RIVER FLOW 2020

Editors: Wim Uijttewaal, Mário J. Franca, Daniel Valero, Victor Chavarrias, Clàudia Ylla Arbós, Ralph Schielen, and Alessandra Crosato

CRC Press
Taylor & Francis Group
A BALKEMA BOOK

River Flow 2020 – Uijttewaal et al (eds)

River training works research to improve navigation conditions on the Elbe River close to the Czech/Germany border

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ABSTRACT: Proposal river training adjustments of the Elbe River in the form of channel dredging and the realization of longitudinal training dams (LTDs) is the part of the project to improve navigation conditions between the city of Ústí nad Labem (CZ) and the Czech/German state border. The research was carried out by the 100 m length physical hydraulic model in 1:70 scale. In this section, the composition of LTDs and channel dredging has been optimised with regard to sediment transport, navigation and environmental conditions around spurs and flood risks in the floodplain. Part of the research was also the verification of the deformations of the river bed for various flows, which was evaluated by means laser scanning technology. Navigational conditions were tested on the model using nautical experiments with radio-controlled cargo ship models. An important aspect of the proposed adjustments is to maintain appropriate environmental conditions for plant communities. For this reason, the LTDs design was verified using another 1:50 hydraulic model. The aim of the research was to ensure the hydraulic conditions between the LTDs and the shore, which ensure the sustainability of the gravel banks and do not allow the space to be filled with fine particles. Since 2009, research on seven experimental LTDs has also been carried out in the area of interest. This research verifies the function of experimental LTDs on a 1:1 scale by hydraulic, morphodynamic and biological monitoring. The results of measurements so far confirm the conclusions of previous researches.

1 INTRODUCTION

An extensive waterway has been built on the Elbe River and on the Vltava River in the Czech Republic in the past. Significant developments took place from the early 19th century, when large-scale regulation works were carried out that aimed primarily at widening, straightening and deepening the fairway and eliminating navigation straits. The Committee for Canalisation of the Vltava and Elbe Rivers in Bohemia was set up in 1896. The committee began implementing a plan to canalise the Elbe-Vltava waterway by building a cascade of 34 weirs that are connected to one another through their backwaters and ensure that the waterway is navigable year-round. To this day, the Lower Vltava has been canalised from Slapy Dam to the town of Mělník (92 km in total), and the Elbe from Chvaletice to the Masaryk Lock in Ústí nad Labem (a total of 172 km). Thus, there exists a relatively extensive waterway in the Czech Republic that, unfortunately, is not reliably linked to European waterways because the section from Ústí nad Labem to the state border with Germany has been made navigable to date only partially through training works. The navigation depth in this section is entirely dependent on the current hydrological situation, and the reliability of economically profitable navigation in this section is only 54%. The issue of minimum flows on Czech rivers is discussed in the study (Balvín et al. 2015). This situation is to be improved by the implementation of a barrage situated downstream the town of Děčín. The 7 km long section between the Děčín barrage and the Czech-German state border will be canalised by means of longitudinal training dams (LTDs) and dredging work to achieve the design parameters that require a fairway width of 50 m, guaranteeing a draught of 1.4 m for 345 days per year and a draught of

2.2 m for 180 days per year. Flow rates marked in further text as Q_{345d}, Q_{210d}, Q_{180d} or Q_{60d} are discharges which have the probability of them being exceeded for 345, 210, 180 or 60 days in a year. These design parameters are fully compatible with the parameters of the Elbe in Germany stated by Gesamtkonzept Elbe (2017). The requirements for new training works include not only guaranteeing the aforementioned navigation depths but it is also necessary to ensure favourable impacts on the environment as the section between Děčín and the Czech-German state border in question is located in a Natura 2000 area. In this respect, there is an important requirement for preserving suitable environmental conditions for the subjects of protection of habitat No. 3270 (Rivers with muddy banks with *Chenopodion rubri p.p.* and *Bidention p.p.* vegetation) under Council Directive 92/43/EEC and suitable conditions for the fish population. Hydraulic research that has been conducted addressed the optimisation of the training works based on more criteria, which include: providing navigation conditions, the environmental aspect, the effect on the sediment regime, the stability of the training works during floods and the effect on the flood control measures in the flood area. The optimisation of the training works was verified on a long-term basis through mathematical modelling, research using physical models and, since 2009, by way of research on in situ experimental LTDs as well.

Initial significant training works in the section between Ústí nad Labem and the Czech-German state border were carried out in the early 19th century. The reinforcement of the river-banks was done using quarry-stone paving placed into a sand gravel bed. The paving was wedged and jointed by grass turf. A paved slope was secured by quarry-stone riprap, with the crest at the level of the present-day water surface corresponding to a discharge of approximately Q_{180d}. A towpath was built on the left bank simultaneously with the protection of the bank slope, for teams of horses that used to tow boats upstream in the past. Nowadays, the path is used as a handling road by the administrator of the water course and as a bike path. The path was built at the level of the water surface at one-year peak flow discharge (Q_1). Adjustments to the right bank were made for a lower water level, and it was only in municipalities that plots of land on the banks were protected by paving for the same level as on the left bank.

The next phase in the period from 1880 to 1920 witnessed further training works on the Elbe stream. Longitudinal training dams connected by transverse groynes with the original bank protection were built at points where the river was wide. Equally as the bank protection, the small dams were paved with quarry stone, secured by a heel made of levelled quarry-stone riprap. The space between the training dams and the bank was subsequently utilized for the deposition of material extracted as part of adjustments to the river bed and material from the extraction of sediments. At some places, this space was spontaneously silted with sediments following floods. The locality of Svádov in Ústí nad Labem is an example, see Figure 1. The implementation of

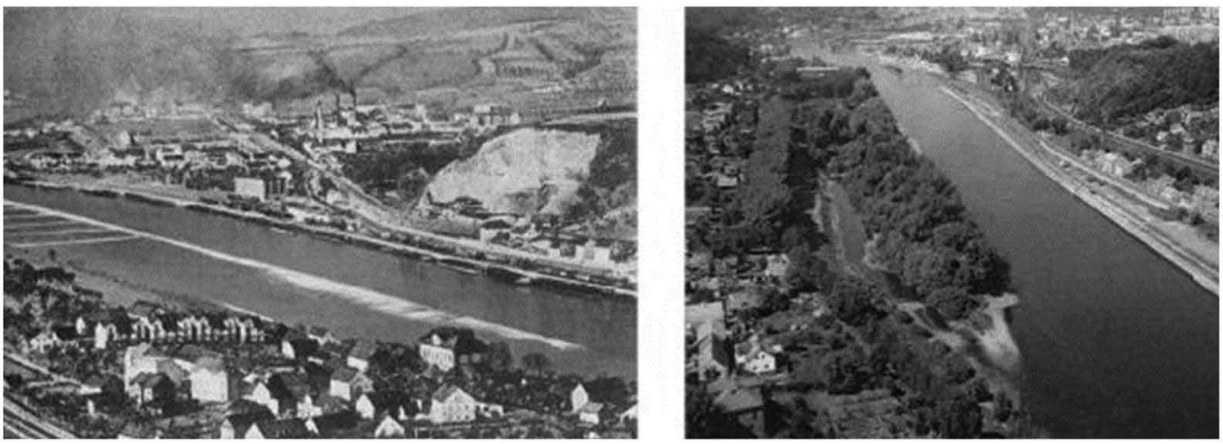

Figure 1. Svádov after the construction of training dams in the late 19th century, and at the present time (archive of River Board Elbe, state enterprise).

training of the Elbe in the 19th century resulted in the river channel being made narrower in places by up to 60 %, i.e. from the original 200 m to 80–100 meters at present. This manifested itself in an increase in the navigation depths at low and medium discharges by tens of centimetres. There was also a rise in the flow velocity by approximately 30 % and, hence, a change in the character of the material of the Elbe river bed, which is gravelly up to stony these days in the section concerned.

In particular, groynes have been made on the Elbe in Germany in the past. According to Henning & Hentschel (2013), groynes form rugged banks of the Elbe and partly make up for environmentally rich habitats that have been lost owing to technical adjustments to the Elbe in the past. However, the space between groynes is at risk of being exposed to the sedimentation process, which leads to the space being silted with fine particles. In order to preserve the hydrodynamic function of the groynes and improve their ecological function, the Federal Waterways Engineering and Research Institute (BAW) studied innovative designs of groynes on the Elbe in Germany. Henning & Hentschel (2013) occupied themselves with the hydrodynamic and morphological evaluation of various types of transverse groynes by means of field measurements during their research spanning 10 years.

Based on the research (Collas et al. 2018), longitudinal training dams prove to be more effective in terms of a fish habitat compared to traditional groynes, see Figure 2. Where groynes are applied, the conditions in littoral zones are severely affected by the navigation traffic and wave motion of the water surface. By contrast, the application of LTDs makes it possible to create a continuous space between the LTDs and the bank which is protected from ship traffic and enables preserving the natural habitat.

Vermeulen et al. (2013) describes the substitution of groynes by LTDs in The Netherlands mainly by reason of providing flood control and navigation depths at low discharges, and he also mentions their environmental benefits. In his paper, he deals with changes in the morphology of the bottom at the inflow into the river bed between the LTDs and the bank by means of a physical model.

2 PHYSICAL MODEL OF THE PILOT ELBE SECTION

Innovative LTDs have been designed in the Elbe section of interest between the planned Děčín barrage and the Czech-German state border with the aim of providing sufficient navigation depths at low discharges, not deteriorating the flood control of floodplain areas and creating environmentally suitable conditions for habitats featuring muddy alluvial deposits. In terms of construction, these are longitudinal boulder dams approx. 100 m long with inclined keying into the bank. The crest of the LTDs is at the level of Q_{180d} and the dam crest in the section featuring the inclined keying is lowered to the level of Q_{345d}. This measure ensures that a stream of water can pass through the space between the LTDs and the bank and no mud and clay particles deposit there. Silting of this space would endanger the existence of gravel banks, which provide suitable habitats to autochthonous plant and animal species. Downstream, the crest of the LTDs widens with the aim of maintaining sufficient flow velocity in the space between the LTDs and the bank at low discharges (Figure 3). First of all, the

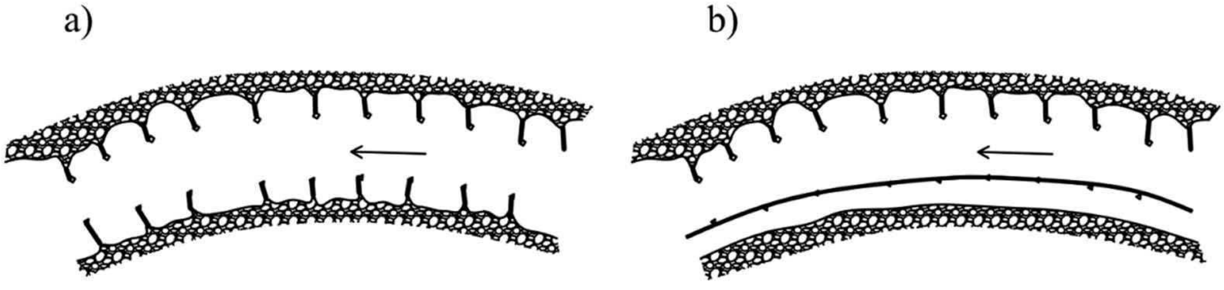

Figure 2. River training dams: a) traditional groynes, b) longitudinal training dam on the left bank.

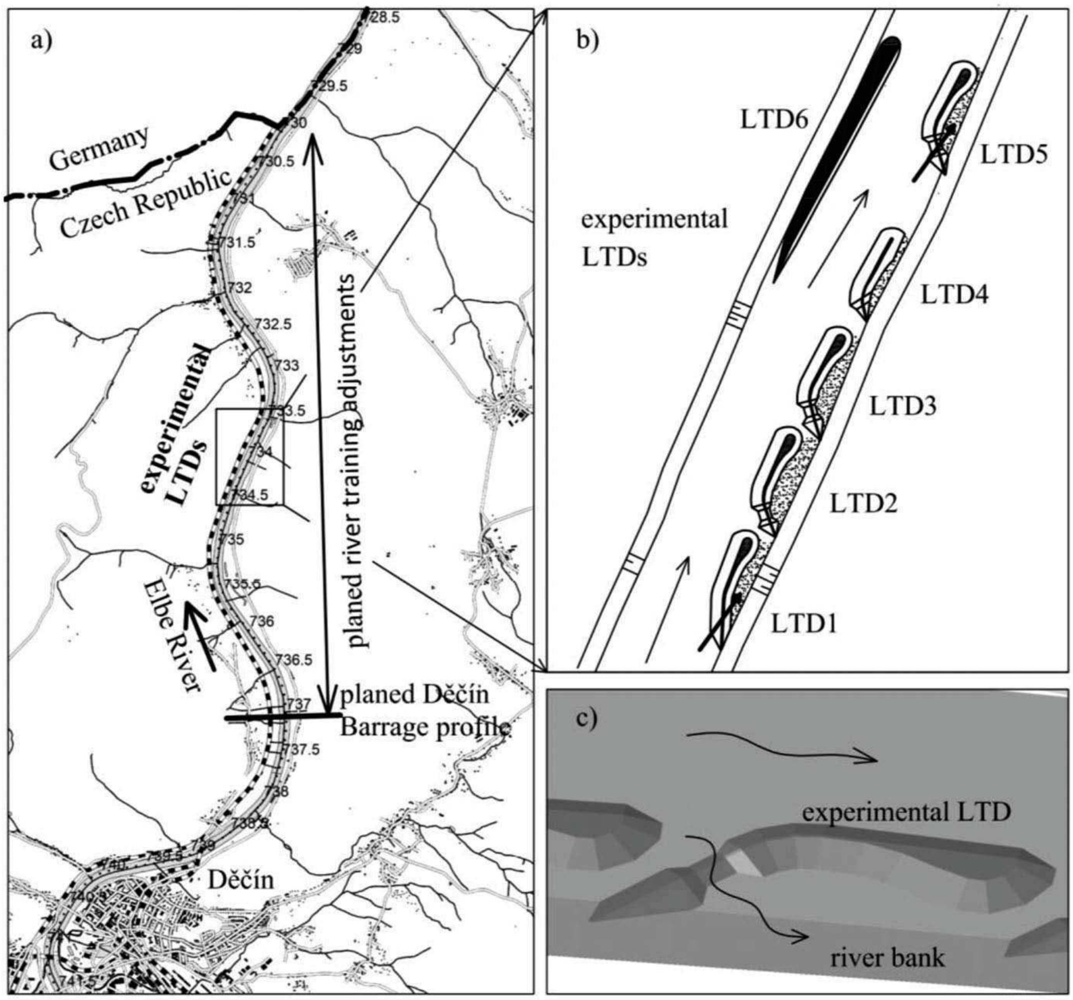

Figure 3. Innovative LTDs: a) situation on the map, b) situation of the experimental LTDs, c) detail of the innovative LTD.

function of the LTDs was verified from a hydrodynamic point of view by means of a 3D numerical model. Only afterwards was simulation started on a physical model.

The physical model was compiled first for the pilot Elbe section, which includes five LTDs on the right bank and one long LTD on the left bank. The total length of the simulated section is 750 m. Several studies have addressed the effect of groynes on the velocity conditions and changes in the morphology of the river bed in the past. They also assessed the influence of the scale of a physical model on the reliability of simulation of river bed deformations (Ettema & Muste 2004, Yossef & de Vriend 2010). For instance, the publications (Yalin 1971, Frostick et al. 2011, Abderrezzak et al. 2013, Julien 2018) recommend selecting a suitable scale of a physical model and preserving similitude conditions.

The physical model has been designed to guarantee similitude pursuant to Froude's law of similitude between the prototype and model, i.e. the ratio of the Froude number of the prototype (index p) and of the model (index m) amounts to one: $F_r = F_p/F_m = 1$. Subject to the validity of Froude's law, the condition of $Re_r = 1$ cannot be fulfilled at the same time. However, it is necessary to ensure for simulated discharges that there are fully turbulent flow conditions and the roughness is not dependent on the Reynolds number with respect to both the prototype and the model. In the case of river models, it is also important to assess the similitude of relative roughness d/h, where d is the diameter of grains on the river bed and h is the depth of water. This condition can usually be met with undistorted models that contain non-cohesive material with grains greater than 0.4 mm. With respect to models featuring bed load transport that do not handle suspended particles, the similitude of the Shields number θ and

Figure 4. Physical model of the pilot section for optimising the longitudinal training dams (LTDs).

the Reynolds number of sediment particles Re^* is usually required. As a rule, the condition of similitude Re^* can be ignored in the case of models featuring fully developed turbulent flow. Figure 4 shows the physical model placed in a laboratory with a geometric scale of l_r = 50.

The model was first verified for discharge conditions (Q_{345d}, Q_{210d}, Q_{180d}, Q_{60d} and Q_1). The course of water levels was checked on the model with the appropriate boundary conditions being complied with. Subsequently, the velocity field at one control section was tested based on a measurement obtained by the ADCP (Acoustic Doppler Current Profiler) method in situ for one focus discharge at the given location. Once the model was verified, the velocity conditions in the fairway and in the space between the LTDs and the bank were evaluated. Whereas there is a logical increase in the velocity in the fairway, velocities in the shallow bed between the LTDs and the bank decreased. Velocity variations in the fairway should be carefully assessed as they may adversely affect navigation conditions (Možiešik et al. 2014). The crucial requirement in this area is preventing the sedimentation of clay and mud particles. Based on the calculation of settling velocity, the minimum necessary transport velocity was quantified for this assessment in order that the resultant of both velocities did not enable clay and mud particles to deposit along the LTDs. The settling velocities were first derived by means of the Stokes equation (for particles with d < 0.1 mm) and the Budryck equation (for particles with 0.1 mm < d <1 mm), (Dietrich 1982). The minimum transport velocity evaluated on the basis of the distance between the lowered crests of the LTDs (approx. 100 m) was at the level of 0.2 to 0.4 m.s^{-1} at discharge Q_{180d}. Flow velocities were measured on the model using a NORTEK AS ultrasonic probe. The said criterion of minimum flow velocity made it possible to optimise the geometric design of the LTDs, which will prevent the environmentally valuable sandy area between the LTDs and the bank from being silted by mud particles. Placing the crest of the LTDs at the water level at discharge Q_{180d} and executing the 10 meters long lowered part of the crest after 100 meters appear to be optimal. The height level of the lowered crest of the LTDs corresponds to the water level at discharge Q_{345d}. The shallow river bed between the LTDs and the bank is comprised of the boulder structure of the LTD on one side and changes via a gently sloping bank into the river margin. These man-made habitats with a sand gravel substrate provide optimum conditions to gravel-loving communities living in the alluvial deposits of the Elbe. For the sake of completeness, it should be added that the flow velocities in the fairway have risen by approximately 10% as a result of the LTDs that were created, which does not pose a dangerous situation in terms of navigation.

The optimised engineering solution to the LTDs was subsequently applied to the entire 7 km long Elbe section from the planned Děčín barrage to the Czech-German state border. The company Aquatis was the designer of the initial solution. In addition to the existing six experimental LTDs, another 18 new LTDs were designed in the entire section. Their functioning was evaluated in 2015 to 2017 through another physical model on a geometric scale of l_r = 70 with a length of 100 m. A total of nine variants were executed on the model with the aim of optimising the navigation conditions, flood control measures and the environmental conditions of communities living in gravel alluvial deposits. The research also involved the verification of river bed deformations for various discharges, which was evaluated by means of the technology of a 3D scanning method (Štroner & Urban 2016). Navigational conditions were tested on the model using nautical experiments with radio-controlled cargo ship models.

3 RESEARCH ON EXPERIMENTAL LTDS IN SITU

Based on the results of the research using the physical model, the creation of six experimental LTDs was commenced in the location of interest in 2009. Figure 5 shows dam LTD2 at discharge between Q_{345d} and Q_{180d} in 2016, and during the dry summer of 2015.

The goal of creating the experimental training dams is to verify their function in a real environment. The innovative LTDs serve to concentrate flow in the stream, protect gravel alluvial deposits and secure a greater area of natural washed banks featuring alluvial deposits. Gravel banks were built purposefully for spreading endangered plant and animal species. Detailed hydraulic, morphological and biological monitoring has been conducted on the experimental LTDs for 10 years now. The aim of the hydraulic monitoring is to verify their effect on the navigation conditions through the detailed observation of water-surface and velocity conditions in the Elbe section of interest. Water levels are gauged at a 5-minute interval and transferred automatically for processing. Inspection geodetic surveying is conducted at measuring sections twice a year. Measurements at eight cross sections in total are conducted using the ADCP method several times a year as part of evaluating the velocity field.

The morphological monitoring aims at verifying the impacts of the experimental LTDs that have been created on the Elbe river bed in terms of a change in the morphology and structure of the substrate of sandy areas between the LTDs and Elbe bank. The following Figure 6 (left) displays the development of the grain size distribution in the space between experimental training dam 3 and the bank, processed by the company Aquatis (2009-2019). The grain size distribution of the gravel area has been monitored since 2009. It follows from the graph that greater sedimentation of particles ranging from fine-grained sand to medium gravel gradually occurs after the creation of the LTDs. This circumstance is partly due to a certain decrease in the velocities between the bank and LTDs. A very significant flood with a culmination of approximately Q_{50} took place on the Elbe in 2013, which evidently manifests itself in the grain size distribution with the removal of finer sand and gravel particles. The following years saw gradual stabilization of the grain size distribution, which corresponds to the conditions at natural Elbe habitats. Figure 6 (right) bears witness to it, showing the grain size distribution curves of all the natural sandy habitats monitored on the Elbe between Ústí nad Labem and Dresden, which provide excellent conditions for protected communities living in gravel alluvial deposits. The analysis was prepared based on data from 2018. A total of 16 natural sites

Figure 5. Experimental dam LTD2: in 2016 at discharge ranging between Q_{345d} and Q_{180d} (left), during the drought in 2015 (right) (Aquatis 2016).

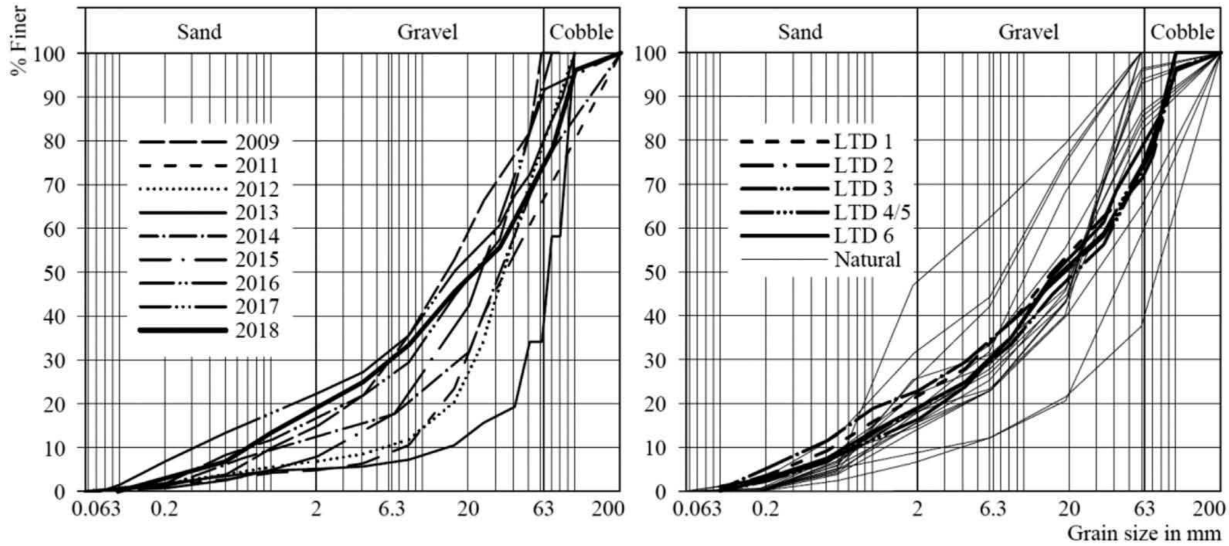

Figure 6. (left) Development of the grain size distribution of the man-made habitat between LTD3 and the Elbe bank in the period 2009-2018. (right) Grain size distribution of natural (thin line) and man-made habitats (thick line) on the Lower Elbe in the section from Ústí nad Labem to Dresden in 2018.

are observed as part of the monitoring. The grain size distribution curves of man-made habitats downstream of experimental training dams LTD1 to LTD6 are plotted in the graph as well. The graph in Figure 6 (right) evidently documents that man-made habitats downstream of the LTDs provide a virtually identical grain size distribution of the sandy and gravel substrate.

The observation of the man-made habitats also involves detailed biological monitoring done by the T. G. Masaryk Water Research Institute and by the company Aquatis (2009-2019). The monitoring focuses on evaluating the number of days when the sandy areas are flooded with water and, in particular, on monitoring the habitat. It is evident from the monitoring that the man-made habitats created between the experimental LTDs and Elbe bank provide comparable conditions to many plant and animal species as natural sandy banks in the Elbe section in question. In some cases, the man-made habitats even achieve better results in this respect than the original alluvial river deposits.

4 CONCLUSION

The Elbe in the Czech territory has been made navigable in the past through a system of weir basins between Pardubice and Ústí nad Labem. The section between Ústí nad Labem and the Czech-German state border has been made navigable to date only partially by means of training works. This situation is to be improved by the implementation of the planned Děčín barrage and longitudinal training dams between the town of Děčín and the Czech-German state border. Suitable parameters of the waterway will be provided by means of innovative LTDs. Research has been conducted in this connection in the past 10 years, coming to the following conclusions:

1) The design of an LTD must meet more criteria: provide sufficient navigation depths compatible with the conditions on the Elbe in Germany; the solution must be environmentally friendly in terms of the plants and animals living in habitats featuring alluvial gravel deposits; the LTDs must be stable during floods and must not deteriorate the flood control measures in the adjacent area.
2) In the first stage, the design of LTDs was optimised by way of a numerical and, in particular, physical model on a geometric scale of $l_r = 50$. The model simulated a section of experimental LTDs at the 750 m long pilot section. The optimisation criterion was enabling

water to flow through the space between the LTDs and the bank to prevent clay and mud particles from depositing there. There is a space between the LTDs and the bank with a small water depth and areas featuring a sand gravel substrate.

3) A total of six experimental LTDs were built in 2009 directly in the Elbe section of interest. Detailed hydraulic, morphological and biological monitoring has been taking place there since then. The results of the monitoring show that the man-made habitats formed between the LTDs and the Elbe bank provide a habitat that is very similar to natural alluvial deposits on the Elbe. Some man-made habitats have even registered better conditions as part of the biological monitoring than natural sandy a gravel banks.
4) The guarantee of navigation depths, stability of the LTDs and change in the morphology of the river bed during floods was verified on another physical model on a geometric scale of $l_r = 70$. This model represented the entire trained section from the planned Děčín barrage to the Czech-Germany state border. The resultant optimised solution to the design of the LTDs ensures suitable navigation conditions compatible with the conditions on the Elbe in Germany.

ACKNOWLEDGEMENTS

The article was written with support from the project "Documentation and Presentation of Technical Cultural Heritage on the Elbe-Vltava Waterway" No. DG18P02OVV004 solved within the National and Cultural Identity program for 2016 to 2022 (NAKI II) administered by the Ministry of Culture of the Czech Republic.

REFERENCES

Aquatis, a.s. & T.G. Masaryk Water Research Institute 2009-2019. *Hydraulic, morphologic and biologic monitoring of the experimental river training dams.*

Balvín, P., Vizina, A., Nesladková, M. & Kašpárek, L. 2015. Determining Czech Republic's minimum residual discharges. In Říha, J., Julínek, T. & Adam, K. (ed.) *Water Management and Hydraulic Engineering 2015: 14th international symposium: September 8th to 10th 2015, Brno, Czech Republic*. Brno: Institute of Water Structures, FCE, Brno University of Technology.

Brabender, M., Weitere, M., Anlanger, C. & Brauns, M. 2016. Secondary production and richness of native and non-native macroinvertebrates are driven by human-altered shoreline morphology in a large river [Online]. *Hydrobiologia*, *776*(1), 51–65.

Collas, F. P. L., Buijse, A. D., van den Heuvel, L., van Kessel, N., Schoor, M. M., Eerden, H. & Leuven, R. S. E. W. 2018. Longitudinal training dams mitigate effects of shipping on environmental conditions and fish density in the littoral zones of the river Rhine [Online]. *Science of the Total Environment*, *619-620*, 1183–1193.

Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora.

Dietrich, W. E. 1982. Settling velocity of natural particles [Online]. *Water Resources Research*, *18*(6), 1615–1626.

Ettema, R. & Muste, M. 2004. Scale Effects in Flume Experiments on Flow around a Spur Dike in Flatbed Channel [Online]. *Journal of Hydraulic Engineering*, *130*(7), 635–646.

Frostick, L.E., McLelland, S.J. & Mercer, T.G. 2011. Users Guide to Physical Modelling and Experimentation Experience of the HYDRALAB Network. CRC Press/Balkema Book, Boca Raton, Leiden, The Netherlands.

Gesamtkonzept Elbe. Strategisches Konzept für die Entwicklung der deutschen Binnenelbe und ihrer Auen. Bundesministerium für Verkehr und digitale Infrastruktur, 2017.

Henning, M. & Hentschel, B. 2013. Sedimentation and flow patterns induced by regular and modified groynes on the River Elbe, Germany [Online]. *Ecohydrology*, *6*(4), 598–610.

Julien, P. Y. 2018. *River mechanics* (Second edition). New York, NY: Cambridge University Press.

Možiešik, Ľ., Šulek, P. & Orfánus, M. 2014 KolÁrovo water structure – preparation of the research and design proposals. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, 1 (3), pp. 447–454.

Štroner, M. & Urban, R. 2016. Unconventional high precision micronetwork determination for the needs of the monitoring of the riverbed model changes caused by the water flow. In *SGEM 2016 conference proceedings: 16th international multidisciplinary scientific geoconference SGEM 2016*. *Vol. 3*, *book 5*. Sofia: STEF92.

Vermeulen, B., Boersema, M. P., Hoitink, A. J. F., Sieben, J., Sloff, C. J. & van der Wal, M. 2014. River scale model of a training dam using lightweight granulates [Online]. *Journal of Hydro-Environment Research*, *8*(2), 88–94.

Yalin, M. S. 1971. *Theory of hydraulic models*. London: Macmillan.

Yossef, M. F. M. & de Vriend, H. J. 2010. Sediment Exchange between a River and Its Groyne Fields: Mobile-Bed Experiment [Online]. *Journal of Hydraulic Engineering*, *136*(9), 610–625.