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A Complete Morphodynamic Study to Face a River Engineering Issue

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Abstract. The last reach of the Tagliamento River, in North East Italy, is progressively changing its planimetric geometry, causing sediment deposition close to a port and preventing the regular navigation in that area. In the present paper, this river engineering issue has been addressed in a complete way, first investigating the cause which brought to the present situation, and then proposing a number of design solution to mitigate the problem. Some of them have been analyzed by means of a morphodynamic numerical model, reproducing the effects on the bottom height of an average year in terms of flow and tides. The results of each simulation are compared to those of the present situation, in order to underline any advantages of the proposed design solution.

1. Introduction

Waterways play an important role in the economy of the surrounding territories, as for example in agriculture or industry. Moreover, in their lower course the usually higher water depth and the moderate current velocities make the rivers a key way of communication. Inland touristic ports are often built close to their mouth, as in the case of the Tagliamento River in the Northern Adriatic coast (Italy), where two marinas are located in the last 3 km before the sea, giving a substantial contribution to the tourism economy of the coast. The profitable use of these structures needs a substantial stability of the riverbed over time, limiting as much as possible sedimentation phenomena near the docks, which could cause a reduction of navigability and hence a limit in the use of the docks themselves.

Nevertheless, rivers are natural environments in constant evolution and they frequently show a change in their planimetric geometry, which gradually moves to a curvilinear trend if they are not strictly regimented. In fact, it is well known that straight stretches of river usually do not cover distances exceeding 10 times the channel width [1]. The stream tends to form meanders of different size, usually proportional to the channel width, as one possible adjustment to natural or anthropogenic imposed conditions like for example water discharge or introduced sediment load [2-5]. In this sense, an artificial alteration of the river course could cause a response by the river itself, involving both short and long time scales, ranging from days up to hundreds of years [6]. These observations suggest that the cause of a current situation could date back to the past, as a consequence of an unaware management of the river. Hence, an in-depth study of past events results as essential to a better understanding of the present state.

On the other hand, it is clear that any intervention could be the disturbance which triggers the morphodynamic instability of the river, and therefore it could have unexpected consequences even after several years. These changes must be predicted in some way in order to avoid uncomfortable or dangerous situations in the future. Thus, any intervention on a watercourse must be preceded by an accurate analysis of its possible effects both in the short term and over years. This kind of investigation can be carried out by means of work experience and with the support of specific numerical models, whose computational domain can be easily modified to take into account for any possible engineering work. In particular, even if tridimensional models are more accurate and suitable to describe local phenomena, bidimensional models (2DH) are still very useful in describing the general evolution of the river with reduced computational effort. This kind of models usually combines a hydrodynamic and a sediment transport module, in order to describe changes in bottom height, due to erosion and deposition phenomena. The models presented in the literature mainly differ for the way they treat the sediment transport problem; for example, most of them are applied to granular sediments only (e.g. [7-11]), whereas river bank often involves also cohesive material (e.g. [12-13]); moreover, there is still an open debate on the choice between the equilibrium or the non-equilibrium approach in handling suspended sediments (e.g. [14-15]).

In the present study an engineering issue close to the mouth of the Tagliamento River has been considered, where the riverside of a touristic marina is undergoing a depositional phenomenon, which prevents for a correct use of the dock and requires continuous dredging operations. Following the approach by Petti and coworkers [16-17], this issue has been addressed with a complete and integrated approach, including an in-depth historical analysis and numerical simulations to support planning choices. In particular, section 2 presents the study site and the historical analysis of the area. In section 3 the adopted numerical model is briefly recalled and the forcings are deeply analyzed in terms of water and sediment inflow and tidal oscillation, as they represent a key point in the numerical study. Section 4 describes the simulation obtained from the present situation, which represents a term of comparison for any other scenario. Finally, in section 5 some design solutions to mitigate the problem are proposed and analyzed.

2. Study site and historical analysis

The Tagliamento River is an alpine river that rises in the mountains between the regions of Veneto and Friuli Venezia-Giulia, in northern Italy. In its upper part, it runs through the mountainous Carnia region, then it crosses the upper and lower Friuli plains, and it finally flows into the Adriatic Sea (figure 1a).

Figure 1. a) The Tagliamento River. b) The last few kilometers of the river, before its mouth.

The downstream reach of the river, close to its mouth, has a meandering pattern, which is typical of most of natural waterways in their lower courses due to instability phenomena which can be triggered by the reduced slopes of the riverbed. In particular, the last stretch of the Tagliamento, with a mean bed

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slope of about 0.1 ‰, consists of a sequence of three meanders, starting from the village of Casabianca (figure 1b). This area, like the whole mouth of the Tagliamento River, is constantly evolving from a geomorphological point of view due to the interaction of multiple factors such as floods, wave motion, tides and not least anthropic interventions [18-19].

In particular, on the left bank of the river there is a small port called Marina Uno (figure 1b-2a), whose docks are subject to a continuous phenomenon of sediment deposition, which obstacles the navigation and hence obligate the regional administration to periodic dredging operations both on the river side and in the internal part of the marina.

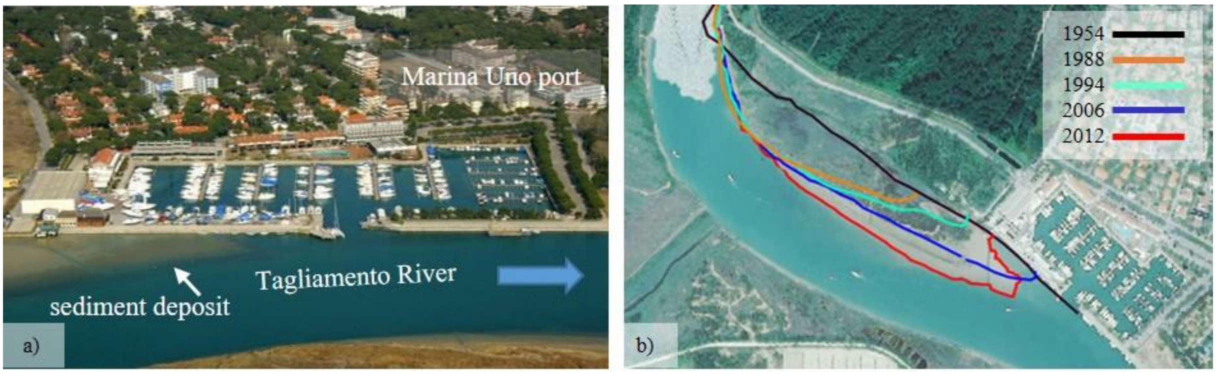

Figure 2. a) Marina Uno touristic port with the sediment deposit close to the northern dock. b) historical reconstruction of the evolution of the left riverbank.

In order to understand the causes which brought to this situation, an in-depth historical analysis has been conducted. The position of the left riverbank just upstream of the marina has been drawn on historical images taken in different years and then plotted together in figure 2b, comparing the position over the years. It can be seen that in 1954 this stretch of the river was substantially straight, whereas in 1988 the presence of an important sediment deposit is observed, which shifts the shoreline of about 90 m towards the centre of the river. After this year, the deposit still occurs, but it is more evident in the downstream sections, where it causes the movement of the front of the deposit towards the river mouth and hence towards Marina Uno port. The front displacement is about 100 m between 1988 and 1994, and 150 m between 1994 and 2006. In 2012 the dock seems clear, but this is due to the fact that the picture was taken just after a dredging work.

To better recognize the reasons of this progressive change of the morphological asset of the left riverbank after 1950s, a sequence of historical maps of this area has been collected and analyzed in figure 3. In 1927 a series of meanders is clearly recognizable, the last of which was located at the present Isola Pingherli, followed by a straight branch until the river mouth. The situation in 1937 is completely different, with a new artificial channel, which cuts the last meander with the probable intention of rectifying the terminal part of the river in order to facilitate navigation or increase the flow capacity. At this stage, artificial channel and original meander seem to work the same way, with no evident prevalence of one with respect to the other.

In 1954 the artificial channel seems to have become the main course of the river, while the original meander is almost deactivated. In 1969 the original meander has practically disappeared, while the artificial channel is no longer straight as it was in the previous image: the flow seems to create a new meander moved downstream from the original one. Moreover, this is the first picture where the Marina Uno dock appears, and it can be seen that it was located in the last straight branch before the river mouth. In this sense, the shift in the position of the left riverbank pointed out in figure 2 can be considered as the natural response of the river system to an invasive anthropic intervention.

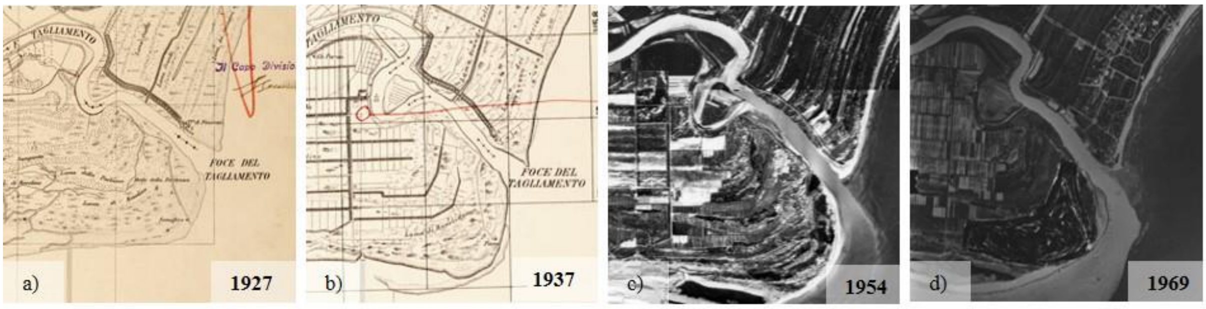

Figure 3. The last reach of the Tagliamento River in different years: a) 1927; b) 1937; c) 1954; d) 1969.

3. Numerical model and simulations set-up

In the present paper, a numerical model has been applied, which is able to describe the morphological evolution of the riverbank. The numerical approach turns out to be very appropriate to study the deposition phenomenon and to evaluate the efficiency of proposed engineering solutions capable of mitigating the problem of navigability near the port. In particular, the morphodynamic model adopted is based on classic bidimensional hydrodynamic shallow water equations, coupled with two depth-averaged advection–diffusion equations to describe the distribution of concentration of granular and cohesive suspended sediments and finally a sediment mass conservation to take into account for changes in bottom height. The resulting numerical model is based on a shock capturing finite volume scheme, and it is second order accurate both in space and time [20-22].

The computational domain depicted in figure 4 covers the last 12 km of river, and it includes the main stream and the riverbanks, in such a way that the lateral boundary conditions are never involved by the flow. The bottom height assigned to the grid nodes derives from DTM available from the local authorities, integrated with a local survey conducted in 2016 in the area close to the marina. Manning roughness coefficients have been assigned as in [18] and they result consistent with the literature [23].

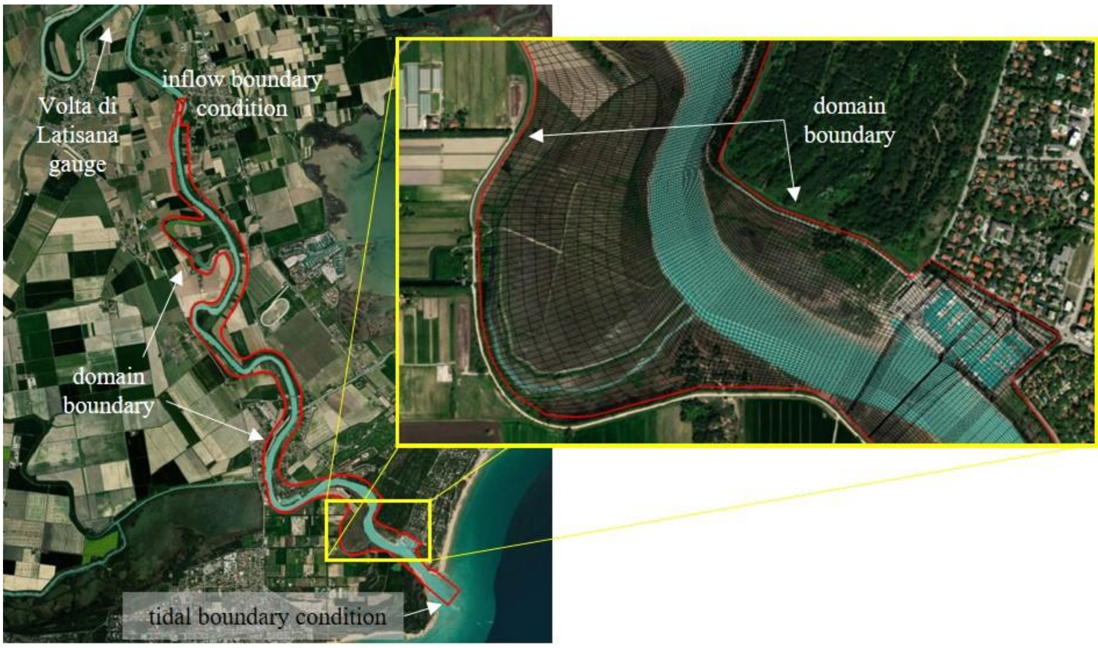

Figure 4. Computational domain used for the numerical simulations.

As the upstream and downstream boundary conditions, an inflow hydrograph and a tidal oscillation have been respectively imposed. The tidal oscillation has been represented as a sine wave, having period of 12 h and amplitude 0.4 m, which represent the average values obtained from a statistical analysis of tidal levels recorded over 24 years at the Grado tide gauge (figure 1a).

The aim of this numerical simulation is to represent the morphological effects produced in a year. Consequently, the inflow hydrograph must be representative of an average year from a morphological point of view. To this end, the hydrometric data recorded in 2008 – 2009 in Volta di Latisana, which is very close to the upstream section (figure 4), were analysed and converted into flow rates. A statistical analysis allowed us to define a flow duration curve depicted in figure 5a.

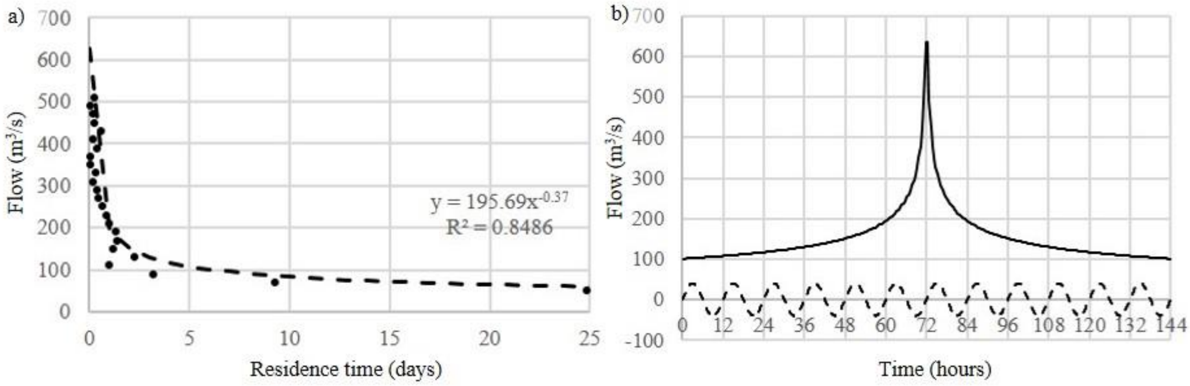

Figure 5. a) duration curve deduced from the hydrometric data registered in Volta di Latisana. b) inflow hydrograph and outflow tidal oscillation.

The annual regime of the Tagliamento river alternates low water levels with moderate or intense flood events. Sediment transport and morphological evolution of the riverbed are usually associated to major events, despite their lower frequency in the year. For this reason, only flow rates characterized by durations higher than 6 days have been considered. This means to neglect flow rates under 100 m^3/s, which is a limit value to have significant sediment transport, as proved by preliminary tests. The maximum flow assumed is 630 m^3/s, which corresponds to a duration of about 1 hour per year. The inflow hydrograph has been built with both a rising and a recession limb, assumed to be perfectly symmetrical with respect to the peak flow. The resulting 144-hour hydrograph, representative of an average year, is shown in figure 5b together with the 12 complete tidal oscillations chosen as the seaside boundary condition.

As the inflow boundary condition, also two sediment hydrographs must be assigned, which are associated to suspended granular and cohesive sediments. To this end, for granular sediments it has been chosen to use formula available in the literature to evaluate sediment flow rate as a function of hydrodynamic variables such as water depth, velocity and flow [24]. Cohesive flow rate has been assigned as in equilibrium condition through a calibration process.

As the initial condition, water depth and velocities have been assigned as deduced from a preliminary simulation with fixed bed, steady flow rate of 100 m^3/s and the same tidal oscillation depicted in figure 5b.

4. Simulation of the present situation

The present situation has been reproduced to evaluate the effects of an average year if no dredging operation were undertaken. Moreover, adopting a comparative approach to assess the efficiency of any design solution proposed to mitigate the present depositional trend, the present simulation can be regarded as the main reference.

In figure 6 the sediment deposits after the simulated average year are shown. The general trend of the riverbed to move towards the right bank is still detectable, with sediment deposits manly limited to the left riverbank and the front of the deposit shifting towards the marina up to involve also its southern dock. Nevertheless, the largest silting is observed in the fairway and at the entrance of the port. Moreover, it can be seen how the sediments spread inside the marina, which is consistent with the areas subject to annual dredging operations.

The growth of the deposit close to the north quay of the marina, estimated in about 20 – 40 cm, tends to isolate Marina Uno from the main flow of the Tagliamento river, obstructing the fairway to the port. After the simulated year, the water depth in the channel was reduced on average by one meter, with local peaks over 1.5 m.

In conclusion, the morphological evolution of the final reach of the Tagliamento river still seems to be aimed at re-forming the original meander of Isola Pingherli even if shifted more downstream. This means that the left bankside has the tendency to assume a profile which completely isolates the dock from the main flow.

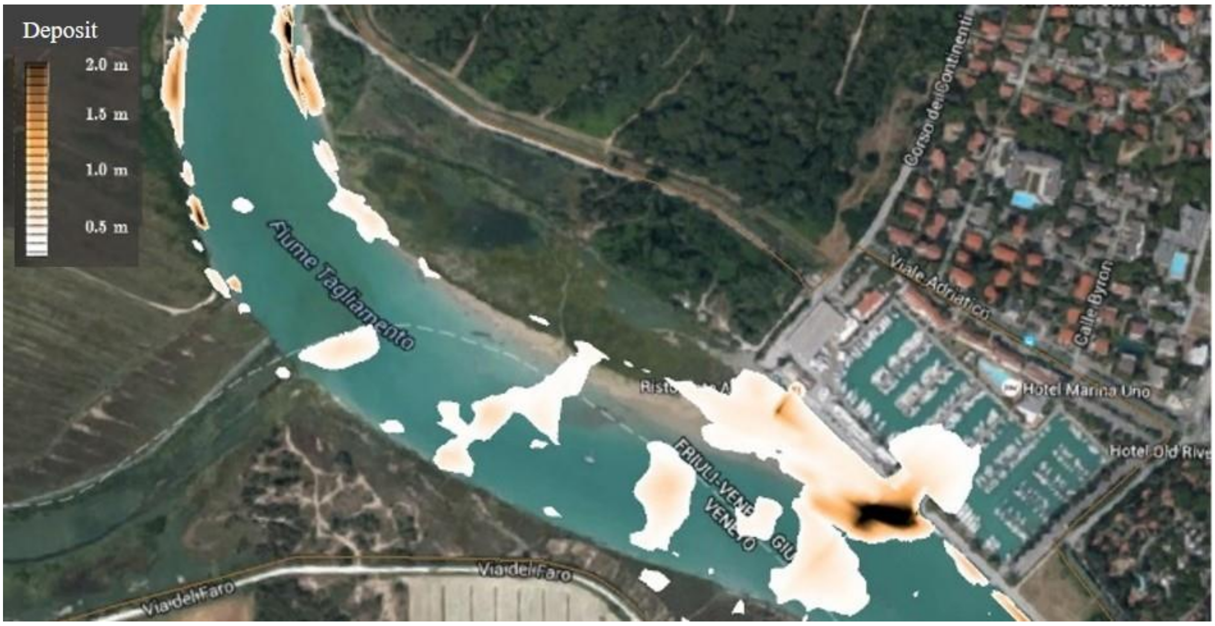

Figure 6. Simulation of the present situation: deposits after1 year.

5. Proposed designed solutions

In order to mitigate the ongoing morphological trend, a number of design solutions have been proposed, as for example the construction of longitudinal defences on the left bank to protect entrance and docks of the marina (figure 7a-c).

Moreover, also the construction of transversal works (groynes) on the left bank has been considered to protect the access to Marina Uno (figure 7d-e) or even more structural intervention such as the displacement of the entrance of the marina from its current position to the end of the southern quay to get it as far as possible from the sediment deposit.

In the following, two further solutions are presented: the construction of a canal in the left riverbank and the construction of longitudinal defences on the right riverbank. These are then evaluated by means of a comparative approach. This means that the computational grid is modified in order to represent the new design solution and the same average year simulation has been conducted as for the present situation, i.e. with the same initial and boundary conditions. The results, in terms of sediment depositions at the end of the simulation are then analysed and compared to those obtained on the present situation, to evaluate any possible convenience of the proposal.

Figure 7. Design solution to mitigate the present depositional trend. a-c) longitudinal defences on the left riverside; d-e) transversal works at the port entrance.

5.1. Canal in the left riverbank

The construction of a canal in the left bank of the Tagliamento river, excavated within the floodplain area immediately upstream of the north quay of the marina has the aim of ensuring the self-cleaning of the quay itself. This should be obtained increasing the current velocity in the canal and in front of the dock, which should prevent sediment deposition. The entrance to the canal has been located in the initial part of the meander, whereas the outlet is immediately upstream of the northern quay of the marina (figure 8a). The overall length of the canal is about 570 m, with a bed slope of 0.1% and a trapezoidal cross section (bottom width of 20 m and bank slope 1:3).

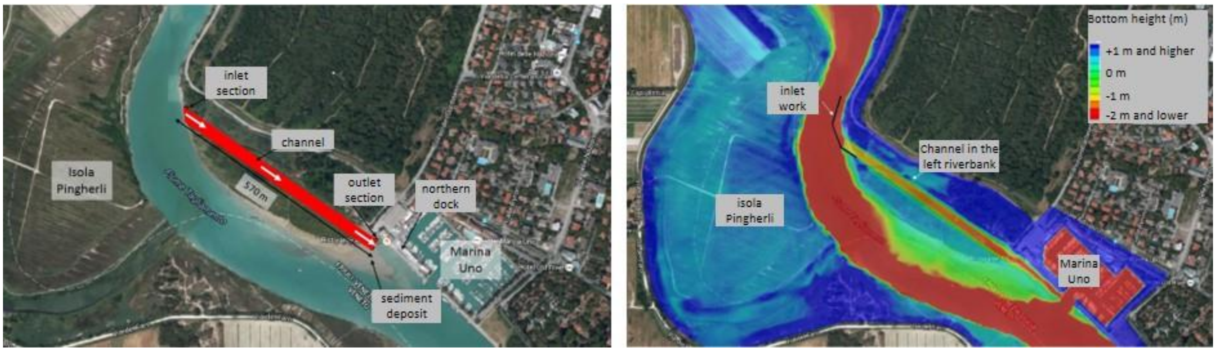

Figure 8. Artificial channel in the left riverbank. a) planimetric view; b) bottom height of the modified mesh.

Construction works of the canal should include an excavation of ca 30000 m^3, the protection of canal banks with stones to avoid erosion, and an intake plant to intercept part of the main flow. The bottom height of the computational domain has been adapted to the new configuration (figure 8b); a Manning coefficient equal to 0.0167 s/m$^{1/3}$ has been assigned to the bottom of the canal, and the same forcings have been assigned as for the simulation of the present situation, in order to simulate the morphological effects of the same medium year.

In figure 9 the deposits resulting at the end of the simulation are depicted. The comparison with the results in absence of the canal (figure 6) shows that the proposed intervention helps to maintain the northern dock cleaner. However, there is no appreciable reduction of the deposit at the entrance of the marina, where dredging operations would always be required. Moreover, there is a tangible tendency to deposition inside the canal, especially in the final part, reducing its efficiency. Furthermore, after only one year the intake plant has already stopped a large quantity of sediments, potentially causing negative effects on the whole work.

Finally, even if the modelled intervention can bring some benefits in terms of reducing the sediment deposition in front of the northern dock, however, it seems not to be crucial in keeping clear the entrance of the marina, and it also causes severe changes in the sediment dynamics of the area close to the canal beginning.

5.2. Longitudinal defences on the right riverbank

The longitudinal defences on the right riverbank just in front of the marina (figure 10a) have the double objective of reducing erosive phenomena on this side of the river, and hence to stop the formation of the new meander. In this way, the riverbed would be stabilized in the present configuration, with benefits for both the left and right banks. The proposed intervention has a total length of about 830 m, and it has been modelled as a submerged cliff made by stones, with an assigned Manning coefficient equal to 0.0167 s/m$^{1/3}$. The computational grid has been modified to better describe this area, adopting for example smaller cells in proximity of the right riverbank.

Figure 9. Canal in the left riverbed: deposits after1 year.

In order to analyse the stabilising effect of the proposed work, it has been decided to model the changes induced by the work on a longer time scale, equal to twenty years, assuming that no dredging operations are carried out in this period. The results are depicted as a cross section in figure 10b, where the bottom height after 20 years with and without longitudinal defence are compared: in the absence of the cliff, the right slope is further eroded, while the accretion of the left slope increases, with largest effect at 2 m depth. This indicates that the accretion of the left bank towards the marina has slowed down, thanks to the longitudinal defence.

Finally, it seems that the cliff has a global stabilizing effect on the riverbed, as the river appears to maintain almost the same width, which is essential to let the flow passing through.

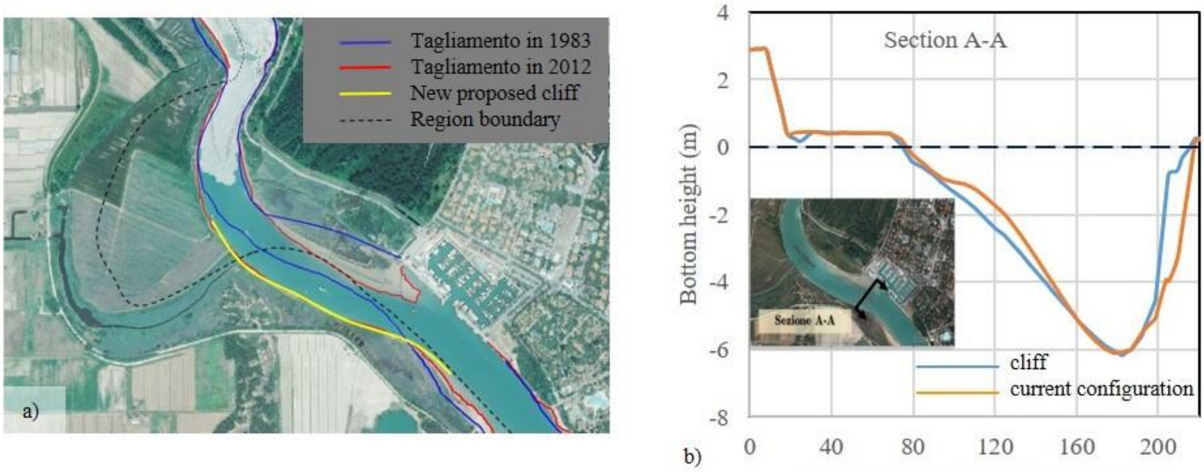

Figure 10. Longitudinal defences on the right riverbank. a) planimetric view; b) results of the simulation of 20 years as a cross section.

6. Conclusions

The last reach of the Tagliamento River in the northern Adriatic coast presents an engineering issue, involving the touristic port Marina Uno, where the growth of a sediment deposit on the riverside prevents the mooring of boats on the external side of the northern dock. The topic has been addressed through a complete approach which includes a study to understand the cause of the current situation, and the formulation of an engineering proposal to solve or at least mitigate the problem.

In particular, first a historical reconstruction has been carried out comparing aerial images, which proved that the deposition phenomenon belongs to a general tendency of the river to divert from a straight course in that area and form a new meander. This trend is likely to be ascribed to a river engineering work executed about 90 years ago, creating an alternative straight channel to the existing meander, probably as an attempt to make a larger discharge flow towards the sea.

Once the main cause of the problem has been recognized, some design solutions have been considered and tested through the application of a morphodynamic numerical model, in order to verify which is the best solution among those analysed. To this end, a careful reconstruction has been carried out of the forcings acting over a medium year and able to influence the river morphodynamics. The application of the model to the present situation and to the proposed interventions points out the advantages and drawbacks of the suggested works with respect to the present configuration.

The results suggest that none of the proposed solution is able to solve the problem, however fixing the position of the right bank seems to stabilize the configuration, slowing down or even stopping the formation of the new meander. This can be probably explained observing that the area of the cross section should remain almost constant to allow the flowing of the discharge, which does not substantially change over the years. In this way, also the river width should not vary considerably.

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