos (lead firm) together with DHI from Denmark and Energoprojekt from Serbia carried out the project “Preparation of documentation for River Training and Dredging Works on Critical Sectors of the Danube River in Serbia”. The project is 100% funded by the EU and the beneficiary is the Directorate for Inland Waterways Plovput.

The project consists of a Pre-Feasibility Study (Phase 1), Feasibility Study (Phase 2) and for six sectors the preparation of Main Designs and Tender Documentation (Phase 3). During the Pre-Feasibility Study 24 critical sectors were identified where the navigation fairway has insufficient depth or width or where the bend radius is too small. For each of these 24 critical sectors various environmentally friendly conceptual designs have been developed to comply with the Danube Commission recommendations in order to assure safe and swift navigation on the Danube. For the six critical sectors located on Serbian territory main designs have been prepared using a 2-D morphological model. The results of the 2-D morphological modelling are presented in this paper.

2 PROJECT STRETCH

The project stretch is located between the Hungarian Border (km 1,433) and Belgrade (km 1,170) as presented in Figure 1. Two tributaries flow into the Danube: the Drava at km 1,383 and Tisa at km 1,215. The Danube is the border between Serbia and Croatia from km 1,433 - 1,295. The river flows entirely in Serbia downstream km 1,295 to Belgrade (km 1,170). The Danube in the project stretch is a meandering river with straight sections. Many bends have pointbars and significant side channels that cut through the floodplains. At the relatively wide straight sections the flow is divided into multiple flow paths leading to the formation of sand bars and islands which are often dynamic in nature. In both situations this may lead to a navigation fairway which is not wide or deep enough according to the Recommendations of the Danube Commission.

Figure 1: Project stretch

3 IDENTIFICATION OF CRITICAL SECTORS

The Danube Commission (DC) recommends that the navigation fairway in the project stretch should have a minimal width of 180 m (200 m in bends), 2.5 m water depth and a bend radius of at least 1,000 m (750 m in exceptionally conditions). 1,300 cross-sections were analysed to check whether these criteria were satisfied (Figure 2). Cross-sections that did not comply with the DC recommendations were marked as critical. The critical cross-sections were merged to form 24 critical sectors.

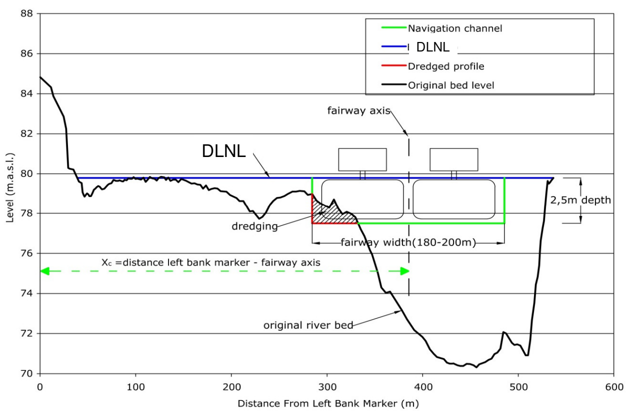


Figure 2: Definition of a critical cross-section

During the Phase 1 of the project a 1-D hydraulic model (MIKE 11) was setup and calibrated to simulate the Design Low Navigation Level (DLNL). The DLNL is the water level that is associated with the 94% discharge duration using the 30 year period 1981-2010 and was used as the reference water level to identify critical sectors and for design purposes.

4 DEVELOPMENT OF SUSTAINABLE OPTIONS

The variety of navigation problems in combination with vulnerable wetland areas surrounding the Danube in the project stretch demands sustainable designs that are fit for purpose. Together with the assistance of the beneficiary the options to solve the critical sectors were developed during the Phase 1 and Phase 2 of the project. The technical options consist of the following river training works:

- Detached downstream facing groynes have been designed at locations where the river is relatively wide to concentrate the flow to the main channel.
- Bottom sills have been designed in river bends to widen the river bed by eroding the part of the point bar that protrudes into the fairway or in side channels to increase the resistance.
- Environmentally friendly bank protections have been proposed at locations along the river where the river banks are unstable.
- Guiding bunds have designed to divert flow from the river banks towards the fairway.
- Chevrons have been proposed as an environmentally friendly structure in the entrance of side channels and at wide river stretches to divert more flow towards the main channel. The chevron structure has been constructed on a number of locations in the Mississippi and Missouri River but is new to the European rivers.
- Dredging and disposal of material back into the river.

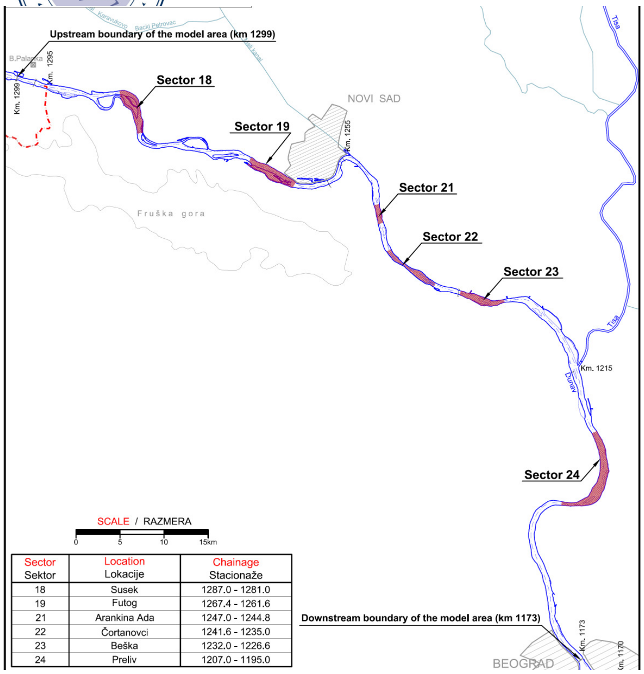
The options to solve the critical sectors were presented and discussed during various Stakeholders' Forum meetings. The Stakeholders' Forum is a multidisciplinary body in which different interests are being represented: navigation, environmental and nature protection, industry, and archaeology. A number of observers are taking part at the Forum meetings, including the Delegation of the European Union to the Republic of Serbia, relevant Serbian ministries and other governmental institutions interested in the project, international river commissions, waterway administrations from other Danube countries, as well as NGOs which are not members of the Forum.

Recommendations received during the Stakeholders' Forum meetings were included in the designs. A Multi Criteria Analysis was used to determine the best options to be developed into conceptual designs. An extensive Financial and Economic Analysis was prepared together with a cost benefit analysis to prove the Feasibility of the project. Parallel to the Phase 2 activities the Environmental Impact Assessment has been prepared describing the current status of the river and the possible impact the proposed river training works have on the environment.

5 APPLICATION OF A 2-D MORPHOLOGICAL MODEL

5.1 *Introduction*

The conceptual designs for the critical sectors located in Serbia (Figure 3) have been further developed into main designs using a 2-D morphological model (MIKE 21C).



Sector Sektor	Location Lokacije	Chainage Stacionaže
18	Susek	1287.0 - 1281.0
19	Futog	1267.4 - 1261.6
21	Arankina Ada	1247.0 - 1244.8
22	Čortanovci	1241.6 - 1235.0
23	Beška	1232.0 - 1226.6
24	Preliv	1207.0 - 1195.0

Figure 3: Location of the six Serbian sectors in the stretch km 1,295 - 1,170

5.2 *Modelling software*

MIKE 21C is a curvilinear flow model developed by DHI. MIKE 21C is an advanced two-dimensional mathematical modelling system for simulation of unsteady flow (hydrodynamics), sediment transport and river bed changes (morphology). The basic steps in such a morphological model are:

1. Simulation of the hydrodynamic flow field.
2. Simulation of sediment transport field based on the flow field.
3. Simulation of bed level changes based on the sediment transport field.
4. Advancing to next time step through updating of model topography based on the calculated bed level changes.

In this way the model will describe the dynamic development of flow, sediment transport and morphology while fully incorporating the feedback from changing morphology on the flow and sediment transport. Further information about MIKE 21C can be found in DHI (2011).

5.3 *Model setup*

A curvilinear grid was established with 50 points in transverse direction and a longitudinal spacing varying from approximately 50 to 200 m, depending on resolution demand. The highest longitudinal resolution was applied in bends located in the critical sectors (20-25 m).

The model bathymetry was based on a single beam survey of river bed profiles that was conducted by the beneficiary. The interval between the profiles is 200 m outside of the critical sectors and 50 m at the critical sectors. A uniform grain size of 0.25 mm was specified which is based on river bed samples taken at various locations in the project stretch.

The boundary conditions of the morphological model are:

- Upstream discharge;
- Downstream water level;
- Upstream sediment transport.

The morphological model was divided into three submodels to shorten the computational time. The calibration results of the most upstream located sub-model (model 1) are presented in this paper. The same parameter settings have been applied for the two downstream located models with similar results.

The locations of up- and downstream ends of the sub models do not coincide with locations of gauging stations except for the upstream boundary of submodel 1. Therefore, the time series of upstream discharge and downstream water level have been extracted from the 1-D hydraulic model established during the Phase 1 of the project. Measured water levels at the gauging station Backa Palanka (km 1,299) were used to calibrate the submodel 1.

5.3 *Model calibration*

The calibration of the morphological model took place in two steps. First the hydrodynamic component was calibrated using measured water levels by adjusting the Manning value of the model. In the second step the morphological component was calibrated. The morphological model was calibrated using the water levels and bathymetrical changes observed during the period July 2011 - July 2012.

Figure 4 presents the result after calibrating the resistance to match the observed water level at the gauging station Backa Palanka (km 1,299). A good match was obtained by applying a constant Manning n value of 0.030 s/m$^{1/3}$ for the submodel 1. The other two submodels used a discharge varying Manning n value.

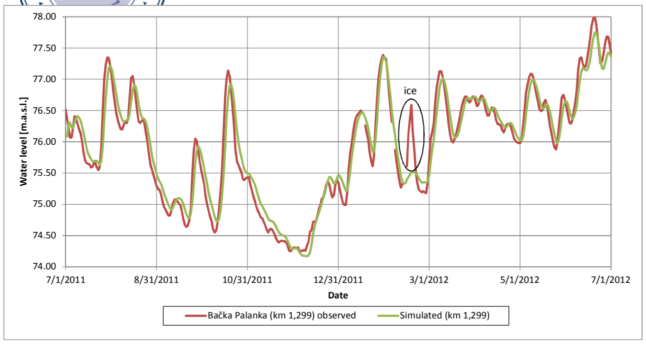


Figure 4: Comparison between measured and modeled water level

Morphological changes (erosion and deposition) are the result of gradients in the sediment transport and are also affected by the distribution between bed and suspended load. The sediment transport formulation and morphological model were therefore calibrated in one integrated process.

The calibration of the morphological component focussed on a bend at critical sector 18: Susek (Figure 3) which is presented in the Figure 5. The reasons for selecting the Susek bend are that:

- most of the critical sectors (Susek, Cortanovci and Preliv) are located in bends, and hence good model performance in bends is crucial;
- the Susek bend developed in a very characteristic manner in the period between the two bathymetry surveys 2011 and 2012 in which the point bar degraded and the bend scour depth reduced;
- the Susek bend is quite sharp, which means strong secondary flow that gives a strong signal in terms of bend scour and point bar development;
- the bend was critical due to insufficient width.

It is evident from Figure 5 that the point bar has scoured by as much as 2-3 m and that the outer bend filled up. The scour at the point bar is evidence of considerable sediment transport over the point in the period between the two surveys. Two effects are causing this scour:

- Bed-load sliding down from the point bar (transverse effect);
- Acceleration of the flow and hence increase in sediment transport on the point bar (longitudinal effect).

In either case there must have been considerable sediment transport on the point bar in order to develop scour, and this in combination with the estimated distribution between bed-load and suspended load was used to select a suitable sediment transport formula for the morphological model.

After testing six different sediment transport formulas it was found that the combination of the sediment transport models of Engelund-Fredsøe (bed-load formula) for bed-load and Yang (total load formula) for suspended load performs best. Figure 7 presents the observed and simulated bed elevation changes after calibration.

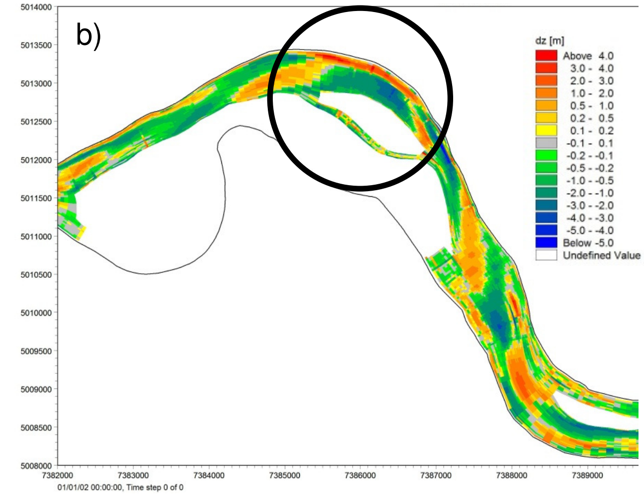


Figure 5: Observed bathymetrical changes at the Susek bend between 2011 and 2012 and focal area for calibration

It can be concluded from Figure 7 that in general the observed erosion and sedimentation pattern is simulated quite well by the calibrated model. It should be noted that perfect agreement cannot be expected in a morphological simulation - only the main bed features can be represented well.

The sediment transport (ST) component was calibrated using existing sediment transport rates near Novi Sad (km 1,257.1) measured by Jaroslav Cerni. The washload was subtracted from the total load. Estimates of the washload range from 55% - 80% (Babic, 2007) which gives a lower and upper limit of the total sediment transport. The simulated and measured total sediment transport is presented in Figure 6. It is observed from this figure that there is good agreement between the measured and simulated sediment transport magnitude.

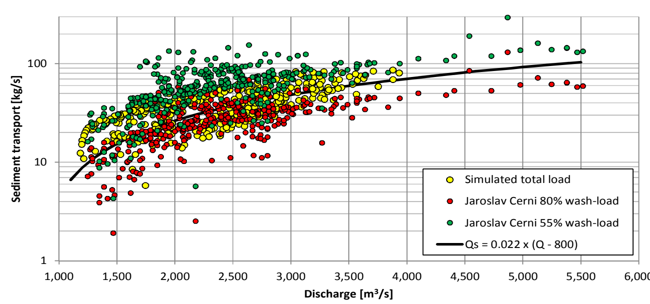


Figure 6: Measured and simulated ST

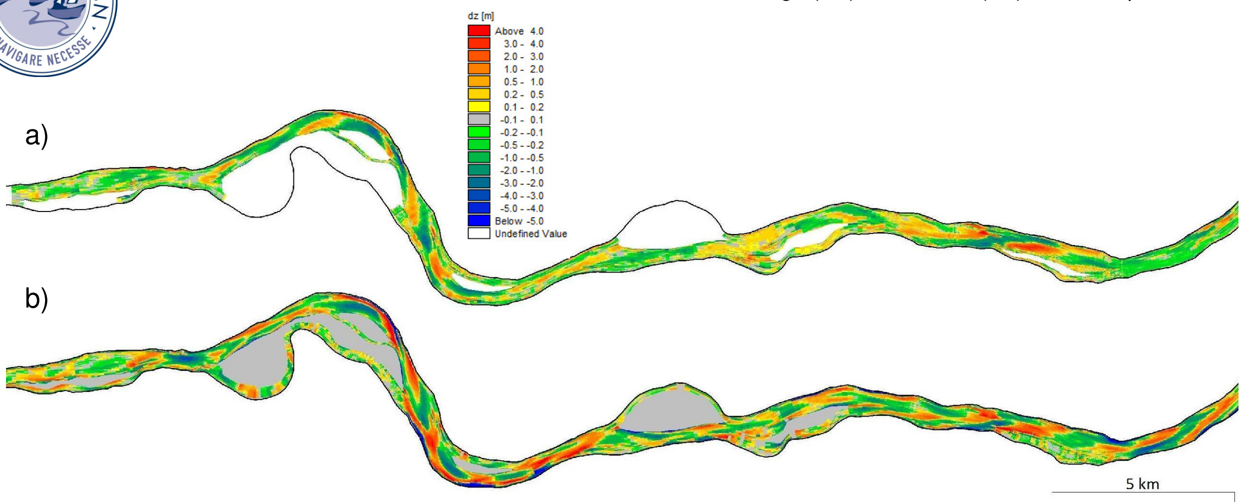


Figure 7: Observed bathymetrical changes between 2011 and 2012 (a) and simulated bed level changes for model 1 (b)

6 MORPHOLOGICAL MODELLING RESULTS

6.1 *Introduction*

The calibrated 2-D morphological model was used to further develop the conceptual designs of the six critical sectors located in Serbia (Figure 6) into main designs. The layout of the river training structures were tested, optimised and adverse morphological effects were mitigated. The morphological modelling resulted in design solutions that contain river training structures in combination with dredging at three of the six critical sectors while only dredging turned out to be the best solution for the other three critical sectors. The results are presented in the following section.

6.2 *Scenario simulations*

The conceptual designs and the additional developed alternative layouts (called "scenarios") were modelled using a three year hydrograph. An average discharge year (2005), a high discharge year (2006) and a low discharge year (2003) were selected from a time series of discharge measurements taken at the gauging station Bogojevo. The discharge time series of these 3 years were merged to form one hydrograph (Figure 8).

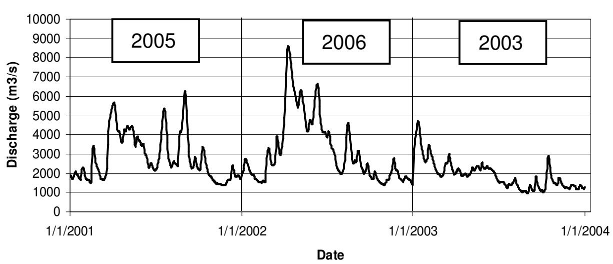


Figure 8: Simulated hydrograph

Although the observed erosion and sedimentation pattern was simulated quite well by the calibrated morphological model the results should be handled with care. Therefore, only the "induced changes" are considered to reduce the noise and model deficiencies. "Induced changes" are relative changes between simulations "without" (i.e. baseline) and "with" river training works.

6.3 *Results*

6.3.1 *Sector 19: Futog*

The critical sector 19: Futog is located between km 1,267.4 - 1,261.6 (Figure 3). This sector is characterised by a sand bar which is protruding into the fairway at km 1,265 (Figure 9). The river widens further downstream resulting in an unstable river bed.

A sand bar is present along the right side of the fairway at km 1,262. Figure 10 shows that the cross-section at km 1,262.825 was critical in 1987 and 1997 due to the sand bar protruding into the right side of the fairway, which eroded in 2004 and 2007. It appears from the survey of 2011 that the sand bar is growing again but it is not protruding into the fairway and therefore not critical.

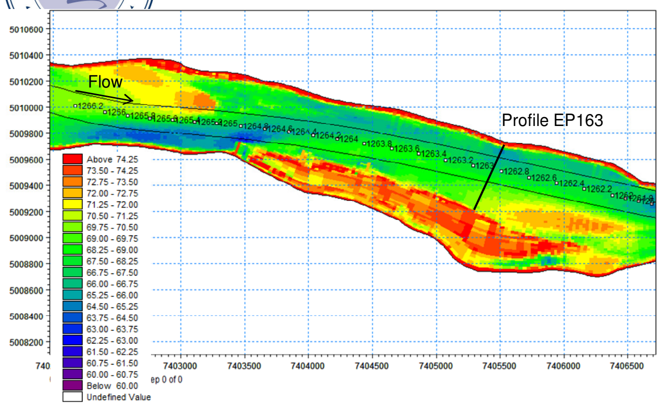


Figure 9: Futog - Existing bathymetry (2012) with location of the fairway and chainages

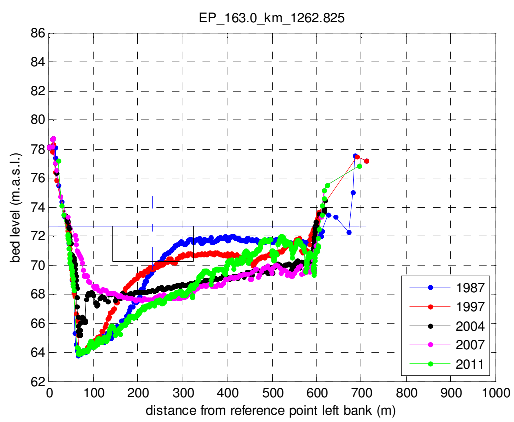


Figure 10: Cross-sectional changes at km 1,262.825

A detached downstream facing groyne and a chevron have been designed to improve the navigation conditions at this critical sector by stabilizing the river bed and to prevent future problems. The groyne has a length of about 125 m and is detached from the right bank by an opening of about 20 m. The maximum height of the groyne is 4.5 m.

The chevron has a U-shape with a width of 92 m and is placed in front of the sand bar at km 1262.8 to stabilize it. The crest level is designed at DLNL +1 m. The maximum height of the chevron is 2.5 m. By detaching the groyne from the bank and by constructing a chevron it is possible for fish to migrate along the right bank. The part of the sand bar protruding into the fairway at the upstream end of the sector (km 1,265) will be removed by means of dredging.

Figure 11 presents the final layout of the structures and the simulated bed level changes after three years.

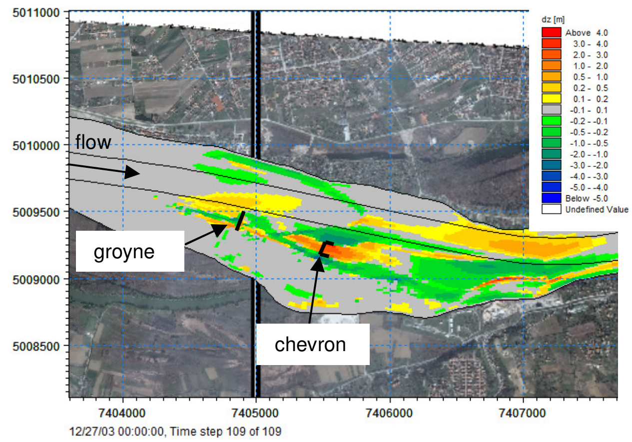


Figure 11: Simulated bed level changes after 3 years

The following observations are made from Figure 11:

- The structures cause a perturbation in the morphology where the flow is first pushed towards the left bank in the stretch where the two structures are located, which is followed by some sedimentation in the inner bend. Basically a perturbation wave with very small amplitudes is generated in the morphology. The perturbation wave does not result in areas inside the fairway that do not comply with Danube Commission recommendations because the fairway in stretch downstream of the sector has depths of more than 4 m.
- Sedimentation occurs behind the chevron while along both legs erosion is observed. The chevron is located such that the existing sand bar at km 1,262 is locked in its current position while providing flow to the existing channel that flows along the right side of the sand bar.

The structures will contribute to stabilizing the river at this stretch without causing too much morphological changes or limiting the connectivity between the river and existing side channels.

6.3.2 *Sector 22: Cortanovci*

The critical sector 22: Cortanovci is located between km 1,241.6 - 1,235 (Figure 3). At the upstream end of the critical sector (km 1,240) a point bar is protruding into the fairway (Figure 12). Further downstream the Danube widens. The river in this stretch has a braiding tendency with three channels separated by an island at the right side of the river and a mid-channel sand bar.

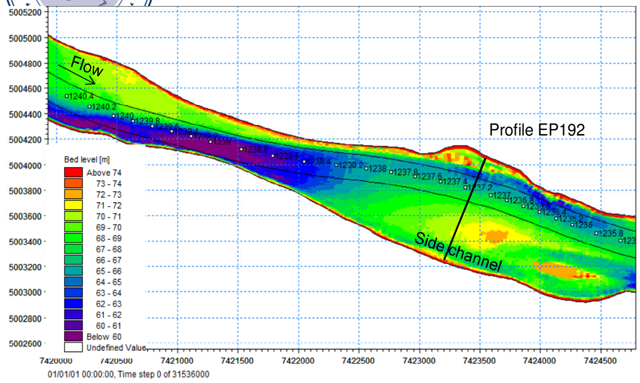


Figure 12: Cortanovci - Existing bathymetry (2012) with location of the fairway and chainages

Figure 13 presents the cross-section km 1,237.175 and the location of the fairway. The right channel between the island and the right bank remained quite stable during the period 2008-2011 while the part at the left side of the side channel is characterized by an unstable riverbed.

Four sills are proposed in the existing side channel along the right bank to increase the resistance of this channel and thereby to divert more flow to the main channel. This will decrease the unstable behavior of the river bed. The part of the point bar protruding into the fairway at km 1,240 will be removed by dredging because it concerns a small volume.

The crest level of the sills has been designed at DLNL -2 m to assure flow over the structures at all water levels for environmental purposes. The maximum height of the sills is between 2 and 3 m. Both the two downstream located sills are designed with an opening of about 35 m next to the sills for environmental purposes.

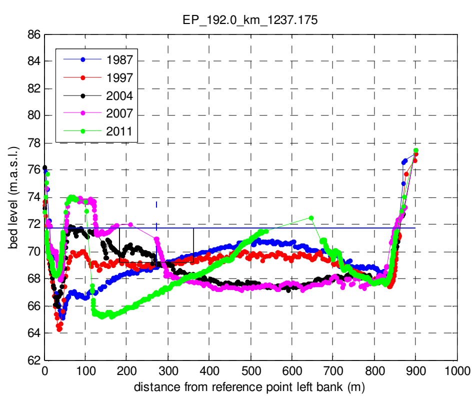


Figure 13: Cross-sectional changes at km 1,237.175

The location of the sills and the simulated bed level changes after 3 years are presented in Figure 14.

The following observations are made from this figure:

- In general the morphological changes are minor (within 1 m). Sedimentation occurs downstream in areas between the sills;
- The river bed in the fairway along the left side of the sills the point bar scours with about 0.2 m.

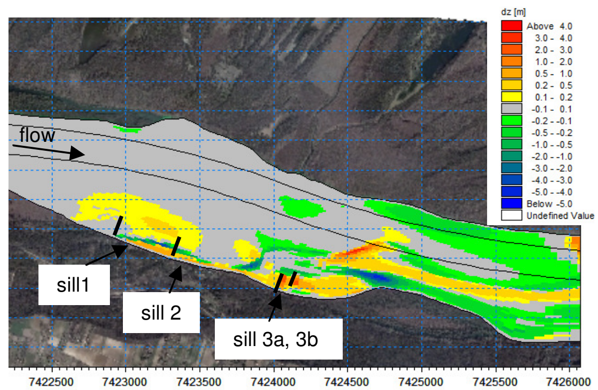


Figure 14: Simulated bed level changes after 3 years

6.3.3 *Sector 24: Preliv*

The critical sector 24: Preliv is located between km 1,207 - 1,195 (Figure 3). Figure 15 presents the existing bathymetry at the critical sector. The river widens at the sector Preliv. An island with unprotected banks diverts the flow into the main channel and a side channel. The main channel is located along the left bank and the side channel is located along the right bank. The side channel is wider and shallower than the main channel. Due to the presence of the side channel in this sector, vessels have experienced major navigation limitations in the past. The sector was not critical in 2012.

Figure 16 presents the EP profile at km 1,199.875 with the cross-sections from 1987 - 2011 and the location of the fairway. It is observed that the river stretch at the sector is highly morphological dynamic. The fairway in 1997 was located in the side channel along the right bank at km 1,199.875 which resulted in unfavorable navigation conditions.

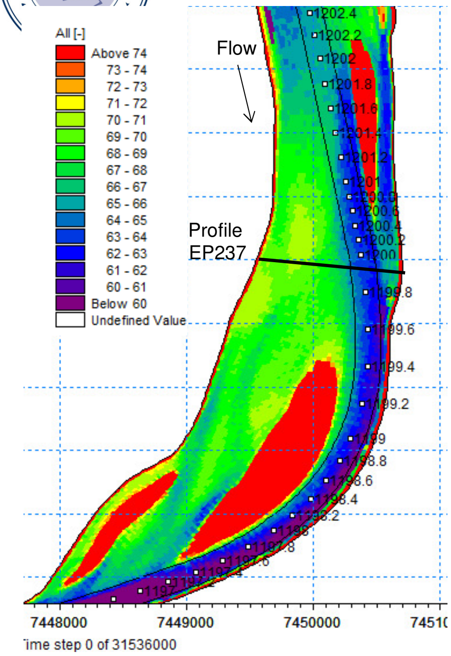


Figure 15: Preliv - Existing bathymetry (2012) with location of the fairway and chainages

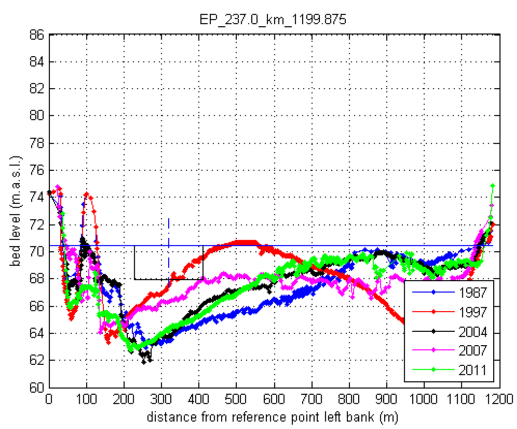


Figure 16: Cross-sectional changes at km 1,199.875

Two chevrons have been designed to divert a part of the flow from the side channel towards the main channel. This will prevent the side channel from becoming dominant while providing some flow through the side channel. The chevrons have a width of 125 m and have a crest level set at DLNL + 1m. The maximum height of the upstream chevron is 2 m whereas chevron 2 has a maximum height of 3 m.

Figure 17 presents the final layout of the structures and the simulated bed level changes after three years. The chevron 1 is placed in front of the existing sand bar (km 1,201) to prevent the sand bar from migrating across the river. The location of the chevron 2 (km 1,199.8) was optimized to limit the impact on the existing island while keeping sufficient distance from the fairway.

The following observations are made from Figure 17:

- Sedimentation occurs behind the chevrons;
- A channel develops between the right bank and the upstream chevron providing sufficient depth for recreational vessels to enter the side channel;
- A diverse system of bars and channels develops in the side channel behind the chevrons;
- The depth in the fairway increases along the left side of the two chevrons resulting in improved navigation conditions;
- In the bend the altered flow distribution results in some sedimentation in the fairway and erosion of the point bar. This does not significantly impact the navigation conditions because the depth is still sufficient.

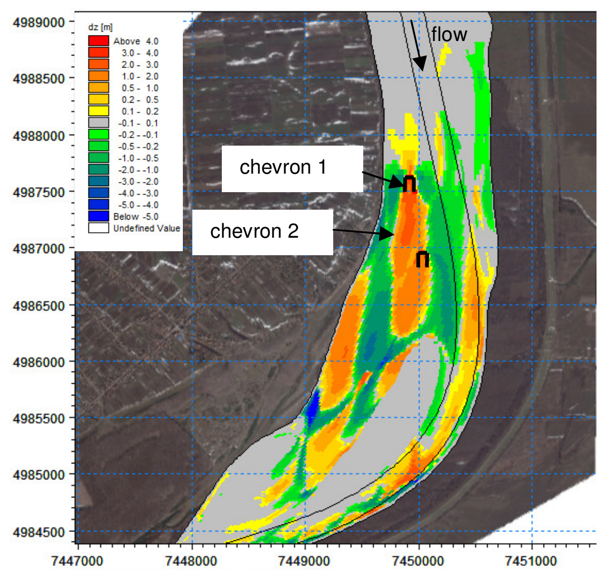


Figure 17: Simulated bed level changes after 3 years

6.3.4 *Sector 18, 21 and 23*

Conceptual designs consisting of structures were tested with the 2-D morphological model for the critical sectors: 18 (Susek), 21 (Arankina Ada) and 23 (Beska). Severe adverse morphological impacts were observed downstream of these sectors which could not be mitigated without designing additional structures. Dredging appeared to be the best solution to solve these critical sectors.

The dredging volume and backfilling time of the dredging areas have been assessed. The backfilling time at these sectors vary between 2 - 5 years depending on the volume, local sediment transport rate and the ratio between the bed load and suspended load. Disposal locations for the dredged material were selected using the bathymetrical survey of 2012 and modeled 2-D flow velocities.

7 CONCLUSION

- Environmentally friendly conceptual designs consisting of: detached groynes, bottom sills, guiding bunds, bank protections and chevrons have been prepared to solve the 24 critical sectors located in the stretch km 1,433 - 1,170;
- The 2-D morphological modeling shows that a combination of dredging and structures is the best solution for two out of a total of six Serbian critical sectors. The designs solution at Preliv consists of structures only;
- It was possible to design environmentally friendly structures that improve the navigation conditions while allowing some flow between the banks and the structures for environmental purposes;
- For three other Serbian critical sectors dredging appears to be the best design solution.

Consortium wishes to thank the Directorate for Inland Waterways and the Stakeholders for their contribution to the successful implementation of the project.

REFERENCES

Babić Mladenović, M, 2007. *Sediment Regime of Danube River*, Zadužbina Andrejević, Beograd.

DHI, 2011. MIKE 21C Curvilinear Model, Scientific Documentation.