D6.9 APPLICATION OF A MORPHOLOGICAL MODEL TO EVALUATE DOWNSTREAM EFFECT OF RESERVOIR FLUSHING OPERATION

WORK PACKAGE 6 - PILOT CASE STUDIES

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INDEX

Figure index

Table index

1. Preface

The present work is an outcome of the project *"SEE HYDROPOWER, targeted to improve water resource management for a growing renewable energy production"*, in the frame of the South-East-Europe Transnational Cooperation Programme, co-funded by the European Regional Development Fund (www.seehydropower.eu).

The project is based on the European Directive on the promotion of Electricity from Renewable Energy Sources respect to the Kyoto protocol targets, that aims to establish an overall binding target of 20% share of renewable energy sources in energy consumption to be achieved by each Member State, as well as binding national targets by 2020 in line with the overall EU target of 20%. Objectives of the *SEE HYDROPOWER* deal with the promotion of hydro energy production in SEE countries, by the optimization of water resource exploitation, in a compatible way with other water users following environmental friendly approaches. Therefore, it gives a strong contribution to the integration between the Water Frame and the RES-e Directives.

Main activities of the project concerns the definition of policies, methodologies and tools for a better water & hydropower planning and management; the establishment of common criteria for preserving water bodies; to assess strategies to improve hydropower implementation, such as small hydropower; testing studies in pilot catchments of partner countries; promotion and dissemination of project outcomes among target groups all over the SEE Region countries.

In particular, here is presented the report D6.9 "Application of a morphological model to evaluate downstream effect of reservoir flushing operation", which is part of the Work Package 6 - Pilot case studies.

2. Summary

The silting of hydroelectric reservoirs, that involve a consequent reduction of the reservoirs capacity, is one of the major problems that Italian dams owners are facing. In the last years, several regulations regarding reservoir management have been amended in Italy to cope with sedimentation processes and prevent ecological impacts in the downstream river reaches. In particular, the Directive DL n. 152/99 enforces precise environmental conditions to be complied during sediment reservoir operations. As consequence, all concessionaires of dams are obliged to perform a reservoir management plan, defining rules for the sediment release operations.

The present deliverable describes the theoretical basis of the MORIMOR-GIS (MOuntain RIver MORphology) model, a morphodynamic model applied by RSE for the computations of sediment transport capacity and morphological changes. The proposed model, aims to be a valid and useful tool for the hydroelectric operators, since it allows the optimization of the flushing and sluicing operations, taking into account the turbidity limits imposed by the regulations, the morphological effects caused in the downstream river, and the consumption of water required by each operation, and therefore, the loss of production. The MORIMOR-GIS model was developed in order to allow the simulation of sediment transport in mountainous rivers, characterized by relatively large longitudinal slopes and strong non-uniform sediments.

The MORIMOR-GIS model was applied to a real pilot case, the Comelico dam located in the North of Italy, to study morphological effects due to sediment release operations.

In particular, the model was used to simulate the flushing operation conducted in 2009 by the dam owner, when more than 300.000 m3 have been released downstream.

The comparison between the calculated and measured values of turbidity has shown the good reliability of the obtained results. The implementation of the Comelico dam model enabled to calculate the suspended and total sediment concentration reached during the flushing operation (compared with the limits established by the law), as well as to assess, qualitatively and quantitatively, the erosion and deposition processes in the first reaches downstream the dam.

3. Background

The sedimentation of hydroelectric reservoirs, and the consequent reduction of the storage capacity, is one of the main problems that the hydropower producers have to deal with, as emerged from the study commissioned in 2010 by ITCOLD, Italian National Committee for Large Dams, (ITCOLD, 2009). The study stated that about 53% of the sites investigated in Italy are suffering from the silting effects, with an average reduction in the reservoir volume of 47% (see Figure 1)

The survey was carried out by considering 285 reservoirs, approximately 52% of the total Italian reservoirs, corresponding to a potential total volume of 7.35 billion m^3, corresponding about 55% of the total volume of all large dams Italian (13.35 billion m^3).

As shown in Figure 1, the ITCOLD study reported that almost half of the analysed reservoirs (134 of 285, 47%) are not affected by siltation phenomena. For the others (151 of 285, 53%) it was estimated a sedimentation rate equal to the 47%. In general, has been evaluated an overall reduction of the storage volume equal to 30%, 2.24 billion m^3 of sediment respect to 7.35 billion m^3 of the total volume for the investigated reservoirs.

Extending this result to all Italian reservoirs, it is estimated a total loss of storage volume of about 4 km^3.

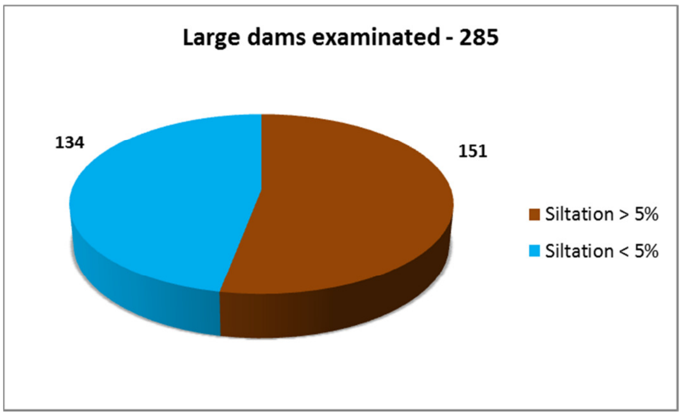

Figure 1 –Silting rate in the 285 reservoirs analysed (ITCOLD, 2009).

	EXAMINATED RESERVOIRS		SILTATION > 5%				SILTATION < 5%	
	Elevation m asl	Number	Reservoirs Number	Storage Volume m^3	Silted Volume m^3	Siltation percentage	Reservoirs Number	Storage Volume m^3
ALPS	> 2000	26	3	4.40E+07	4.67E+06	11%	23	2.65E+08
	> 1000	47	16	1.22E+08	4.40E+07	36%	31	4.18E+08
	< 1000	50	38	3.33E+08	4.40E+07	13%	12	3.31E+08
APENNINES	> 1000	16	8	4.18E+08	3.37E+07	8%	8	1.61E+08
	< 1000	146	86	3.84E+09	2.11E+09	55%	60	1.44E+09
TOTAL		**285**	**151**	**4.76E+09**	**2.24E+09**	**47%**	**134**	**2.62E+09**

Table 1 – Volumes and silting rates for the 285 analysed reservoirs, divided by altitude and mountain region.

In the last years, the Italian legislation concerning the sediment management made great efforts to face the challenges related to reservoirs siltation.

In 1976, the Merli law imposed at the dams owners to respect the turbidity limit of 80 mg/l in the water outlets, assimilating them at the industrial discharges. As consequence, most of the hydroelectric producers stopped the normal practice of the sediment release operations, in order to avoid financial penalties. The result was that some reservoirs lost more than 50% of their storage capacity, due to sedimentation processes, with damages both under the economic and safety point of view. In some cases, the outlet works have been completely or partially blocked by sediments, losing their functionality, with the result that the supervisory body on the dams safety (ex Registro Italiano Dighe - RID), imposed heavy restrictions on the reservoir water levels.

With the amendment of the Directive DL n. 152/99, to cope with sedimentation processes, the legislator recognized that sediment release operations (flushing, sluicing, etc.) aim to “ensure the maintenance of the storage capacity”. Consequently, the dams operators were allowed to evacuate the sediments also through the outlet works, but with the respected of new environmental constrains. Now, the dams owners are required to prepare a document, called “*Sediment management Plan*”, with the information concerning timing and methods to be adopted for the sediments removal. The document, that should be approved by the competent Region, reports also the operational activities program, indicating the suspended solid concentrations that cannot be exceeded during the flushing operations, for the protection of ecosystems downstream.

The legislation which regulates the procedures for the flushing/sluicing operations is faulty in many operational aspects. The deficiencies in the national regulatory framework concern the operations control methods, the definition of shared analytical approaches, but above all the lack of references and guidelines to identify the limit thresholds. All these aspects increase the need for technical reference standards in order to support the local authorities and the competent Public Administrations.

In principle, numerous procedures and techniques can be applied to prevent, reduce and mitigate reservoirs sedimentation, through “*active*” measures that consist on the reduction of sediment yield in the catchment area, or “*passive*” methods, based on control of the siltation in the reservoirs. Among the latter, the sediment release operations through the bottom outlets (*flushing*) is one of the most functional and economical techniques.

The flushing operations, with an high water level in the reservoir, allows the removal of the material settled in the proximity of the outlet works. Moreover, if this technique is frequently repeated, it could be extremely efficient for the total evacuation of the fine sediment that deposits during the ordinary operation of the dam. For the release of the coarse sediment, which normally settles in the initial area of the reservoir, it is necessary that the flushing is executed for an enough period, maintaining a low water level in the basin.

The release of significant amounts of sediment, in quite high concentrations, can have negative consequences, such as the temporary increase of turbidity in the water course downstream or the occasional clogging of the bottom outlets. For this reason it is fundamental plan, test and simulate these events in advance, in order to ensure an optimal and safe control of the operations.

In the SEE HYDROPOWER project, RSE proposed the application of a morphodynamic model, the so-called MORIMOR-GIS - Mountain River MORphology model (Peviani, 2003), able to describe and reproduce the effects of the flushing operations in the rivers located

downstream the reservoirs affected by sedimentation. The model wants to be a valid and useful tool for the hydroelectric producers, since it allows the optimization of the sediment release operations, taking into account the turbidity limits imposed by the regulations, the morphological effects induced downstream, and the consumption of water required for each operation, and therefore, the loss of production.

In the Chapters 5, 6 and 7 of this report, the application of the MORIMOR-GIS model to a real case study, the Comelico dam, is illustrated; the selected dam belongs to the complex hydroelectric system of the Piave river, serving the Pelos power plant. The comparison between the results obtained by the numerical model (MORIMOR-GIS) and the “in situ“ measurements, proved the validity of the proposed instrument.

In particular, Chapter 5 is referred to the MORIMOR-GIS application at the Comelico dam, with a general description of the basin, the main issues related to the reservoir siltation, that the dam owner has to face, as well as the main input data necessary for the model.

Chapter 6 and 7, describe the numerical simulations performed with the MORIMOR-GIS in order to reproduce, under a modeling point of view, the flushing operation executed at the Comelico dam in the 2009 spring.

4. MORIMOR-GIS, MOuntain RIver MORphology model

During the sediment release operations (such as flushing or sluicing) from artificial lakes, a large amount of material feed the downstream river within a time period of hours or days, with consequent rather fast change of bed elevation. An acceptable representation of the physical phenomena can be obtained by MORIMOR GIS, a morphodynamic GIS integrated model, particularly indicated to study non-uniform grain-size sediment transport capacity at basin scale and for both short- and long-term morphological analysis.

4.1. Theoretical formulation

Mountain streams are generally part of a dense hydrographic network, with extremely variable, both in time and space, hydrological, morphological and sedimentological characteristics. The MORIMOR model was developed in order to allow the simulation of strong non-uniform sediments and relatively large longitudinal slopes, which are typical characteristics of mountainous rivers.

The hydrodynamic module is based on the simplified unsteady shallow water equations (Kinematic wave model). The sediment transport module permits to choose between the *Di Silvio*, *Van Rijn* and *Engelund & Hansen* equations for the calculation of sediment transport of heterogeneous grain-size sediment, which is divided in granulometric classes. In the present model the water flow equations are solved together with the sediment equations in a quasi-coupled way, using a finite difference approximation by means of a predictor-corrector numerical scheme.

4.1.1. Liquid phase: Kinematic Wave Model

Neglecting inertia and pressure differential terms in the dynamic equation for unsteady gradually varied flow in open channels and then combining it with the continuity equation we obtain:

$$\frac{\partial Q}{\partial t} + c_w \frac{\partial Q}{\partial x} = c_w\, q_l \qquad 1$$

in which Q is the water discharge (m^3/s), q_l is the input lateral water discharge per unit length (m^2/s) and c_w is the kinematic wave celerity (m/s) which is equal to (*Cunge et al* 1980; *Miller* 1984):

$$c_w = \left.\frac{\partial Q}{\partial A}\right|_x \qquad 2$$

where water discharge Q is expressed by the Manning-Strickler equation:

$$Q = K_s\, A\, R^{2/3}\, S_f^{1/2} \qquad 3$$

in which A is the wetted area (m^2), R is the hydraulic radius (m), S_f is the friction slope and K_s is the Strickler's coefficient related to grain roughness ($m^{1/3}/s$), which is calculated by means of the following expression:

$$K_s = \frac{26}{d_{90}^{1/6}} \quad 4$$

where d_{90} is the grain diameter present in the bed for which 90% of the material is finer (m). It is important to stress that, in the MORIMOR-GIS model, K_s is allowed to vary through time and space as bed material composition adjusts during simulated morphology evolution of the river.

The solution *Q(x,t)* of eq. (1) in the domain $x_0<x<x_L$ requires one initial value *Q(x,0)* at each point of the domain and one boundary condition $Q(x_0,t)$.

4.1.2. Solid phase: 2 layers model

The mass balance for each granulometric class takes into account two layers: the *transport layer* containing particles transported in suspension and as bed load and the *mixing layer* containing particles instantaneously at rest but susceptible to vertical movements to and from the transport layer, as reported in Figure 6.

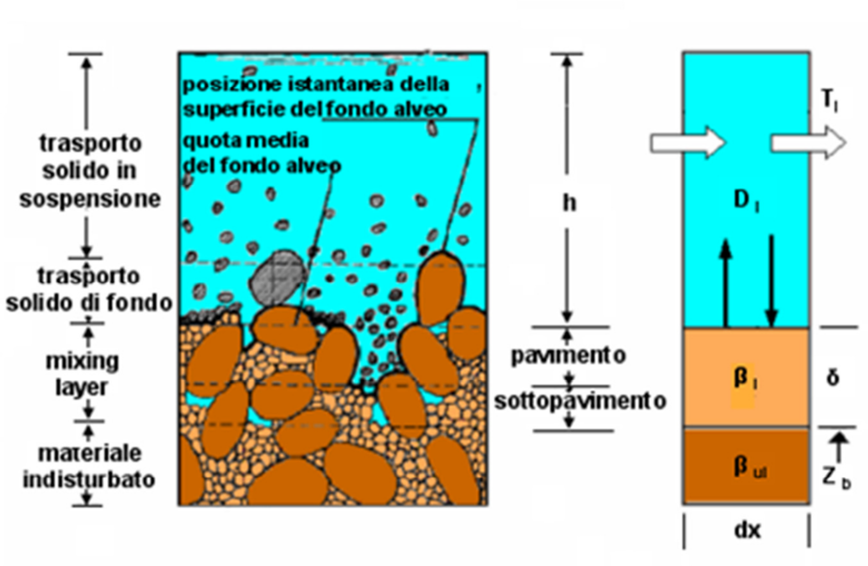

Figure 2 – Physical process of multi granular sediment transport (redrawn by Di Silvio and Brunelli).

Sediment continuity in the transport layer (including porosity):

$$B_t D_i + \frac{\partial T_i}{\partial x} = g_i \quad 5$$

in which B_t is the bottom width (m), D_i is the deposition rate of the i-th class (m/s), T_i is the total sediment transport for the i-th class (m^3/s) and g_i is the input lateral sediment discharge per unit length for the i-th class (m^2/s).

Vertical sediment balance in the mixing layer:

$$\frac{\partial(\delta\beta_i)}{\partial t} + \beta_i^* \left(\frac{\partial z_b}{\partial t} - \frac{\partial \delta}{\partial t}\right) = D_i \qquad 6$$

where δ is the mixing layer thickness (m), β_i is the fraction of the i-th class in the mixing layer, z_b is the bottom level (m) and β_i^* is:

$$\beta_i^* \begin{cases} \beta_i \leftrightarrow \dfrac{\partial z_b}{\partial t} > 0 \ (deposition) \\ \beta_{ui} \leftrightarrow \dfrac{\partial z_b}{\partial t} < 0 \ (erosion) \end{cases} \qquad 7$$

where β_{ui} is the fraction of the i-th class in the undisturbed material located below the mixing layer. It is interesting to note that summing-up all the grain-size classes, 4 classes in MORIMOR-GIS, in equation (6) we obtain the temporal bed elevation changes which is equal to the net deposition rate:

$$\frac{\partial z_b}{\partial t} = \sum_{i=1}^{4} D_i \qquad 8$$

in the absence of bedforms, the mixing layer thickness δ may be taken equal to twice the size of the largest particles, say:

$$\delta = 2\, d_{90} \qquad 9$$

4.1.3. Sediment transport equation

The sediment transport of each class is computed as a function of the local hydrodynamics and sedimentological parameters by means of the following equation:

$$T_i = \alpha \frac{Q^m I^n}{B^p d_i^q} \beta_i \xi_i \qquad 10$$

in which d_i is the representative grain diameter corresponding to the i-th class, I is the bottom slope and α, m, n, p, q are coefficients.

Equation (10) is the formula of Di Silvio, 1990; adapted to the computation of sediment transport of non-uniform grain-size materials. It is done by introducing the corresponding fraction of the i-th class present in the streambed β_i, and a "hiding and exposure" coefficient that accounts for the smaller (higher) mobility of finer (coarser) particles in a mixture, compared to the mobility of the same particles in a uniform grain size material. This coefficient can be expressed as follows:

$$\xi_i = \left(\frac{d_i}{d_m}\right)^s \qquad 11$$

in which d_m is the mean grain diameter:

$$d_m = \sum_{i=1}^{4} \beta_i \, d_i \qquad 12$$

In addition, the simplified equations of Van Rijn, 1984 and the formula of Engelund & Hansen, 1967 were also included in the sediment transport module of the model. These formulas were adapted to the computation of sediment transport of heterogeneous grain-size sediments in the same way as described for the equation of Di Silvio, 1983.

4.2. Lateral sediment inputs and internal boundary conditions

In the model, the lateral tributaries sediment conditions and the internal boundary conditions can be represented in different ways depending upon the kind of processes to be simulated. These can be briefly described as follows:

Tributary conveying material as ordinary sediment transport:

In this case the sediment transported by the water flow before a landslide event is computed (by the transport equation) with the local hydrodynamic and sedimentological characteristics of the final reach of the tributary.

Tributary conveying material from a nearby landslide as extraordinary sediment transport:

- In this case, to compute the sediment input as a function of the tributary water discharge, it is assumed that the bed material composition of the tributary (slope less than 10-15 %), immediately after the landslide event, changes to that of the landslide material and remains until the total volume is transported by the flow.

- It is possible however to consider the input of a debris flow (tributary slope greater than 15-20 %) by changing the composition of the riverbed to that of the debris material and by assuming a constant debris flow velocity entering the main stream.

In both cases the landslide material composition and volume as well as the time of occurrence and the locations of the landslide events must be known before starting with the morphological calculations.

In mountain river reaches with fixed rocky bottom are usually encountered along the main streams, in this case erosion cannot progress below the rocky bottom and the sediment load coming from upstream is transferred to the downstream reaches as overpassing loads.

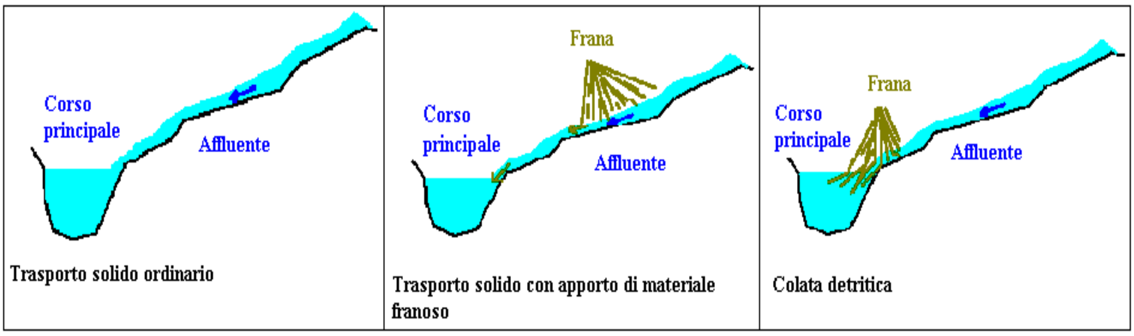

Figure 3 – Scheme of lateral sediment inputs.

4.3. "User-friendly" interface

A Visual Basic 6 user friendly interface was built-in. It permits a user to easily input the data related to the liquid hydrographs and the sediment load hydrographs, for both the tributaries and the river upstream boundary, as reported in Figure 2.

It permits the easy management of the simulations scenarios, besides the introduction and changing the data concerning initial and boundary conditions. For each "scenario" file, the MORIMOR-GIS create the corresponding "result" file, with the results obtained by the run of the model.

Through the user-friendly interface, it is possible to carry out all the phases for the implementation of the model.

- Phase 1, feeding the model with data measured in situ. The main parameters (bottom granulometric composition, cross sections, longitudinal profile, etc.) of the analysed river should be entered in the model.

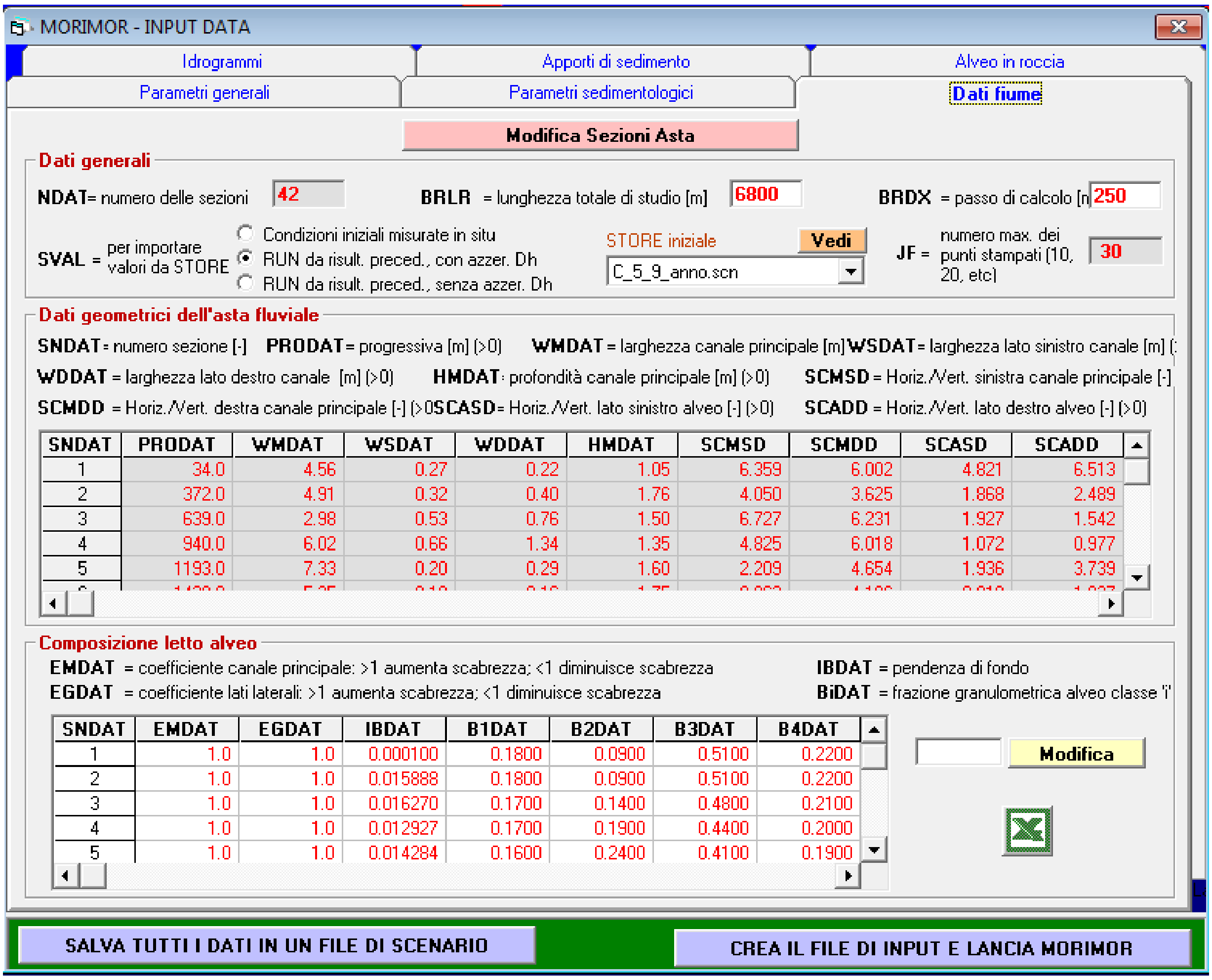

Figure 4 – MORIMOR-GIS interface developed in Visual Basic language to introduce the input data in the numerical model.

- Phase 2, granulometric initial equilibrium condition research. The initial condition of the river bed granulometric distribution is measured in a given quantity of cross sections by means of onsite surveys and then interpolated to the whole river domain for each “grid point”. To be sure that the river bed and the granulometric variations are only a consequence of a boundary variation, an equilibrium condition must be obtained. To achieve this, a series of long term runs must be done, supplying the model with a constant discharge, which represents the whole erosion-deposition process during the river life.

- Phase 3, simulation of hypothetical scenarios. In this phase, it is possible to simulate natural and artificial floods, with release of huge quantity of sediment. These simulations can be useful to predict the effect of the planned flushing operations.

5. MORIMOR-GIS application to the Comelico dam

In the previous chapter, the theoretical formulation of the MORMOR-GIS has been presented, besides the initial and boundary conditions required for the simulation of the flushing operations conducted in the reservoirs affected by sedimentation.

During the SEE HYDROPOWER project, the MORIMOR-GIS model was applied at the case study of the Comelico dam, located in Province of Belluno, to test the validity and functionality of the proposed tool. In the last years, the ENEL company (owner of the dam) has carried out several sediment release operation with a two-yearly frequency, in order to restore the original capacity of the reservoir, ensure the efficiency of the discharge outlets, and therefore the safety of the dam. Thanks to the measures performed during these operations, a huge quantity of data, such as turbidity, granulometric composition, sediment and water volume released downstream, are available, allowing the model calibration and validation.

In the present chapter, it is reported a general description of the Comelico basin, and in addition a sedimentological and morphological characterization of the examined Piave river reach. In fact, the MORIMOR-GIS model required several input data to execute the numerical simulation on sediment transport such as: longitudinal profile, cross sections geometry and granulometric composition in the river bottom.

In the following chapters 4 and 5, the simulations conducted with the MORIMOR-GIS model will be described in details, presenting the main results.

5.1. General information on the Comelico reservoir

The Comelico reservoir, located in the municipalities of Vigo di Cadore, Auronzo and Santo Stefano (Province of Belluno), is originated from the dam construction in 1930-1931 along the Piave river, before the confluence with the Ansiei torrent (see Figure 5, in which is reported the location of the Comelico dam).

The catchment area closed at the Comelico dam is 372 km^2; the basin borders on Val di Sesto in the North, on Degano and Ongare basins in the East, and with Piova basin in the South. The minimum altitude of the basin is 785 m asl in proximity of the dam section, the maximum elevation is 3092 m at the summit of Cima Undici mountain, while the average altitude is 1681 m. The area under consideration is formed of permeable soils for 51% of the total area, with 0.23 km^2 covered by glaciers.

The concrete arch dam that forms the Comelico reservoir has a variable thickness, and it extends from the portion of 784.21 m asl to a height of 827.71 m asl. Under the foundation (from 784.21 to 780.21 m) the radius of curvature and the thickness (10 m) remain constant. The structure along its entire profile of the foundation has been linked to the rock by iron rods. The basin is managed in conjunction with another gravity dam, Santa Caterina di Auronzo, at the same maximum operating level (ENEL 2008, ANIDEL ,1951).

The reservoirs feed the power plant located in Pelos di Cadore, managed by ENEL Spa. In Table 2 the main characteristics of the Comelico dam and related reservoir are reported.

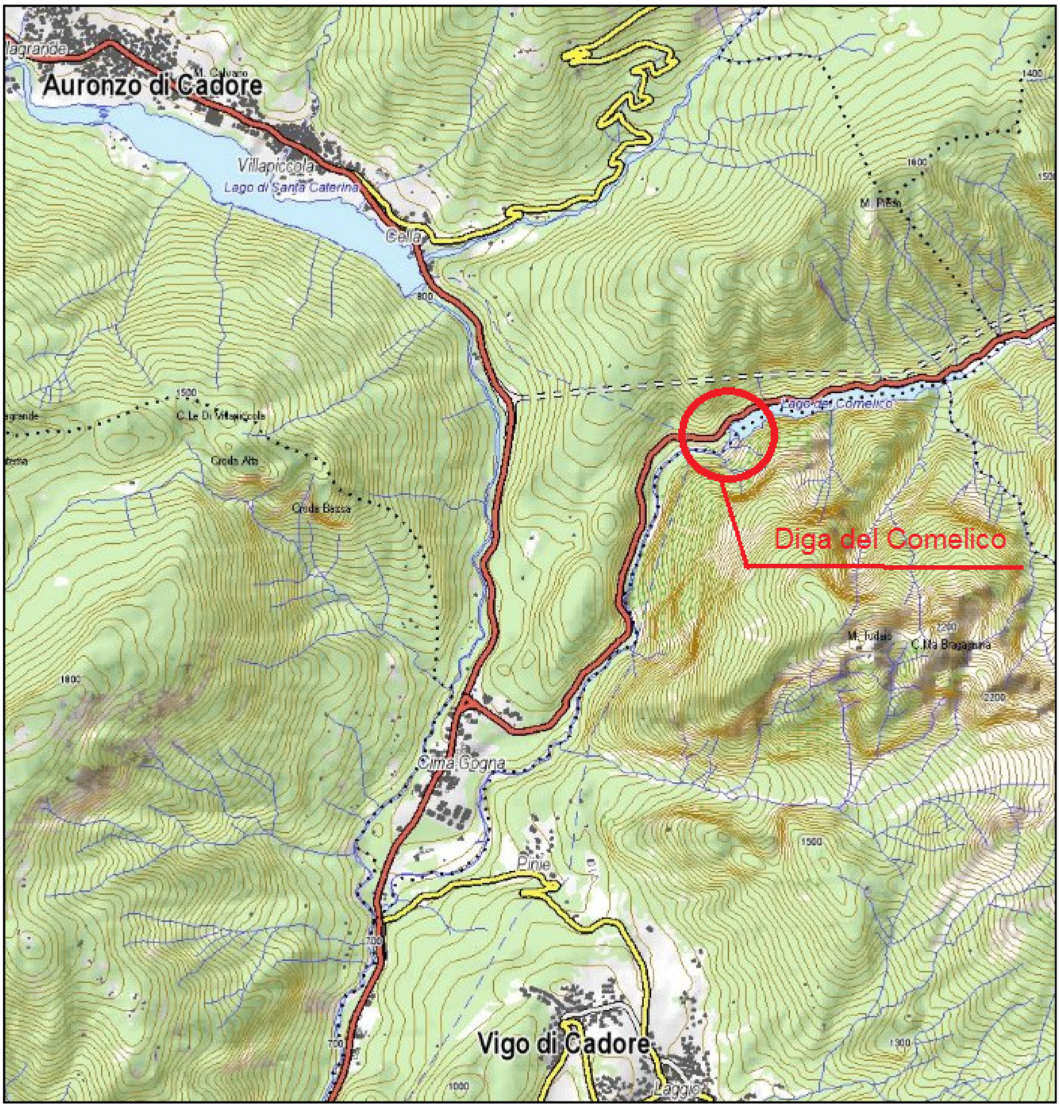

Figure 5 – Comelico basin, from 1:25,000 scale map.

Currently the dam is equipped with two surface spillways, a mid-level outlet and two bottom outlets. Following, a brief description of the outlets is reported.

Surface spillway

It consists of two groups of wells located on the right bank. The first groups is composed by 8 shaft spillways with an elliptical section (6.00 x 3.00 m) and sill at 826.21 m.a.s.l. The total length of the spillway is 128 m, and the maximum draft on the spillway can be 1.5 m. The derived water discharge is conveyed in the bottom outlet gallery. The second group is formed by 3 elliptical shaft spillways (6.00 x 3.00 m) and by a well with a square section (6.00 x 6.00 m): they are connected with mid-level outlet gallery. The maximum water draft on the sill (elevation 826.41 m asl) is 1.3 m. The spillways are equipped with air vents.

Mid-level outlet

It consists of a channel on the right bank, connected with a group of 3 shaft spillways. The structure is provided with a gate at the entrance of 3.00 x 6.00 m. The elevation of the entrance is equal to 816.21 m above sea level.

Bottom outlet

It consists of a tunnel on the right bank of the reservoir, servicing the group of eight shaft spillway. The organs of interception, placed 51 m from the inlet, are constituted by two flat sliding gates, placed in series, the dimensions of 3.00 x 4.00 m.

Additional bottom outlet

It is located on the right bank, between the original bottom and mid-level outlet. The position allows to avoid the sediment deposition just upstream the dam. The water discharge is conveyed into the mid-level outlet channel. At the entrance there are two parallel gates, with the dimension of 3.00 x 4.00 m.

Derivation outlet

It is located on the left bank with a threshold at 801.72 m above sea level. This work consists of 2 tunnel, regulated through gates at an altitude of 797.03 m.a.s.l., to derive the water discharge to the power plant. The 2 tunnels have different dimension, the first is 4.50 x 5.50 m, and the second is 2.30 x 2.45.

Table 2 – General information about Comelico dam (ENEL 2008).

Dam		
Dam name:	Comelico dam	
Dam owner:	Enel Produzione S.p.A.	
River:	Piave	
Province:	Belluno	
Region:	Veneto	
Correlated Power Plant:	Pelòs power plant	
Reservoir		
Catchment area:	372	km^2
Maximum operating level:	826.21	m a.s.l.
Minimum operating level:	803.21.	m a.s.l.
Surface spillway elevation (main group)	826.21	m a.s.l.
Surface spillway elevation (auxiliary group)	826.41	m a.s.l.
Mid-level outlet elevation	816.21	m a.s.l.
Bottom outlet elevation	791.40	m a.s.l.
Additional bottom outlet elevation	802.00	m a.s.l.
Derivation outlet sill elevation	801.72	m a.s.l.
Original storage volume	1 226 000	m^3

Current storage volume	1 010 000	m^3

Figure 6 – Comelico dam and reservoir.

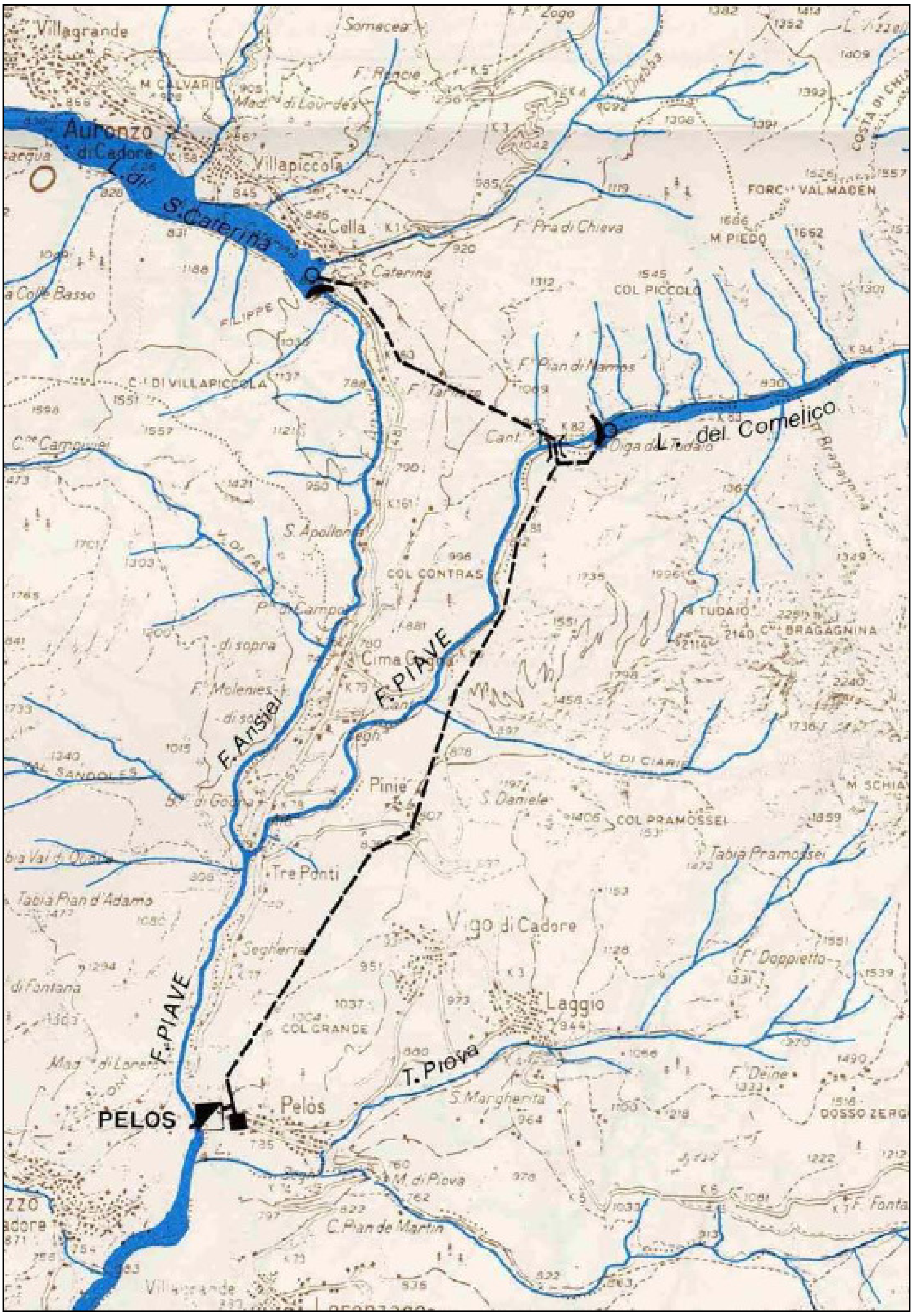

Figure 7 – Layout of the Pelos power plant system

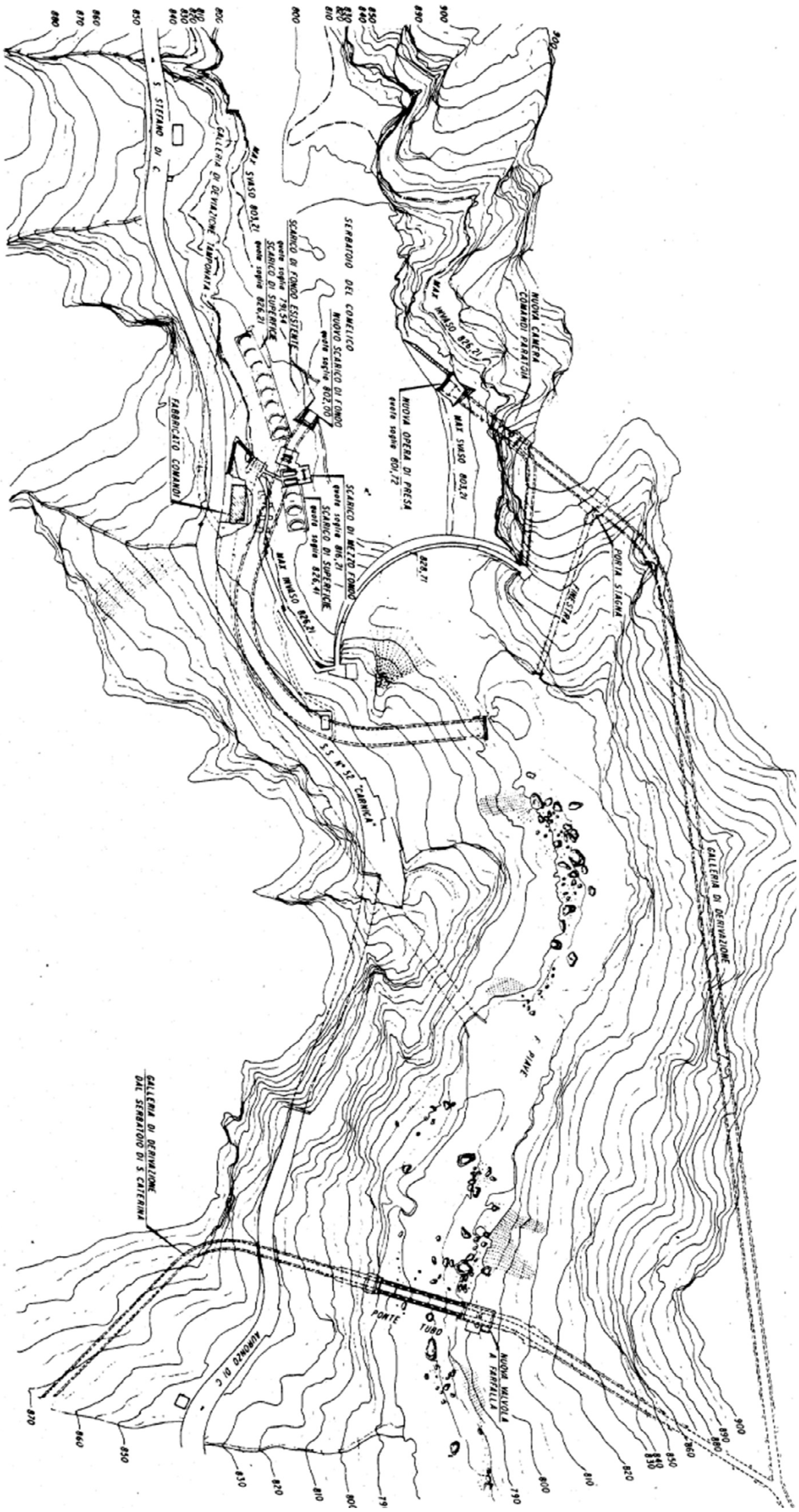

Figure 8 – Topographical plan of the dam (from of Operation and Maintenance Sheets).

5.2. Reservoir sediment management

The analysis of the reservoir siltation at the Comelico reservoir was performed by comparing the current bathymetric and topographic data with the original ones. From the survey carried out in June 2008, the following new data are deducted:

- the total storage volume at maximum operating level (826.21 m a.s.l) is approximately 1.023.000 m^3.

- the active (useful) storage at the maximum operating level (826.21 m asl), calculated respect to the minimum operating level (803.21 m asl), is approximately 1.023.000 m^3.

From the comparison with the original condition of the reservoir, it was possible to estimate that the volume of sediment trapped inside the reservoir is approximately 216.000 m^3.

The analysis annual siltation of the reservoir is performed by comparing the data of the most recent bathymetric survey with the previous ones, taking into account any artificial removal of settled material. The dam owner has estimated the annual sediment yield (50.000 m^3 / year) coming from the watershed, that is deposited in the reservoir in absence of artificial interventions.

The bathymetric survey related to the area close to the dam structure has allowed to check the status of the derivation and outlet works. The topographic survey carried out in 2008 showed the conditions of the outlet works, in particular:

- bottom outlet: the structure was affected by sedimentation. The elevation of the sediment accumulated in front of the outlet was higher than the entrance elevation;

- derivation work: it was not affected by sedimentation phenomena.

Comparing the sediment yield rate in the reservoir (about 50.000 m3/year) with the total storage volume in June 2008 (1.198.000 m3), it appears that the reservoir could be affected by a considerable reduction of the storage capacity over time; furthermore, the amount of sediments already trapped inside the active storage and, more generally the hydrodynamics of the water in the reservoir, promotes the deposition of additional material near the outlet works.

Since the tank is subject to silting phenomena, ENEL has decided to perform with frequency, at least in the last decade, management of operational actions such as to ensure over time the functionality of the switching devices and, at the same time, control the amount of material deposited in the reservoir.

Due to the fact that the reservoir is subject to silting phenomena, ENEL (dam owner) has decided to perform operating management operation with frequency to guarantee the functionality of the switching devices and, at the same time, control the amount of sediment settled in the reservoir.

Consequently, ENEL has defined the operational management of the reservoir for the removal of settled material and increase the storage capacity.

5.2.1. Flushing and sediment release operations

The flushing operation, or sediment release in general, aims to reduce the amount of settled material in the reservoir; the sediment is removed thanks to the erosion caused by water flow in transit, and released downstream through mid-level and bottom outlets.

As far as the Comelico dam, the flushing operations are carried out through the bottom outlet, releasing downstream the quantity of solid material that accumulates close to the outlets, during intense hydrological events.

The silting material is released downstream the dam while the water is drained through the bottom outlet: the drag force that induces the flow of water in contact with the settled sediment on the bottom determines the outflow of a quantity of suspended sediment in accordance with the magnitude of the water flow in transit.

The local hydrological regime allows to plan these management operations for late spring or late autumn, on occasion of quite intense hydrologic events.

Over the last decade, the owner has carried out flushing operations in 2002, 2004, 2009 and 2011.

5.2.2. Suspended concentrations limits during flushing operations

The Veneto Region with the resolution n. 138, January 31st 2006, has fixed the maximum limits of the suspended sediment concentration that have to be respected in the water discharge released downstream during the flushing operations. In Table 3 are reported the turbidity limits for reservoirs with volume greater than 20.000 m^3 or dam higher than 2 m.

Table 3 – Turbidity limits to be respected during the flushing operations.

average maximum value in 2 hours*	2% v/v (about 30 g/l)
average maximum value in 4 hours*	1 % v/v (about 15 g/l)
maximum value as average for the entire flushing operation	0.65% v/v (about 9.8 g/l)
guideline value as average in 2 hours*	1 % v/v (about 15 g/l)
guideline value as average for the entire flushing operation	0.40% v/v (about 6g/l)

* Continuously acquired data, every 5 minutes.

5.3. MORIMOR-GIS implementation at the Comelico dam case study

The implementation of the MORIMOR-GIS model at the Comelico reservoir, aims to assess the effects (qualitatively and quantitatively) of the flushing operations, or sediment releases in general, in the Pave river, in the reach downstream the dam.

The sediment transport model was applied to the Piave River in the stretch between the

Comelico dam and the Centro Cadore Lake, formed by the Pieve di Cadore dam. Figure 9 reports the geographical domain under study.

The preliminary operations for the application of the MORIMOR-GIS model concerns the introduction of the input data related to river morphology and the granulometric composition of the river bottom.

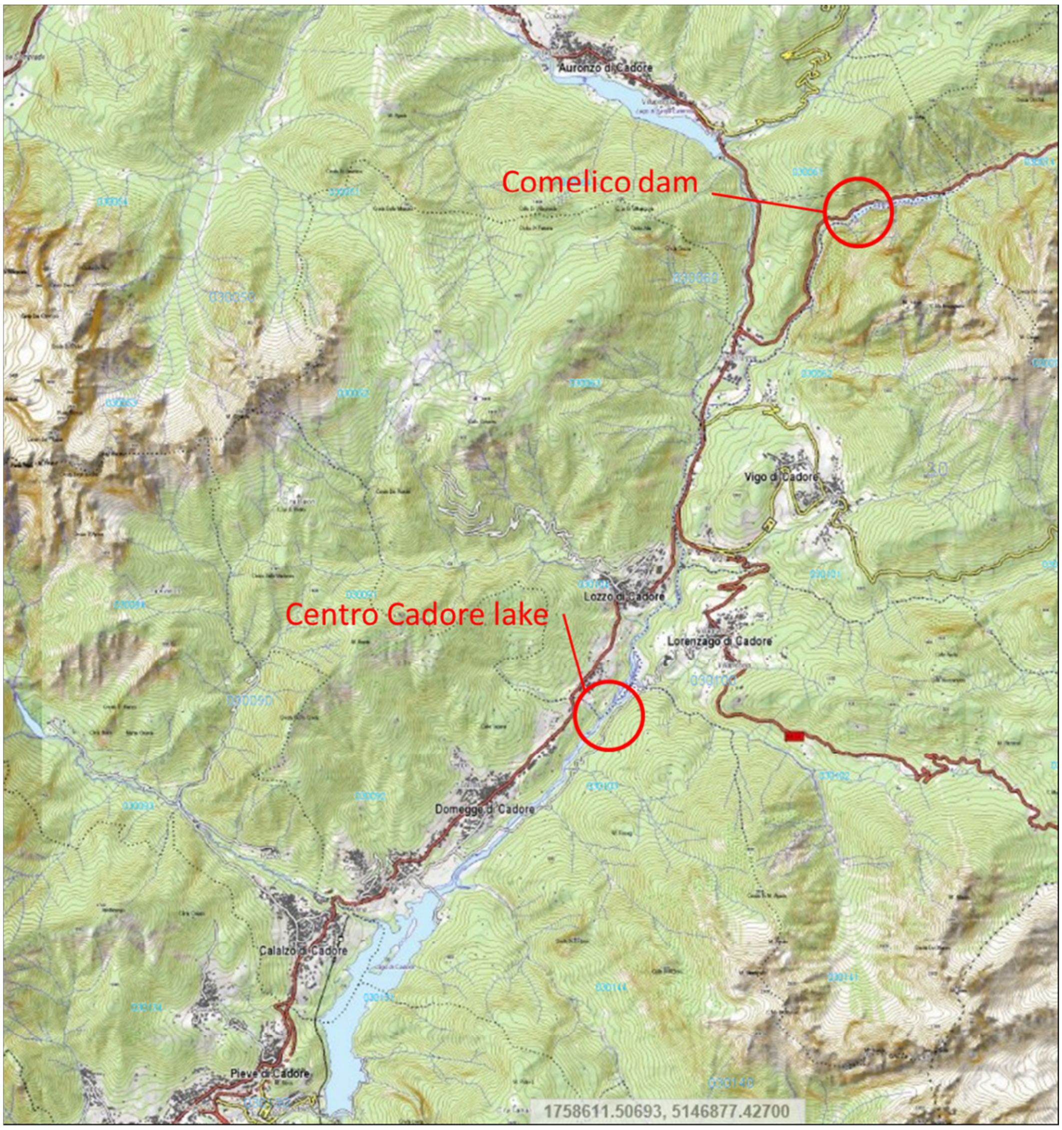

Figure 9 – Stretch of the Piave river simulated with the MORIMOR-GIS.

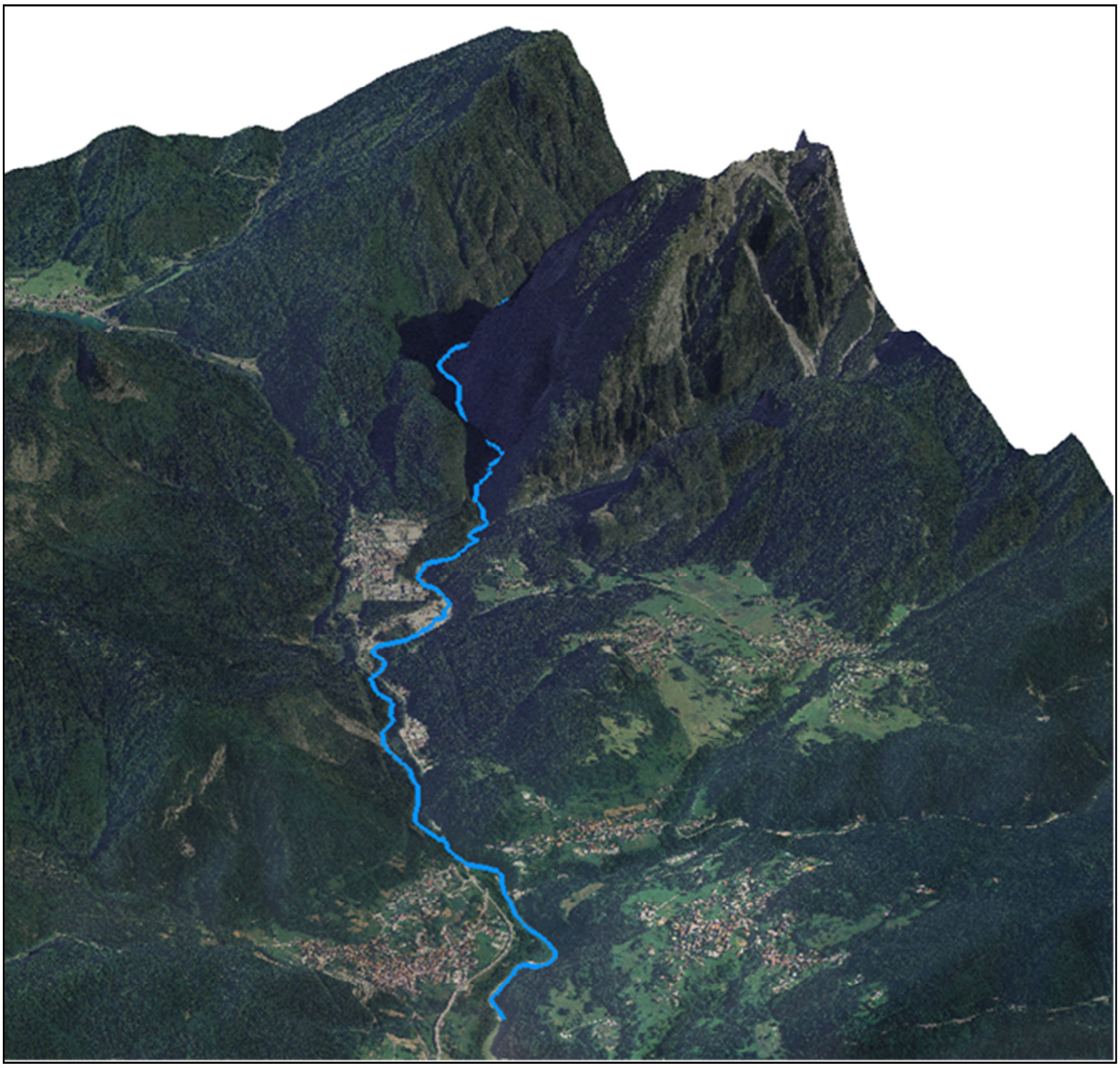

Figure 10 – Piave river, from Comelico dam to Pieve di Cadore lake, displayed in GIS environment.

5.3.1. Morphological characterization (longitudinal profile and cross sections)

As mentioned above, the simulations carried out with the MORIMOR-GIS regards to the stretch of Piave river between the outlet of the bottom channel and the confluence with the Centro Cadore Lake (Figure 9), for a total length of about 7 km. For an adequate morphological description of the Piave River, a topographical survey was carried out in August 2012, measuring 7 cross sections; successively, these data were integrated with additional information (12 cross sections) obtained in a previous study, dated in 2004.

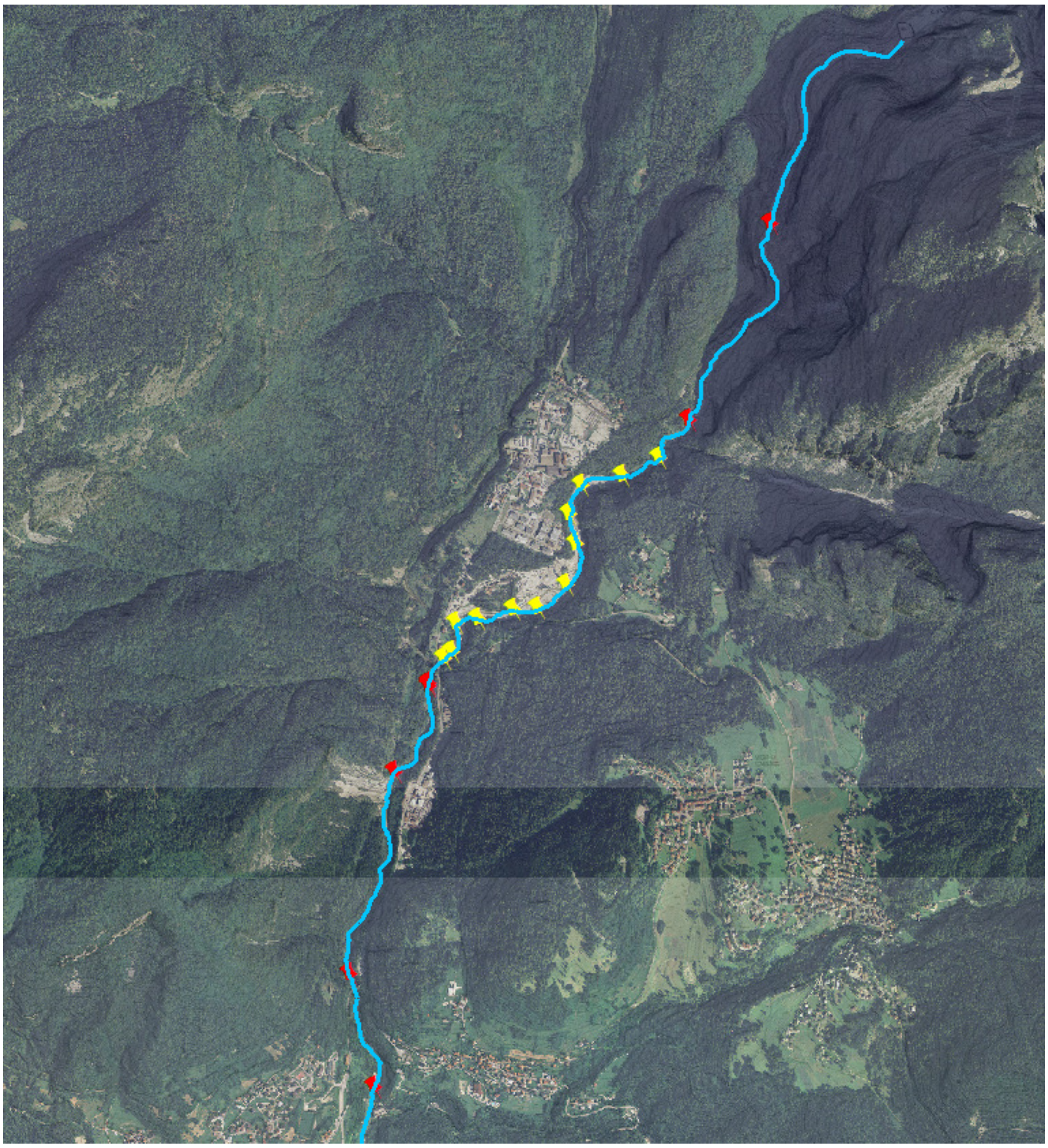

Figure 11 – Location of the topographical survey on the digital map. Cross sections measured in 2012 (in red) and in 20004 (in yellow).

The graph in Figure 12 reports the elevations of the measured cross sections along the Piave river, fixing the origin at the dam section. Due to steepness of the lateral banks, the river stretches located just downstream the dam, and the end of the study were inaccessible for topographic surveys.

In order to get the pattern of the Piave river longitudinal profile in detail, it was used the Digital Elevation Model (DEM) of the Veneto Region with resolution of 5 meters: consequently it was obtained the line of the lowest elevation or thalweg (green line in the graph of Figure 12). Since there was a little difference between the elevation of the cross sections (from topographical survey) and the profile obtained from the DEM, the green line was shifted forcing the passage of the longitudinal profile trough the elevations of the cross sections, getting a new revised profile (blue line in Figure 12).

The geometry of the cross sections, with a certain density, are required by the MORIMOR-GIS model as input data; in fact as explained before the sediment transport (equation 10) is

function of the slope and width of the riverbed. In the present pilot case study, we have used 42 cross sections: 19 obtained from the topographical surveys, and the remaining from the DEM of the Veneto Region. The model do not use the actual geometry of the cross sections, but an *equivalent* geometry, characterized by a double trapeze shape. The *equivalent sections*, input data of the model, are processed by the MORIMOR-GIS to elaborate new sections in correspondence of each grid point (every 250 m). The advantage of this approach is to get a uniform discretization of the model domain. ANNEX 1: Topographic survey, shows the geometry of the 19 cross sections achieved with measures in situ.

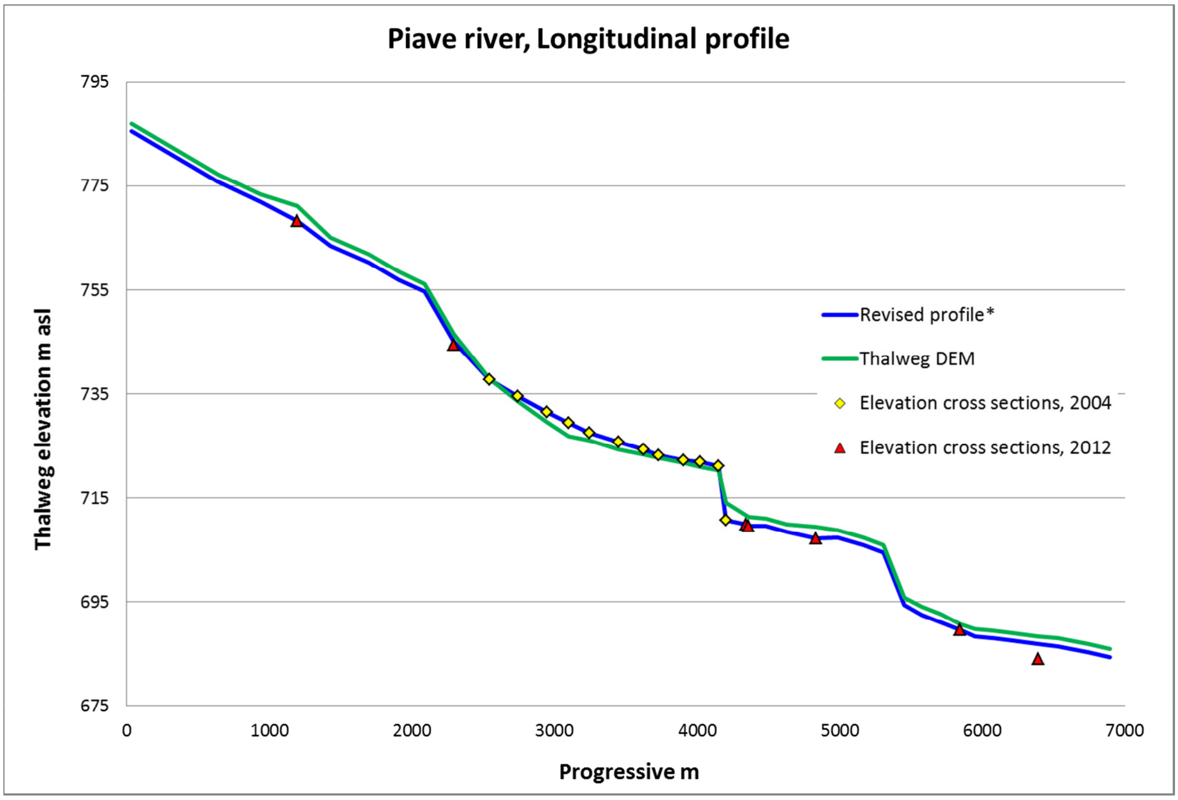

Figure 12 – Longitudinal bed profile of the Piave river obtained through the topographical survey and the Digital Elevation Model (5 m resolutions).

5.3.2. River bed composition

Equation 10 in § 4.1.3 that governs the sediment transport, requires the knowledge of the particle size composition of the riverbed for each grid point. In the present case study, 5 granulometric surveys have been conducted to characterize the bottom composition of the Piave river (see Figure 13), of which one located upstream the reservoir.

The choice of sample points was made taking into account the accessibility to the Piave river Piave and trying to have at least one measure for each river stretch with the same morpho-dynamics characteristics.

For the determination of the sediment composition of the riverbed, 5 excavations (40x40x40 cm) have been executed: the material has been sieved and subsequently the finest part

(mean diameter less than 1 centimetre) has been analysed in the laboratory. The dimension of the excavations assured that the samples were not representative of the only surface layer.

The graphs of Figure 14, Figure 15, Figure 16, Figure 17 and Figure 18, show the sediment distribution in the river bed. The granulometric curves have been subdivided in 4 classes, on the basis of the grain size:

- Class 1 = fine sediment, characterized by a mean diameter of the grains between 0.1 mm and 1 mm;
- Class 2 = sediment with diameter between 1 mm and 10 mm;
- Class 3 = sediment with diameter between 10 mm and 100 mm;
- Class 4 = coarse sediment, with diameter between 100 mm and 1000 mm.

The model required the weight percentages of each granulometric class, in correspondence of the surveys progressive. By interpolation, MORIMOR-GIS calculated the granulometric composition in each grid point, necessary operation before to proceed with the simulations.

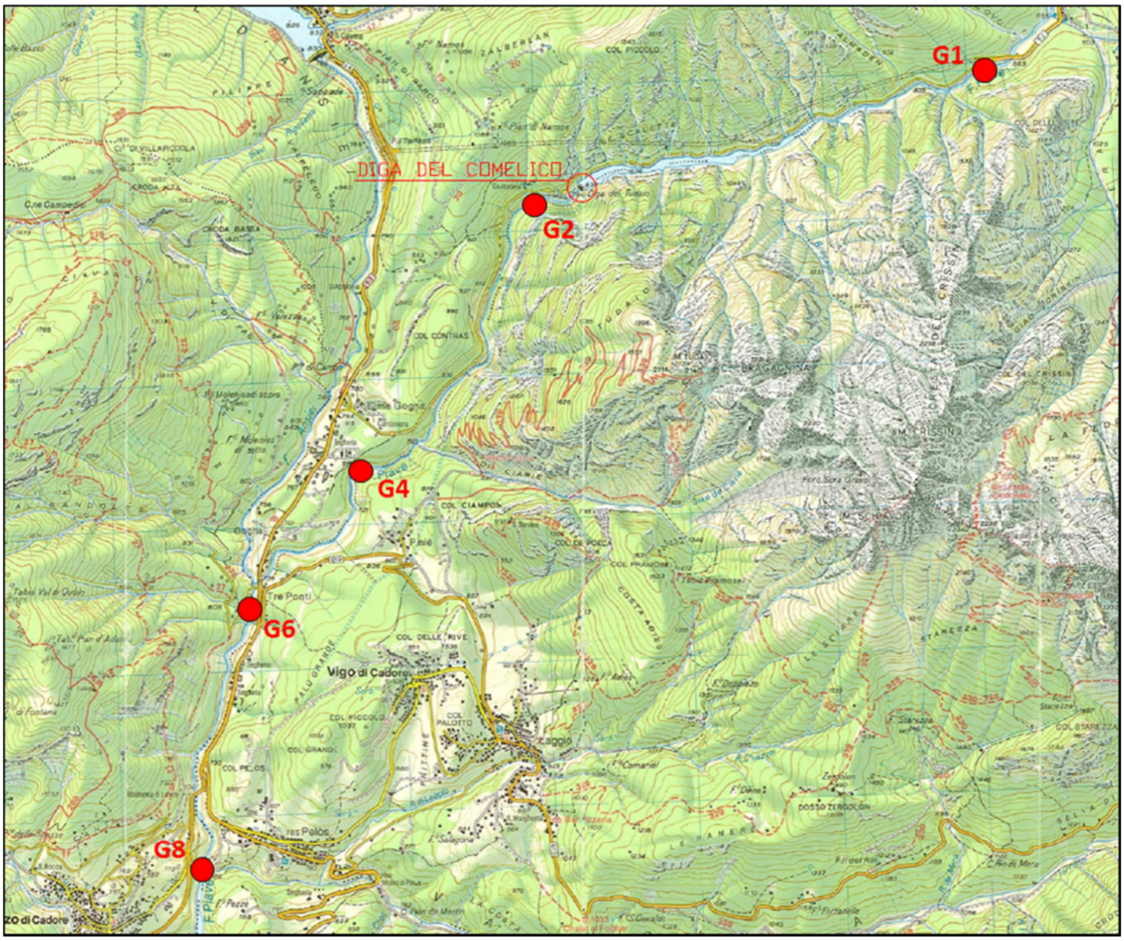

Figure 13 – The map shows the location in which the granulometric surveys have been carried out. The survey point G1 is upstream the Comelico reservoir.

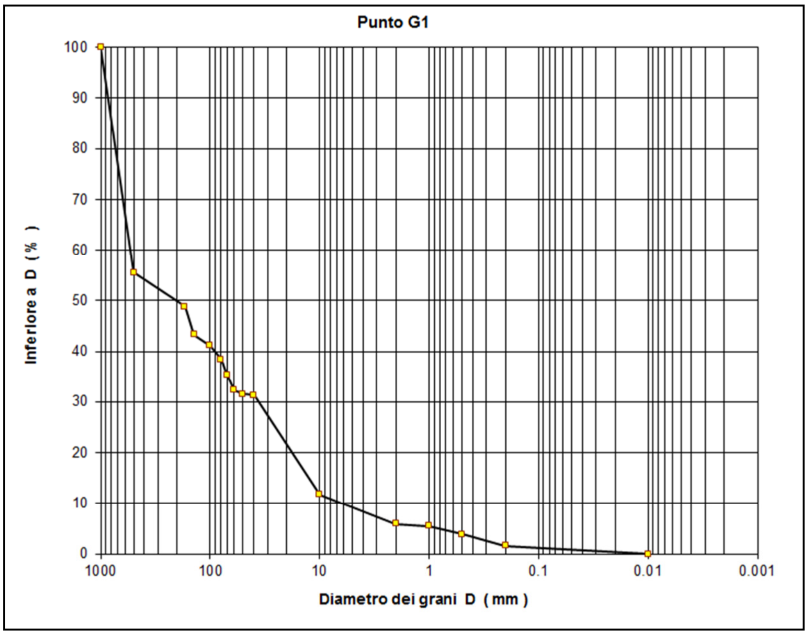

Figure 14 – Granulometric curve in the survey point G1.

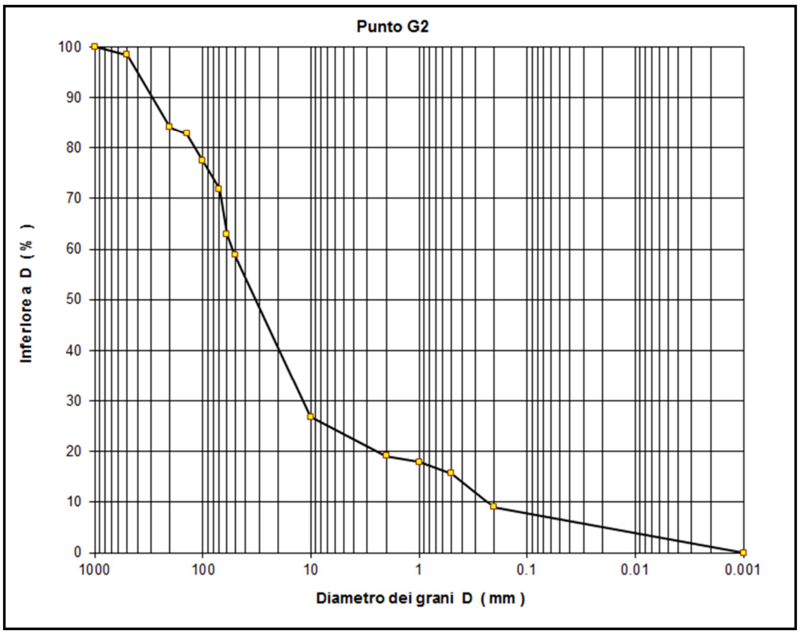

Figure 15 – Granulometric curve in the survey point G2.

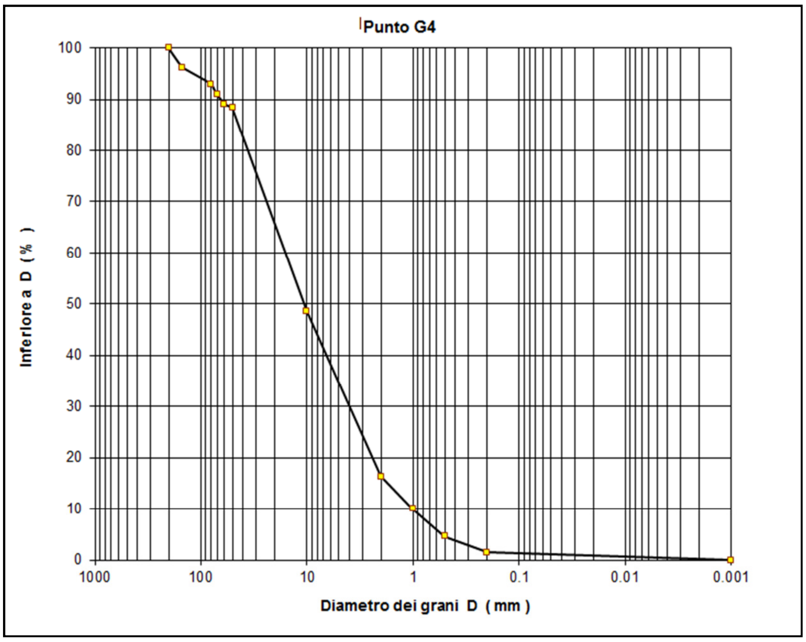

Figure 16 – Granulometric curve in the survey point G4.

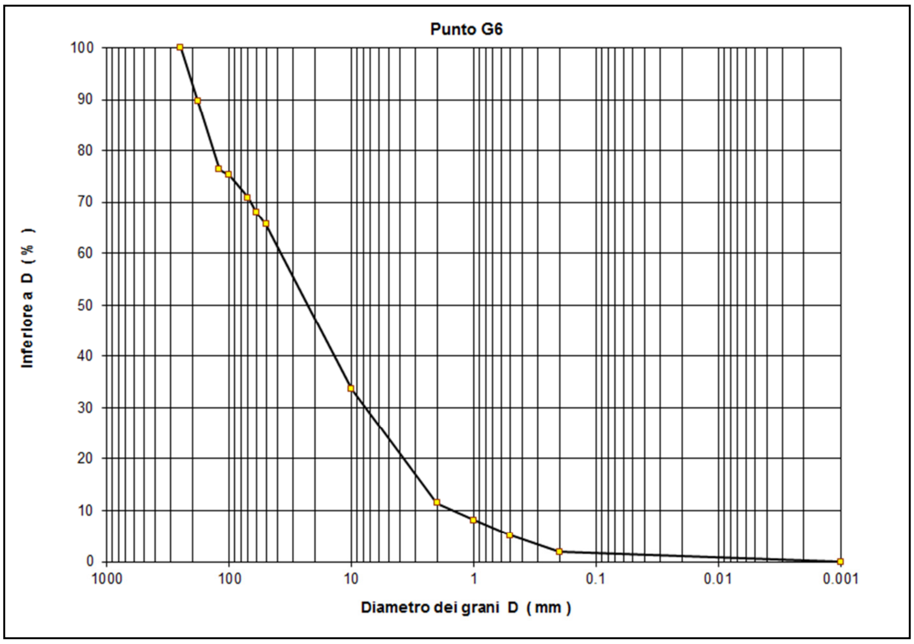

Figure 17 – Granulometric curve in the survey point G6.

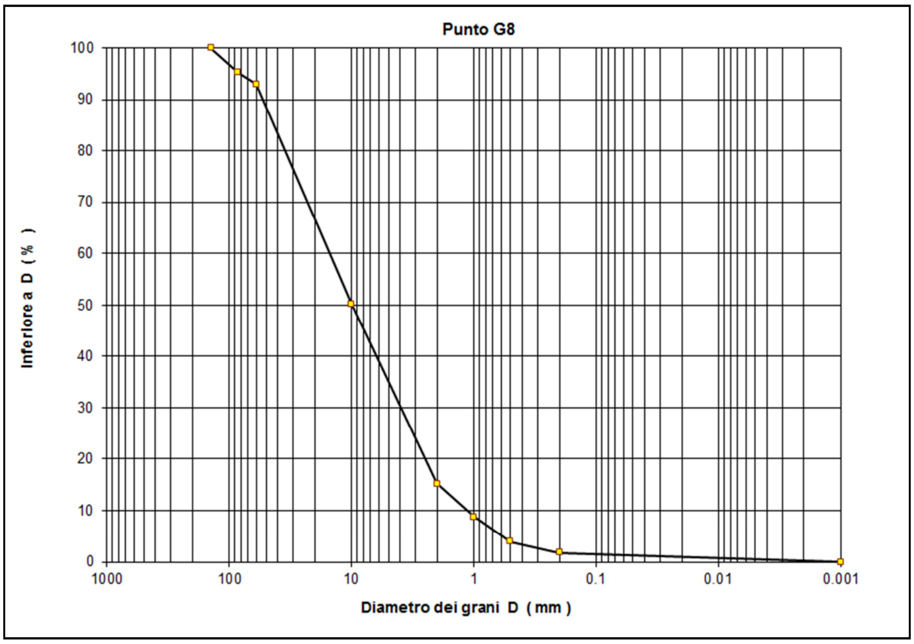

Figure 18 – Granulometric curve in the survey point G8.

6. Long term simulations

The measurements of sedimentological data (grain size distribution of the bottom material), are usually quite expensive, and certain cross section could not be easily accessible as well: therefore it is difficult to obtain data in all the branches of the hydrographic network or with the density required by the numerical model. In addition, onsite surveys are subjected to practical problems of representativeness of the average conditions of the river, as they are carried out in a given period of the year and only in a certain quantity of points of the riverbed. Indeed, it is necessary to reconstruct the composition of the bottom material in the Piave river under ordinary flow condition (Di Silvio, Peviani, 1991).

6.1. Objective of the long term simulation

The object of the long term simulation (10 years or more) is to estimate, by a numerical approach, the granulometric composition of the riverbed in each grid points of the MORIMOR-GIS model: as explained before, the grain size distribution was measured only in 5 cross section by means of onsite surveys and then interpolated to the whole river domain. During the simulations for the equilibrium conditions research, the river morphology (width and slope) is kept fixed (available from topographic surveys), while the bottom granulometric composition is free to change and adapt until it remains constant over the time: this condition is achieved when the grain size distribution of the riverbed is in equilibrium with the other morphological characteristics of the river (dynamic equilibrium configuration).

To be sure that the river bed and the granulometric variations are only a consequence of a boundary variation, an initial quasi-equilibrium condition of the bottom composition should be obtained. To achieve this issue, a series of long term runs has been done, supplying the model with a constant equivalent discharge and sediment input, which represents the typical hydrological year. The application of the model during a long period will reconstruct the composition of the bottom material in the Piave river under ordinary flow condition. This result will be used as initial condition for the successively study of sediment release event.

In the following paragraphs (6.2 and 6.3) the boundary conditions and initial the conditions ,as well, taken into account for the long term simulations are described.

6.2. Equivalent discharge

The long-term simulations were carried out considering the average hydraulic conditions. In particular, for the model boundary condition, we resorted at the concept of "*equivalent*" discharge.

The water discharge realised from the Comelico dam is not constant over the time: there is an alternation of long period in which only the minimum instream flow (MIF) is released downstream, to short period, during flood events or maintenance works, in which the discharge value is much higher.

In long term simulation, due to the calculation constrains, it's opportune to operate with a constant discharge in time. If the mean discharge value was used, the calculation of the sediment transport rate in the Piave river would be underestimated. In fact, considering the form of equation 10, the sediment transport T_s is exponentially proportional to the water discharge Q, then the periods with high flow rate, although short in time, influence much

more the calculation of T_s. In long term simulations, the model was supplied with the *equivalent* discharge, a constant discharge that is able to generate the same value of the solid transport that would occur with the actual hydrograph and the whole erosion-deposition process in the river. Therefore, the *equivalent* flow rate is always greater than the mean discharge.

During the equilibrium condition research for the Piave river, two different scenarios have been consecutively simulated:

- *Scenario A*, simulation of the Piave river conditions before the dam construction;
- *Scenario B*, simulation of the Piave river conditions after the dam construction.

The equivalent discharge considered for the scenario *A* was obtained from the hydrograph registered at the "*Ponte della Lasta*" control section, located upstream the Comelico reservoir. The measured discharge may be considered as equivalent to the natural flow in the condition before the construction of the dam, since the registration is achieved upstream the confluence with the reservoir.

For the period August 1989 - December 2012, in which the discharge values were available, it was possible to calculate the mean discharge, equal to 9.61 m^3/s, and the equivalent discharge, identical to 11.92 m^3/s. Since there was a lack of measurements in the period between 5 October 1992 and 3 October 1993, only the interval of time between October 1993 and December 2012 was considered, obtaining the following results:

- Mean discharge Q_m = 9.79 m^3/s;
- Equivalent discharge Q_e = 12.18 m^3/s.

The graph of Figure 19 shows the flow rate measured at the "Ponte della Lasta" control section and the equivalent discharge, with a red line, considered for the long term simulation regarding the *scenario A*.

To reproduce the correct value of the discharge in the river network, it was necessary to take into account the input lateral water discharge to the Piave river coming from the tributaries. For the Ansiei river, main tributary of the Piave river, it was followed the same procedure described above to estimate the corresponding equivalent discharge (equal to 3.8 m^3/s).

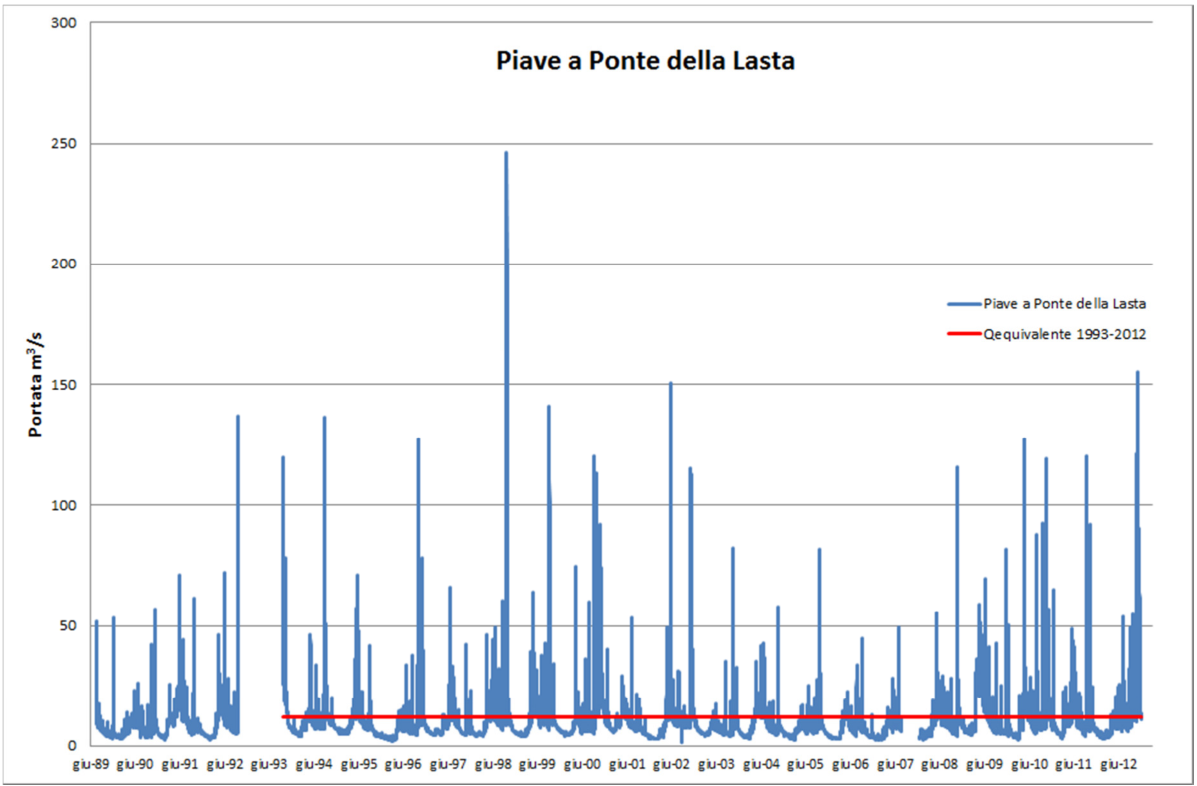

Figure 19 – Waterflow hydrograph of the Piave river, measured at "Ponte della Lasta". The red line represent the equivalent discharge.

After the construction of the Comelico dam for hydroelectric purposes, the total water discharge of the Piave river is derived to the power plant with the exception of the MIF. This caused:

- decrease of the flow rate in the Piave reach downstream the dam;
- and at same time, reduction of the sediment transport. In fact the solid material transported by the current tends to deposits inside the reservoir.

The equivalent discharge for the *scenario B*, in which we evaluated the evolution of the grain size distribution in the Piave riverbed after the construction of the Comelico dam, was calculated from the series of water flow released downstream the dam.

Considering the sheet management of the dam related to the year 2009 (the only one obtained by the operator), it was estimated the equivalent discharge, equal to 7.31 m^3/s, and the mean flow (4.11 m^3/s).

6.3. The input of sediment in the long term simulations

The Table 4 reports the data regarding the sediment volume and the grain size distribution considered in the long term simulations.

Table 4 – Table of the boundary conditions, related to the sediment input, considered in the long term simulations

	Sediment volume	Grain size distribution
Scenario A before dam	50.000 m^3/year	Granulometric composition obtained in the point of survey G1, upstream the reservoir
Scenario B after dam	50.000 m^3/year	Sediment distribution of the survey G1, considering only the finer part

In the scenario A, in which we simulated the granulometric composition in the bottom of the Piave river, before the construction of the dam, we have considered a solid input of 50.000 m^3/year, which corresponds to the volume of sediment that settles inside the reservoir each year. Furthermore, it was considered the granulometric composition obtained in the point of survey G1 (Figure 14), since, being upstream the reservoir, appears to be more representative of the natural condition of the Piave river, not influenced by the construction of the dam.

After the construction of the dam, under ordinary management of the reservoir, only clean water is realised from the dam in the Piave river downstream, without any sediment quantity. In the last decade, the dam owner (ENEL) has carried out several flushing operations, approximately every two years, conveying downstream approximately 100.000 m^3 of sediment for each operation.

Indeed, in the simulation of the scenario B, it was considered an input of sediment equal to 50.000 m^3/year.

During the flushing operations, only the finer fraction of the sediment trapped inside the basin is released downstream: in fact, the current generated during the flushing operations is not enough to move also the coarser sediment. For the characterization of the sediment (in the Scenario B), it was used the granulometric curve obtained in the survey point G1, but considering only the grains with a diameter less than 20 cm.

6.4. Results of the equilibrium condition research

The long time-scale simulation was executed for a defined river morphology and ordinary hydraulic conditions, allowing to the grain size distribution to evolve until the material composition of the riverbed remains almost constant. At that point, the particle size distribution of the bottom material can be considered in equilibrium with the morphological characteristics (slope, width) of the Piave river. This situation has been reached through numerical simulations of several years, considering ordinary water flow and sediment input (*Scenario A* + *Scenario B*).

Through long-term simulations (about 20 years) it was possible to reach the dynamic equilibrium condition between particle size distribution and the river morphology: increasing the simulation period, no significant changes of the granulometric distribution in the riverbed were possible to appreciate.

The value of the exponent *s* in the exposure coefficient (equation 10) has been calibrated

by confronting the granulometric distribution of the bottom material computed with the model against that one from the “in situ” samples (see graph in Figure 20).

In this case the value that gave the best fit was s = 0.6.

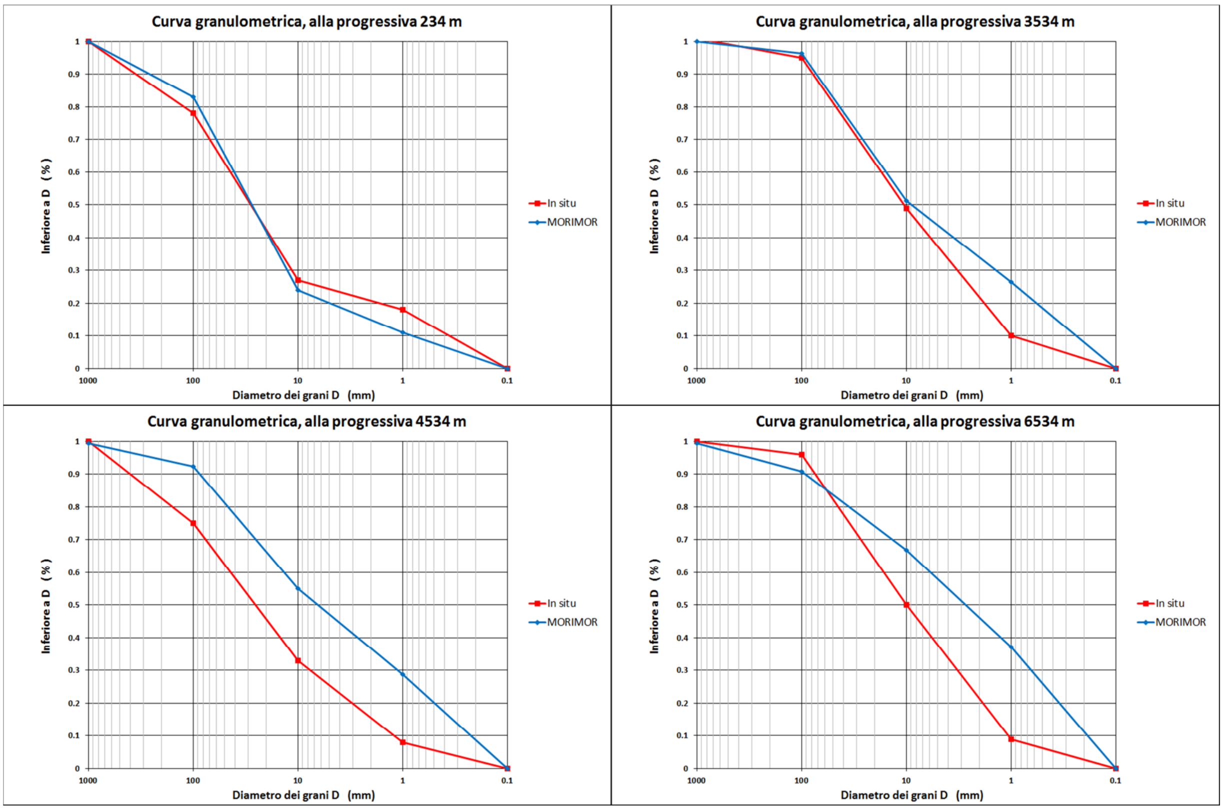

Figure 20 – Comparison between the “in situ” samples (in red) and the computation after reaching the equilibrium configuration (in blue), by MORIMOR-GIS, with the exposure coefficient equal to 0.6, in four different cross section.

7. SIMULATION OF THE 2009 FLUSHING OPERATION

The present chapter describes the flushing operation executed by ENEL in the 2009 spring, in order to reduce the silting of the reservoir, and increase the storage capacity of the reservoir; and at the same time free up the muddy sediment accumulated in the proximity of the outlet works. By means of MORIMOR-GIS, we tried to reproduce this event, considering as initial condition of the model, the water and sediment volumes released downstream during the operation. The intent is to verify the quality of the proposed model (MORIMOR-GIS) in estimating the effects on river morphology caused by the flushing operations, comparing the computed results with the “in situ” measurements.

It should be mentioned, that several flushing operations have been performed at the Comelico dam in the last decade. Due to the considerable amount of available data related to the 2009 operation, we decided to reproduced that event with MORIMOR-GIS.

7.1. General description of the sediment release operation

The aim of the flushing operation (ENEL 2008) was the reduction of the sediment amount trapped inside the reservoir, removing the solid material by erosion caused by the water flow and release the sediment downstream through the bottom outlets. The flushing operation was performed following the operational procedures described in the “Reservoir project management” and approved by the Veneto Region with DGR n. 4058 (30 December 2008).

The activities started on May 26 at 7 am, divided into the following phases:

- progressive lowering of the water level till the minimum operating level, through the use of the derivation outlet.

- gradual opening of the bottom outlet, in order to avoid uncontrolled releases, and consequently progressive lowering of the water level (until the conditions of so-called "on channel").

- control of the turbidity in the water discharged downstream the reservoir, by means of the simultaneous use of the available outlets and / or derivation channels, that have permitted to release clear water from the reservoir to dilute the outlet discharge.

ENEL continuously checked that the amount of silt removed downstream was compatible with the turbidity values measured at the monitoring station located along the Piave river, slowing down or temporarily suspending the activity: closing the outlet gates, in case of turbidity values exceeding the limits imposed by the law. In some circumstances, clear water was released from the S.Caterina reservoir, long Ansiei torrent (tributary of the Piave river) to return under the limits fixed by the regional regulation.

- Release of sediment for a time and in a concentration sufficient to remove predetermined quantity of solid material (operation carried out under continuous control of the main characterization parameters). The activity was conducted by alternating fluitation conditions to temporary closure of the bottom outlet with partial increase of the water level in the reservoir and successive sediment releases; in order to a more uniform “cleaning” of the reservoir, and to avoid over aggradation phenomena in proximity to the bottom outlet.

- end of the flushing operation on June 13, by closing the bottom outlet and reducing the water flow discharged in the Piave river, restoring the initial water level in the reservoir.

The operations were conducted only during the daylight hours, reducing the water discharge released downstream during the night-time and, if necessary by carrying on partial restoring.

At the end of the operations, to promote the restoration of the instream conditions pre-flushing, the gate of the bottom outlet remained open allowing the flow of the natural discharge in the river for the necessary time period (not less than 12 hours).

The entire flushing operation was monitored both by ENEL and ARPAV (institution responsible for the control of the river and lake water quality) by continuous measurements of turbidity and dissolved oxygen. ARPAV placed a turbidity instrument downstream the confluence of the rivers Piave with the Ansiei torrent (see Figure 21) and has calibrated the instrument by comparison with the cones Imhoff measurements. The controls were carried out continuously only in few days, with permanence of the technical staff for of 4 - 8 hours, while in the other days just surveys of short duration have been executed, observing the situation and taking samples to be subsequently analysed in the laboratory. The controls by ARPAV technicians is documented in the daily reports.

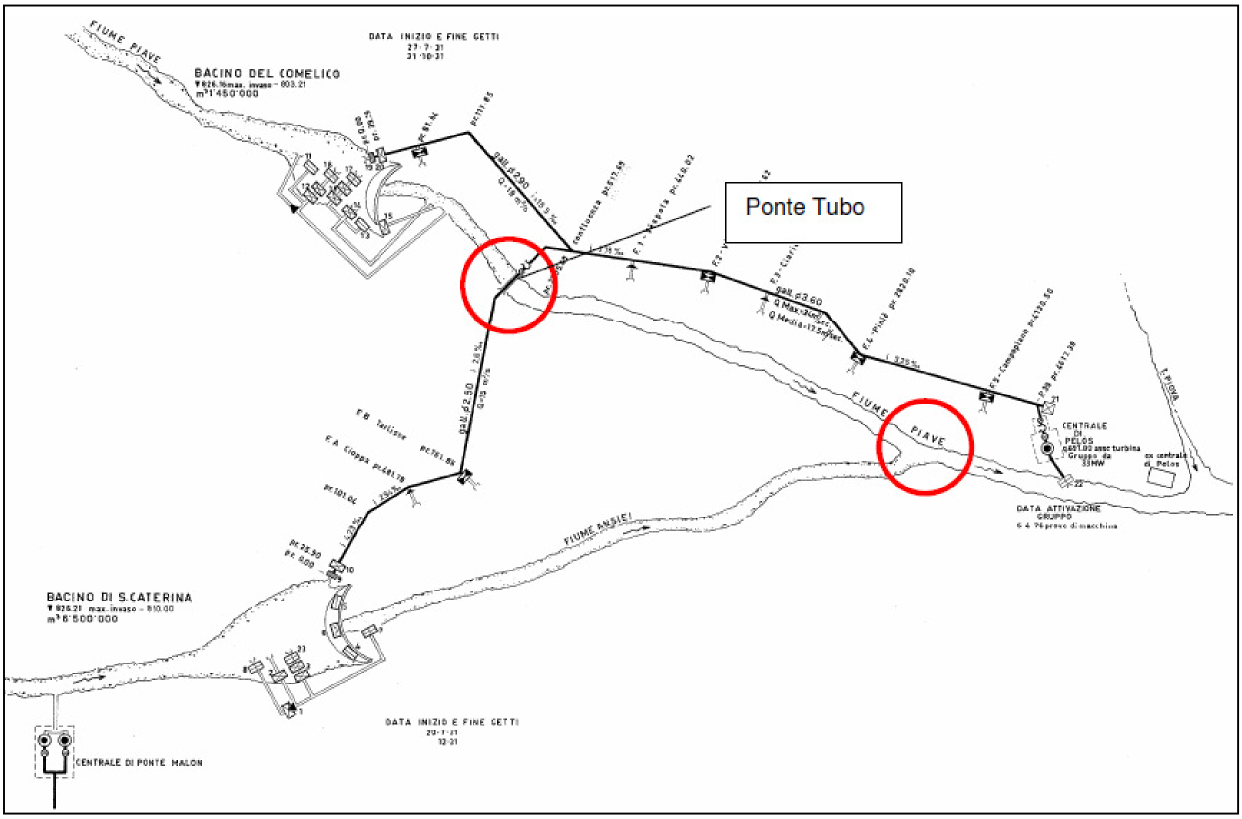

Figure 21 – Monitoring points during the flushing operation.

Figure 22 – Flushing operations in 2011. View of the reservoir.

Figure 23 – Flushing operations in 2011. Upstream view of the reservoir.

Figure 24 – Flushing operations in 2011. Detail of the derivation channel intake.

Figure 25 – Flushing operations in 2011. Detail of the outlets.

Figure 26 – Flushing operations in 2011. Outlet of the bottom tunnel.

Figure 27 – Flushing operations in 2011. Confluence of the muddy Piave river (on the right) with the clear Ansiei torrent (on the left).

Figure 28 – Flushing operations in 2011. Turbidity measurement executed by ARPAV with the Imhoff cones.

7.2. Simulation of the flushing event with the MORIMOR-GIS

The simulation of the release sediment operation planned in spring 2009 was performed considering the initial conditions (upstream hydrograph, volume and grain size of the floated sediment) measured and/or detected during the flushing event, and the granulometric composition obtained during the equilibrium condition research (see paragraph 6.4 Results of the equilibrium condition research).

In the following paragraphs, the initial conditions introduced in the model are described.

7.2.1. Water discharge released during the event

For a proper execution of the flushing operations, and reduce the reservoir siltation, it is necessary to operate with a good water discharge in the Piave river (typically during the spring or autumn period). The exact date of the operations has been agreed by the operator (ENEL) in accordance with ARPAV, Province of Belluno and Civil Engineering, sufficiently in advance, depending on the forecast of the water conditions.

For the simulation of the flushing event through the MORIMOR-GIS model, it is necessary to know the water discharge values, released downstream the dam during the operations. The operator provided the sheet of management related to the Comelico dam, with the values of discharge derived at the power station, and the water releases at the Piave river during the whole of 2009. The daily averages were the only available data, even if due to the sudden opening/closing operations of the outlet woks during the flushing, it would have been more appropriate to feed the model with the average hourly discharges (released downstream) for better consistency of the results.

The graph in Figure 29 shows the average daily water discharge released downstream the reservoir during the days of the flushing operation. For the period of the flushing event, more than 38 million cubic meters of water have been released downstream, for an average daily flow of 23 m^3/s.

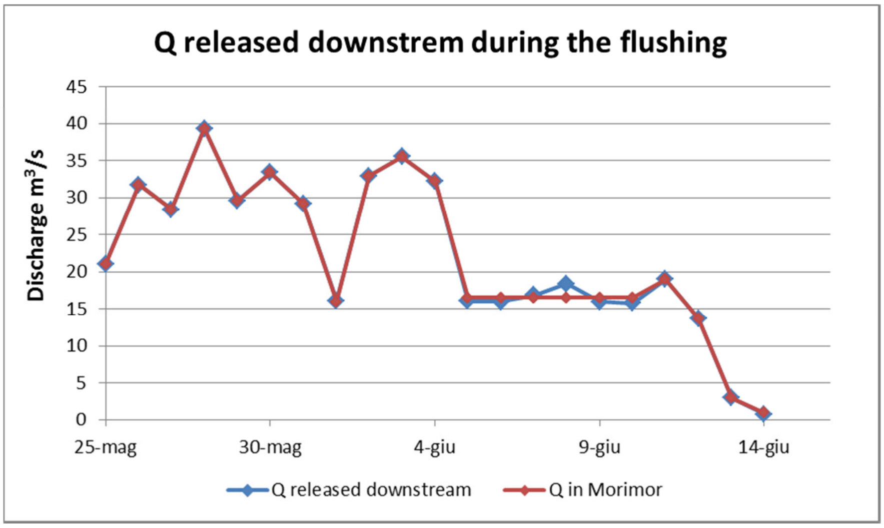

Figure 29 – Water discharge release downstream the Comelico dam during the flushing event in 2009. The brown line represents the discharge used by the model as initial condition.

7.2.2. Grain size distribution of the sediment released during the event

Because no bathymetric surveys of the reservoir have been executed before and after the flushing operation to estimate the amount of sediment released downstream, it was used the data provided by the dam owner: it means 250,000 m^3 of gravel and 80.00 m^3 of fine material.

Regarding the particle size composition of the material released downstream during the flushing event, it was assumed that:

- The 25% of the sediment released downstream had a grain size less than one millimetre. This percentage was calculated as the ratio of 80.00 m^3 of fine sediment and 335,000 m^3 of the total material (Savio, 2012).

- The remaining 75% of material was considered to have the same granulometric distribution of the sample obtained at the survey point G1 (see Figure 14), located upstream the reservoir. It was assumed that only the grains with a diameter less than 20 cm have been released downstream.

7.3. Results from the MORIMOR-GIS model

The simulation of the flushing operation executed in spring 2009 has been performed considering in sediment transport equation (10) the exponent *s* of the "hiding and exposure" coefficient equal to 0.6, and the coefficient *α* to 0.085.

The reliability of the results obtained with the model was evaluated by comparing the concentration of suspended sediment measured by ARPAV, at the monitoring point downstream of the confluence of the Piave river with the Ansiei torrent (see Figure 21), with the computed values from MORIMOR-GIS at the same progressive. The graph in Figure 30 shows a good correspondence between the measured and the computed values of turbidity, ensuring a good calibration of the model. It should be noted that since no hourly data of the water flow released from the dam during the 2009 flushing operation were available, the numerical model has been implemented with the average daily flow, resulting an underestimation of the calculated peak values of turbidity. The rather high values of turbidity measured during the last phase of the flushing operation are somewhat anomalous for its own ARPAV admission: in some moments of the monitoring the river flow was quite low, and the measuring instruments emerged from the surface, distorting and rounding up the registration (ARPAV, 2009). It is most probable that the last days of flushing event have been characterized by low water discharge in the riverbed.

The double scale graph in Figure 31, shows the variation of the bottom level of the Piave riverbed, with the areas affected by erosion and/or deposition phenomena. It is possible to see that the main deposit areas are localized in correspondence of the most flat branches of the Piave river, around the progressive 3000 m, 4500 m and 6000 m, as well as near the outlet of the bottom tunnel. This last case is documented by the photographic survey in Figure 32.

Analysing the results obtained with the model, it was noted that 90% of the material removed from the reservoir is floated downstream in the first 10 days of the flushing operation, as confirmed by the same operator. Subsequently, clean water with low content of sediment is released from the dam, with the object to promote the "washout" of the deposits in the river, preventing over aggradation phenomena, and restoring in part the river conditions before the flushing.

The average concentration of the suspended sediment calculated by the model, for the whole duration of the operation, is equal to 0.29% v/v. The turbidity limit set by the regional legislation is 0.65%, while the guide value is equal to 0.40%.

In conclusion, in Figure 33 and Figure 34, some results of the main parameters calculated by MORIMOR-GIS are reported in GIS environment.

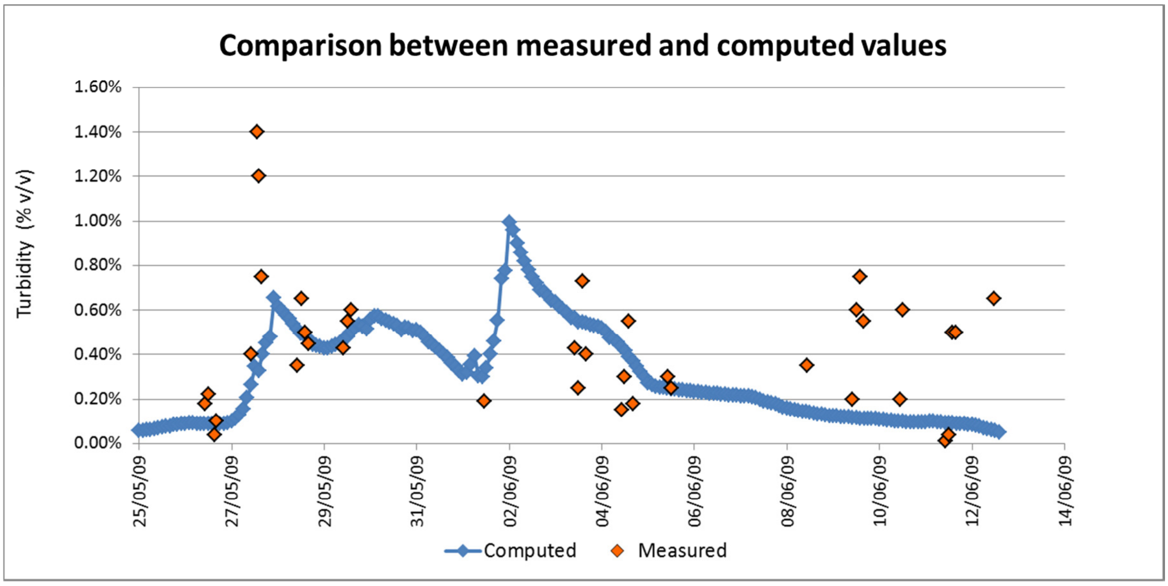

Figure 30 – Comparison between the turbidity values measured by ARPAV at the monitoring point (in orange), with the results obtained by the MORIMOR-GIS model (in blue).

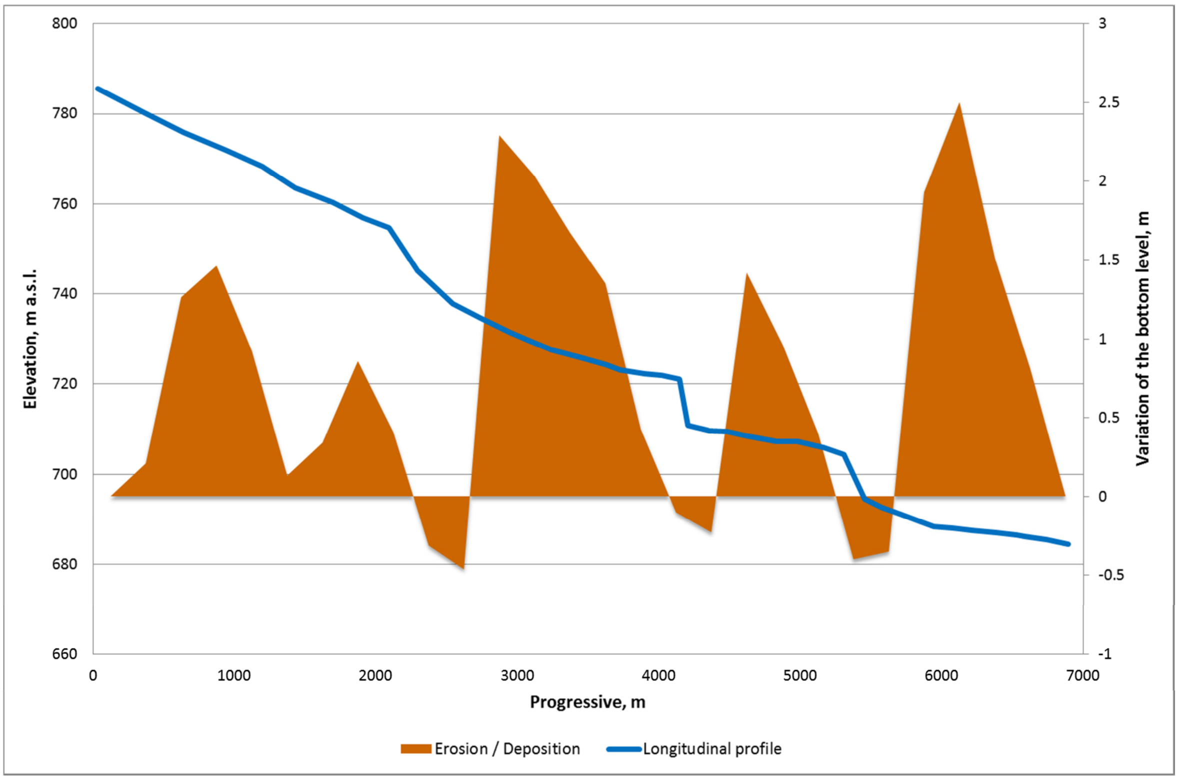

Figure 31 –Erosion and deposit phenomena (bottom level variation) along the Piave river, after the flushing operation

Figure 32 –Deposits of fine material along the left bank of the Piave river, located just downstream the outlet of the bottom tunnel.

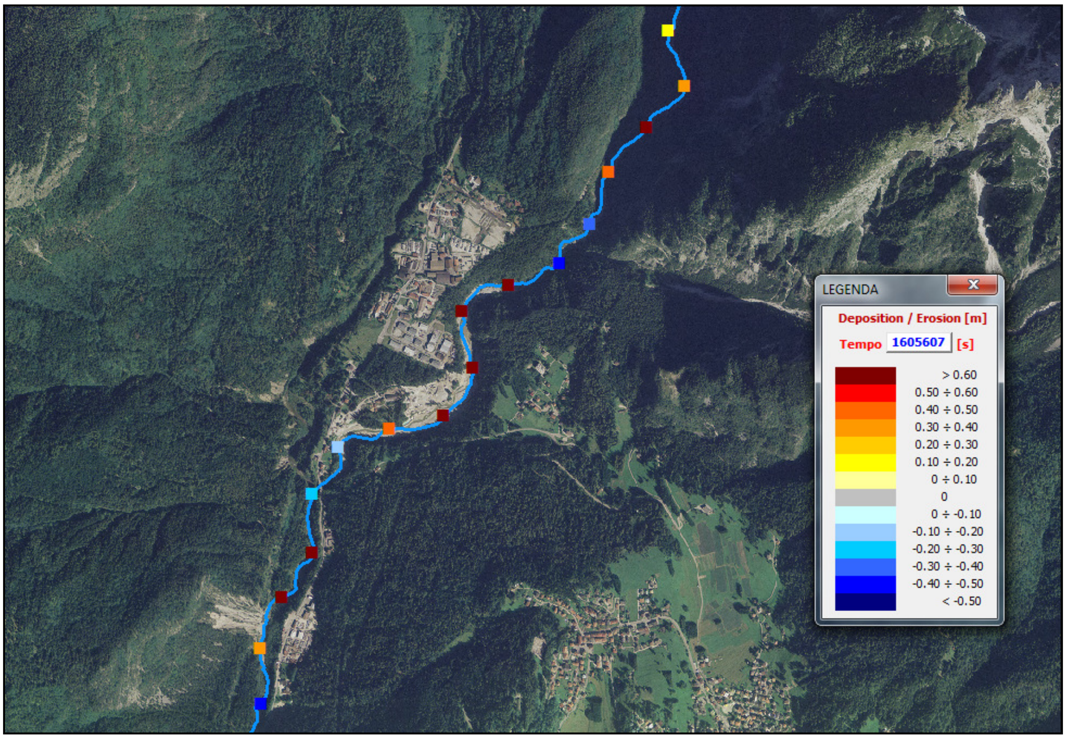

Figure 33 –The erosion deposition pattern along the Piave river, displayed in GIS environment.

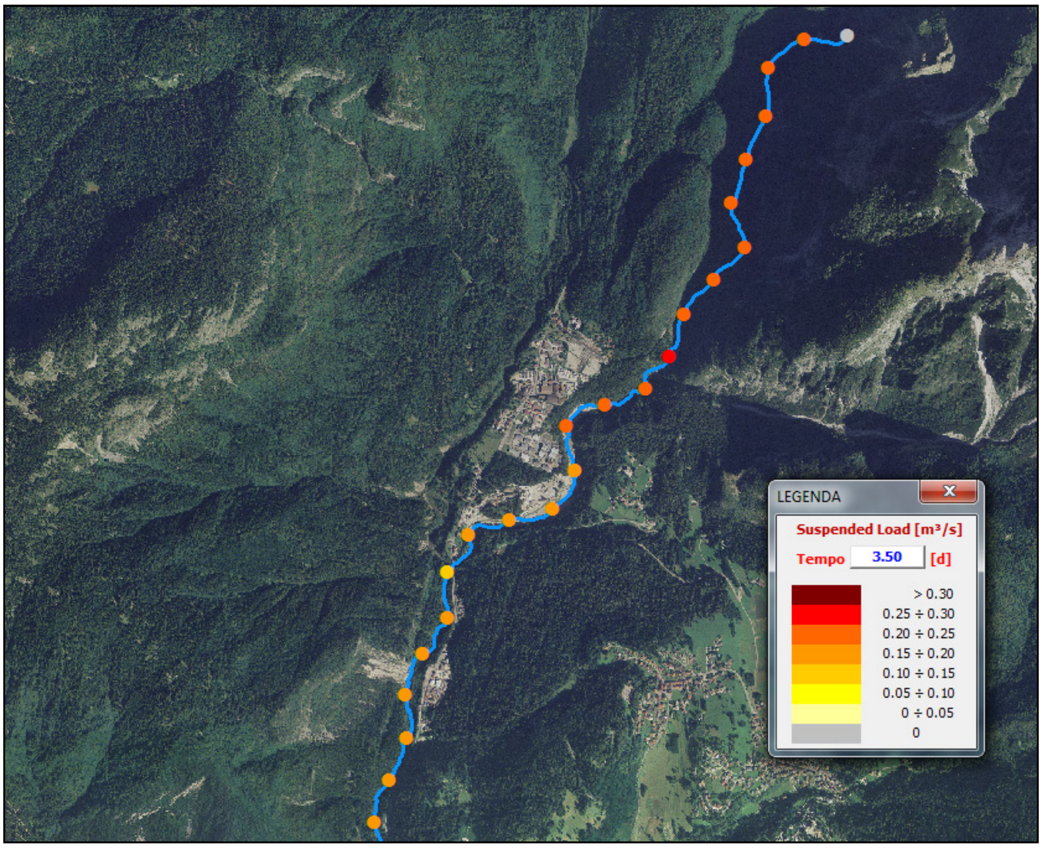

Figure 34 – Sediment load along the Piave river obtained with the MORIMOR-GIS model, displayed in GIS environment.

8. CONCLUSIONS

The mitigation of reservoirs siltation, and correlatively the preservation of the water quality in the reservoirs and downstream in the river bodies, involves a combination of hydraulic aspects, sedimentology, physical-chemical, plant engineering, environmental, economic, and social to be considered in parallel.

The current Italian and European regulatory framework concerning the protection of waters, invites the adoption of a comprehensive approach through an application of innovative methods or through the use of an adequate pool of indicators, allowing the integration of information related to all environmental compartments directly or indirectly affected by the water body. The use of innovative methodologies, as well as a different orientation of the requests at the regulatory level, it is also motivated by a general increase of interest in environmental issues among the general public.

The aim of the present work was to provide the development and the application in a real case study (Comelico dam) of an innovative methodology and instrument to support Public Administration and stakeholders in general, to face the problems concerning the reservoirs siltation and effects caused by the flushing operations.

The proposed MORIMOR-GIS model, in the Comelico dam application, showed to be a useful instrument in order to analyse the sediment transport and the river morphology evolution during sediment release operation. Therefore it could be used to predict the undeliverable effects in the downstream habitat, and to optimize the flushing operation. The model was developed to be used in the mountains area, with torrents/rivers characterized by large slope and multi granular sediment composition.

The simulations of the flushing operations executed at the Comelico dam in 2009, achieved results comparable with the “in situ” measurements, regarding the turbidity values in the Piave river, and localization of the river branches interested by sedimentation processes. The deposits of sediment calculated by the model at the end of the flushing event do not represent a source of excessive risk for the over aggradation of the riverbed.

The average concentration of suspended sediment, estimated for the entire duration of the flushing event with the MORIMOR-GIS model, is less than the maximum limit for the sediment release operations established by Veneto Region in the DGR 138 on 31/01/2006, and is in line with the guide value reported in the legislation. The maximum turbidity values obtained with the model are underestimated, since they having been calculated using the average daily discharges release from the Comelico reservoir, instead of the hourly flows for a more precise calculation.

MORIMOR-GIS aims to be an useful tool both for the Public Administration and for the hydropower producers, to estimate (qualitatively and quantitatively) the undesired effects caused by the planned flushing operations in the river receptors, and in sediment managing.

A proper use of the model allows also the economical optimization of the flushing operations, forecasting the water consumption required by each operation, and indirectly, the loss of production.

9. References

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ANNEX 1: Topographic survey

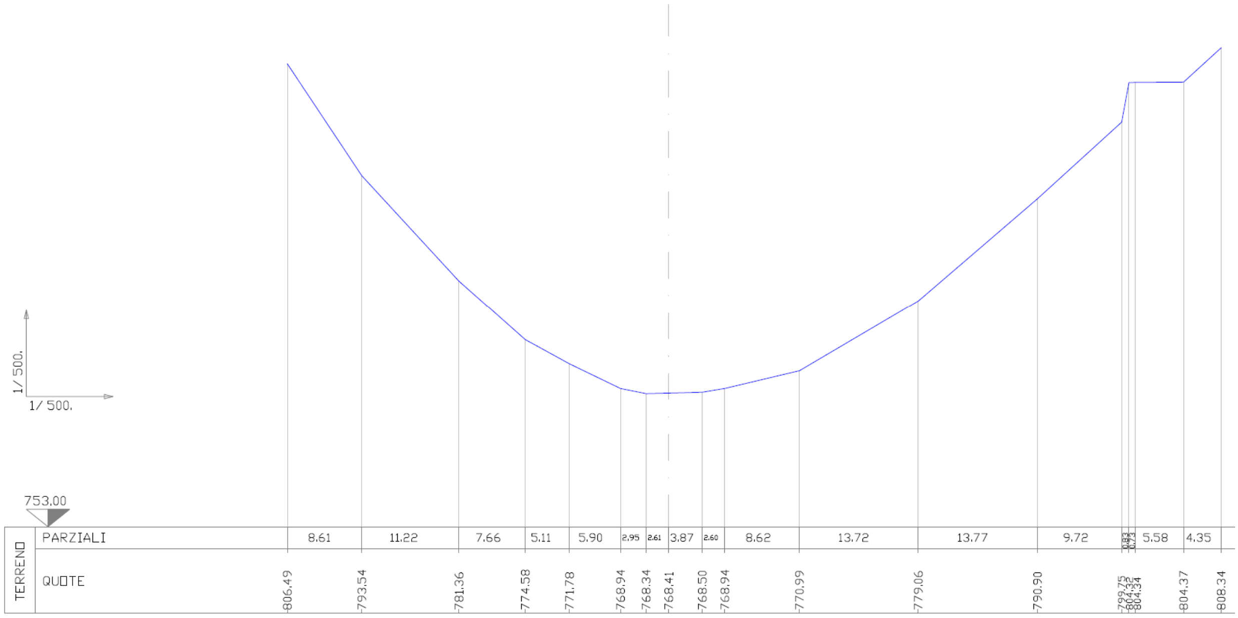

Figure 35 – Cross section of the Piave river, progressive 1200 m.

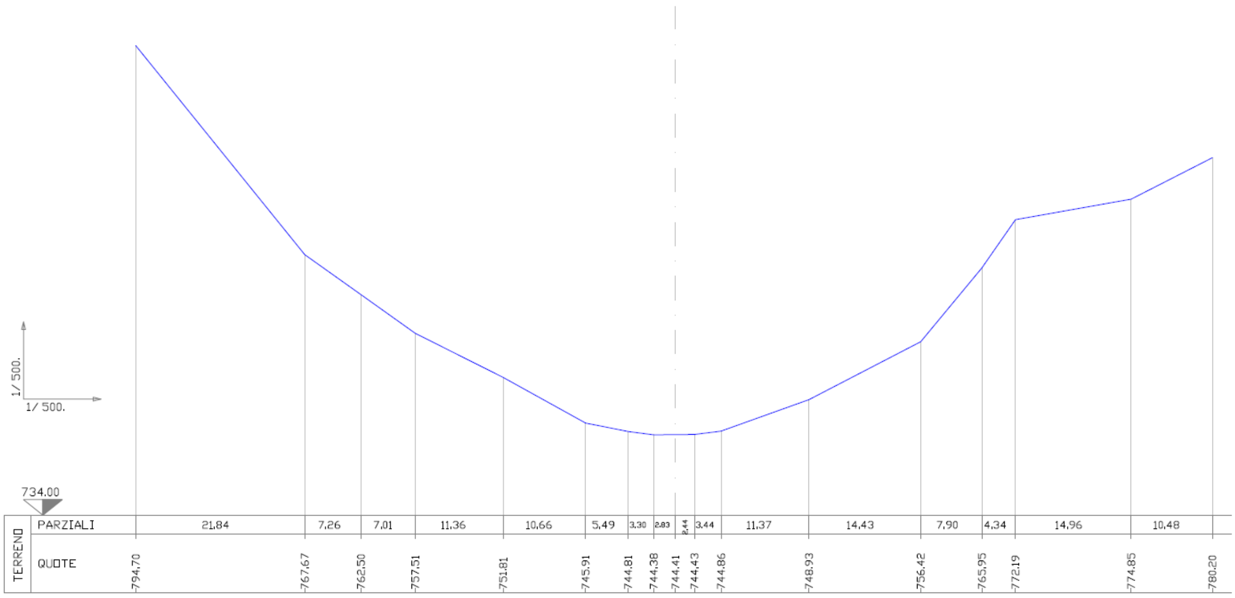

Figure 36 – Cross section of the Piave river, progressive 2300 m.

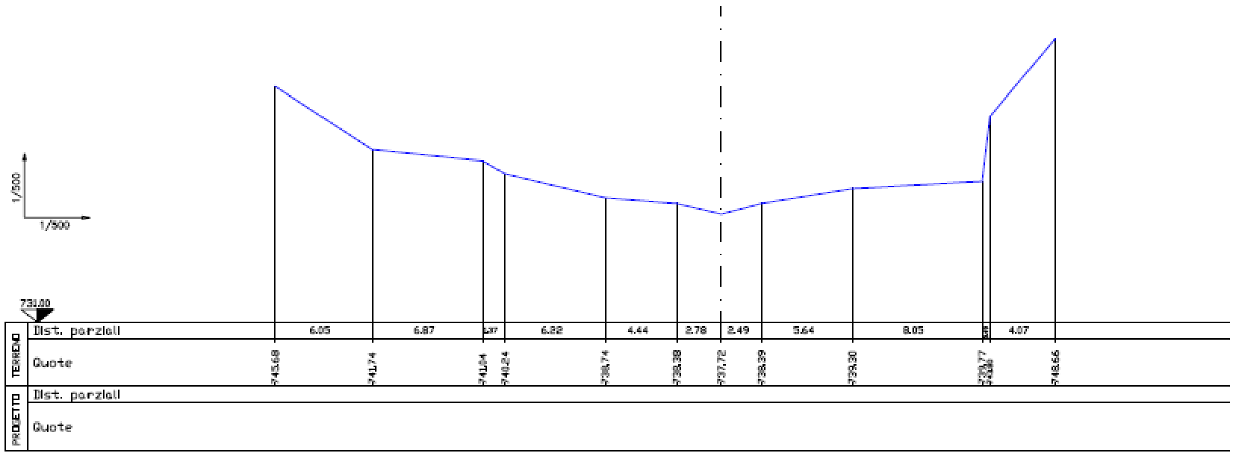

Figure 37 – Cross section of the Piave river, progressive 2540 m.

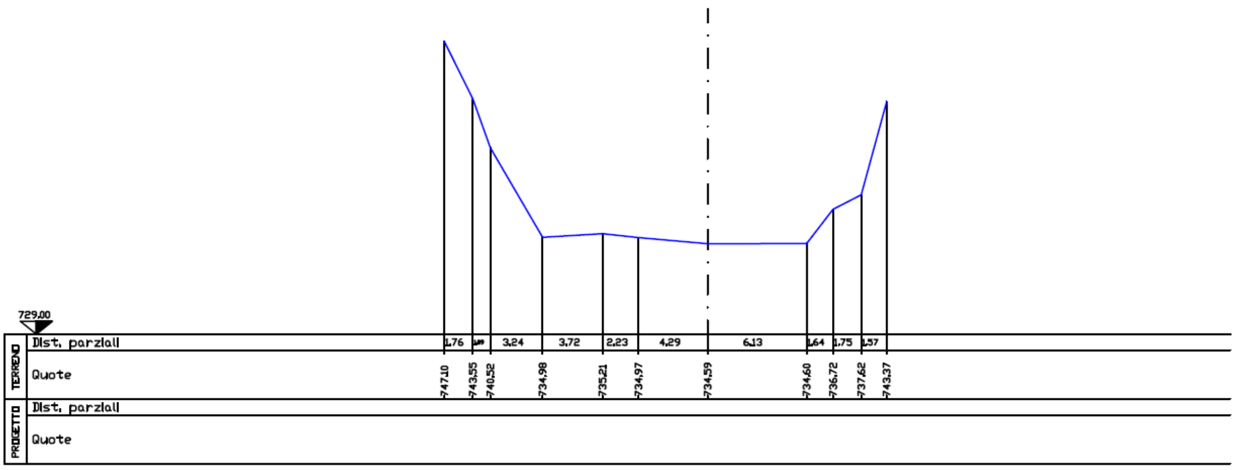

Figure 38 – Cross section of the Piave river, progressive 2740 m.

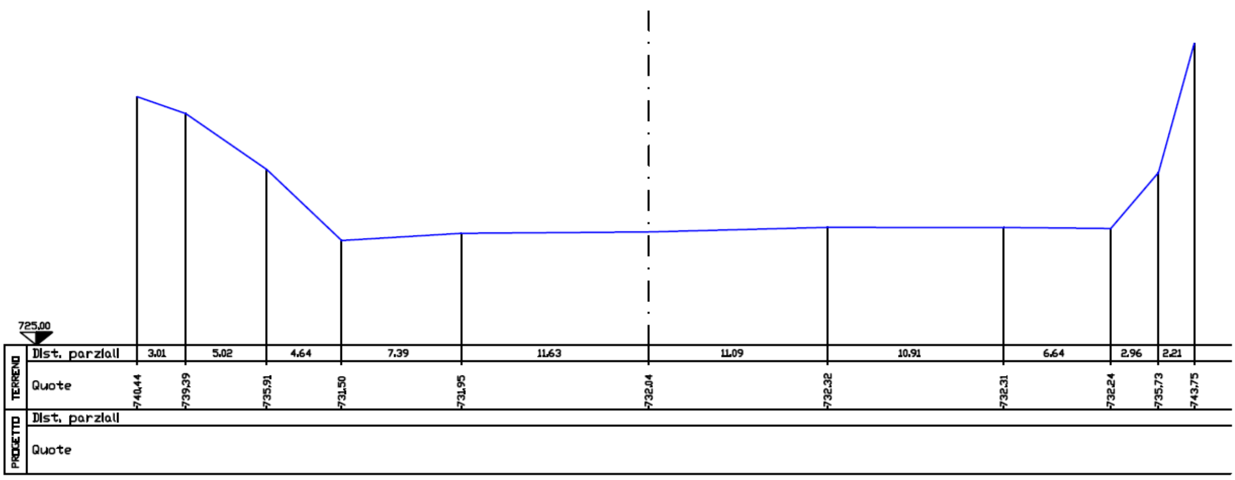

Figure 39 – Cross section of the Piave river, progressive 2940 m.

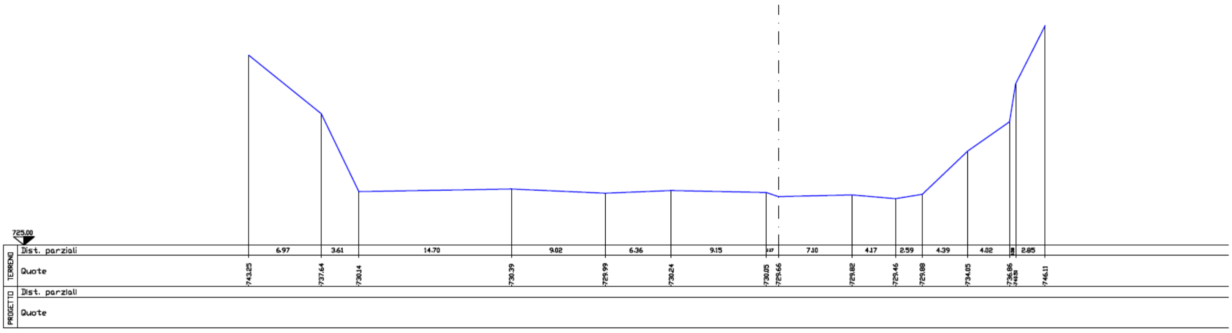

Figure 40 – Cross section of the Piave river, progressive 3100 m.

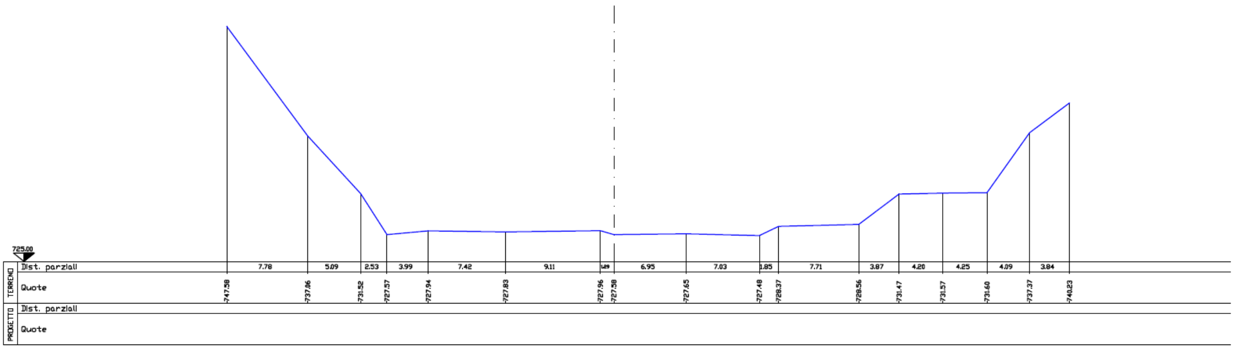

Figure 41 – Cross section of the Piave river, progressive 3240 m.

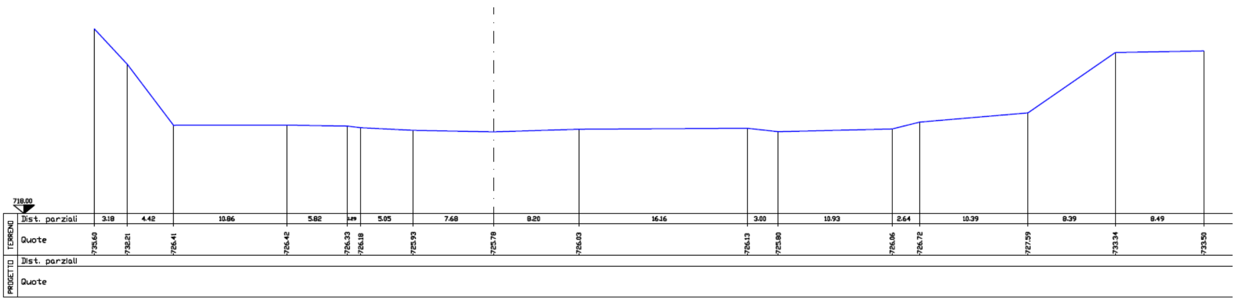

Figure 42 – Cross section of the Piave river, progressive 3450 m.

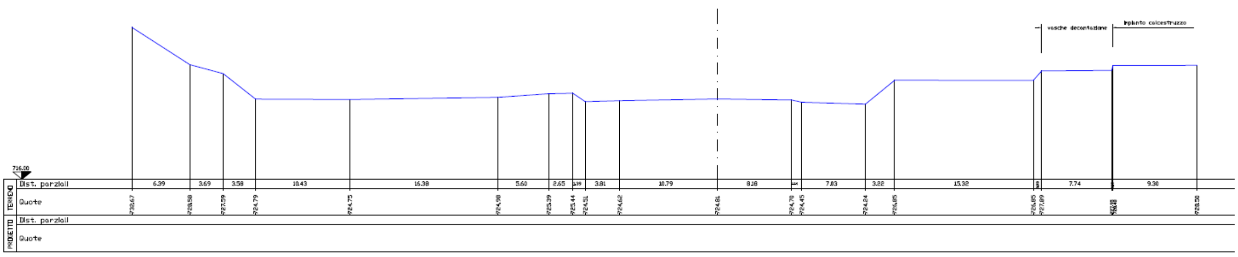

Figure 43 – Cross section of the Piave river, progressive 3620 m.

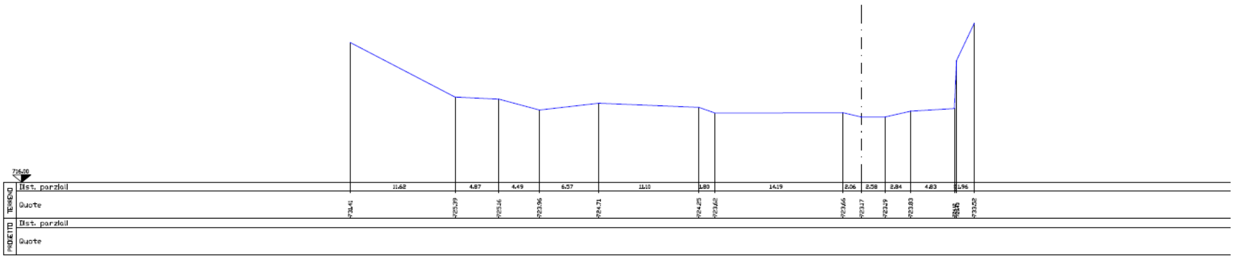

Figure 44 – Cross section of the Piave river, progressive 3730 m.

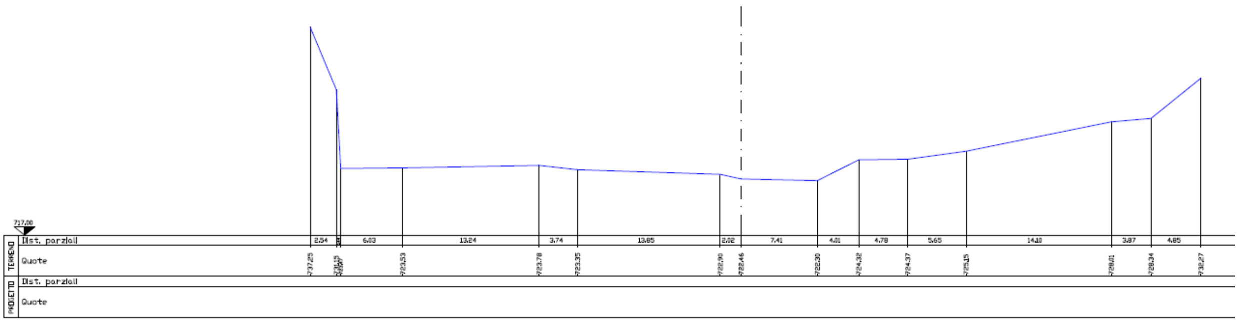

Figure 45 – Cross section of the Piave river, progressive 3900 m.

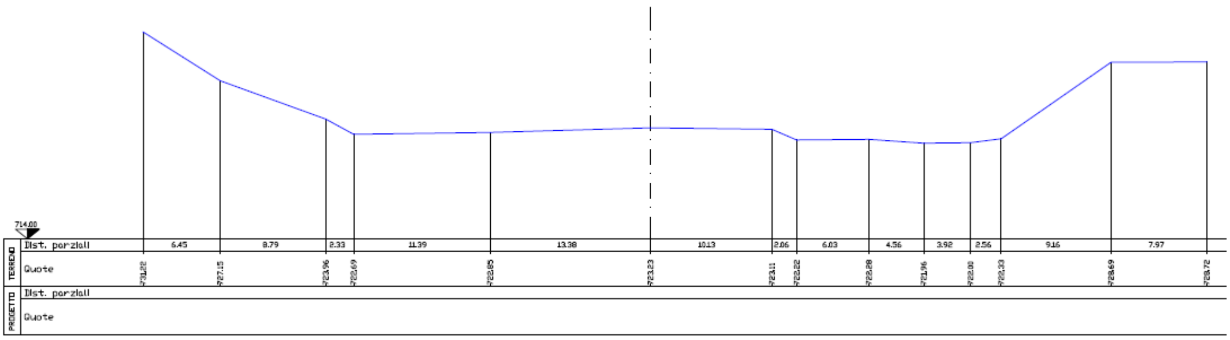

Figure 46 – Cross section of the Piave river, progressive 4020 m.

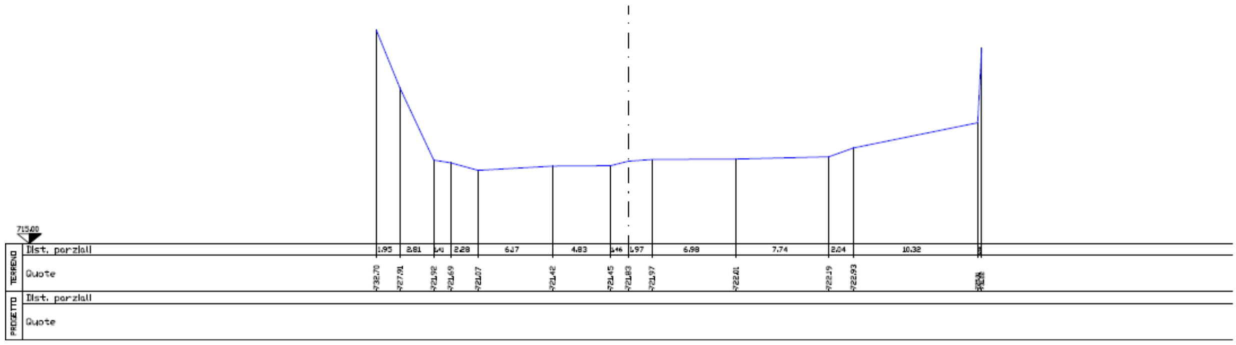

Figure 47 – Cross section of the Piave river, progressive 4150 m.

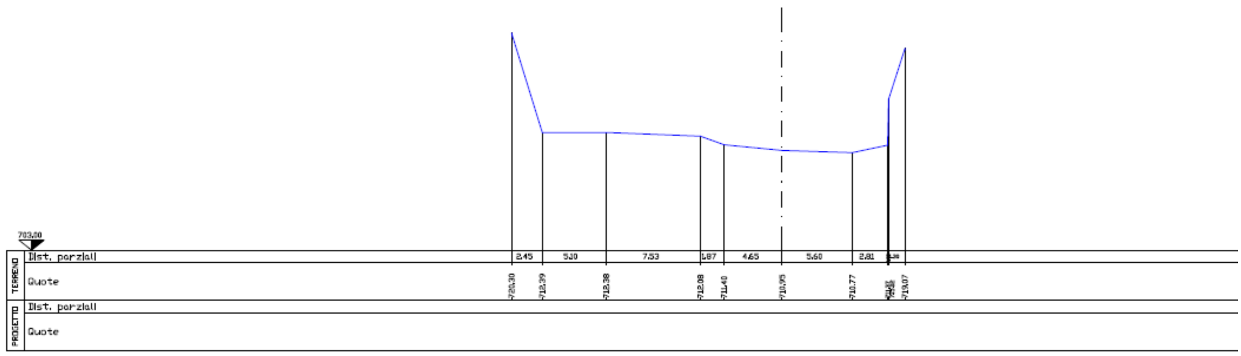

Figure 48 – Cross section of the Piave river, progressive 4200 m.

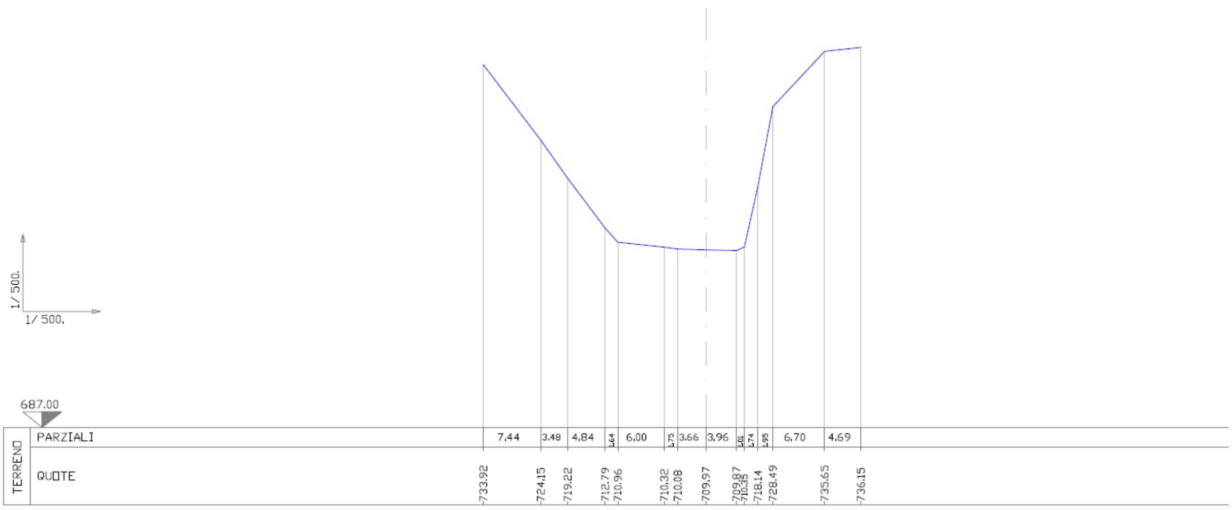

Figure 49 – Cross section of the Piave river, progressive 4340 m.

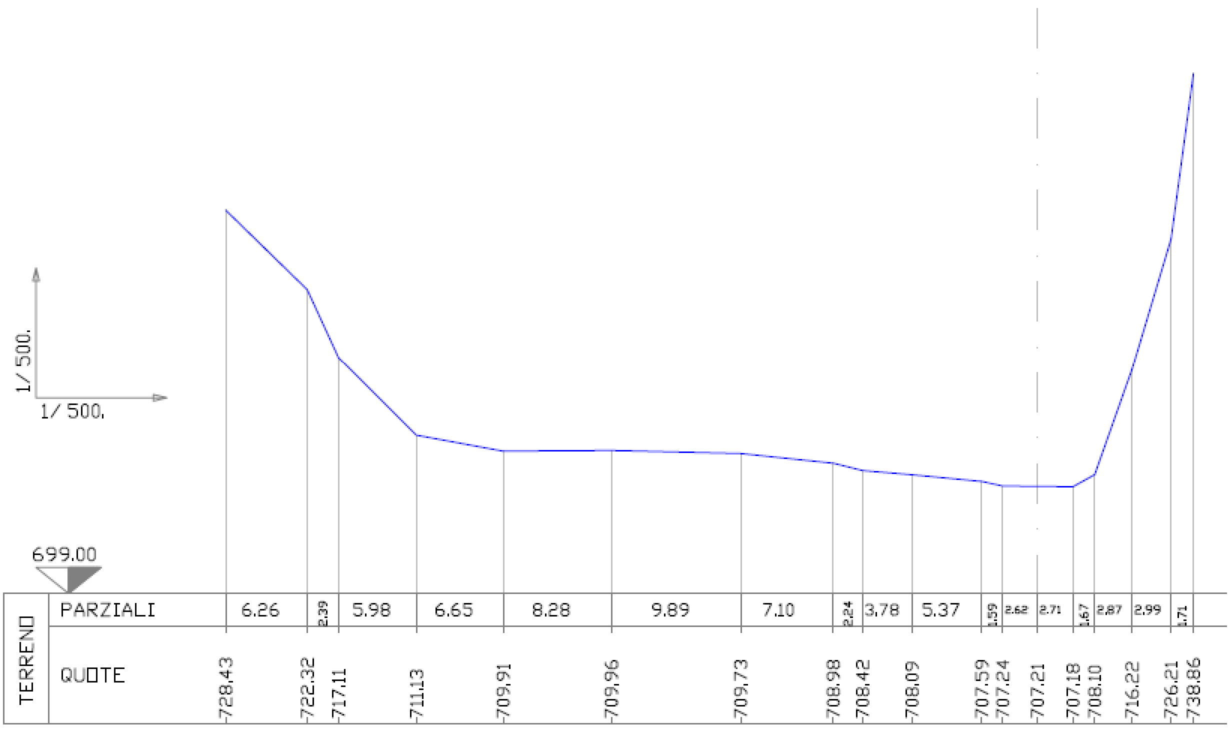

Figure 50 – Cross section of the Piave river, progressive 4830 m.

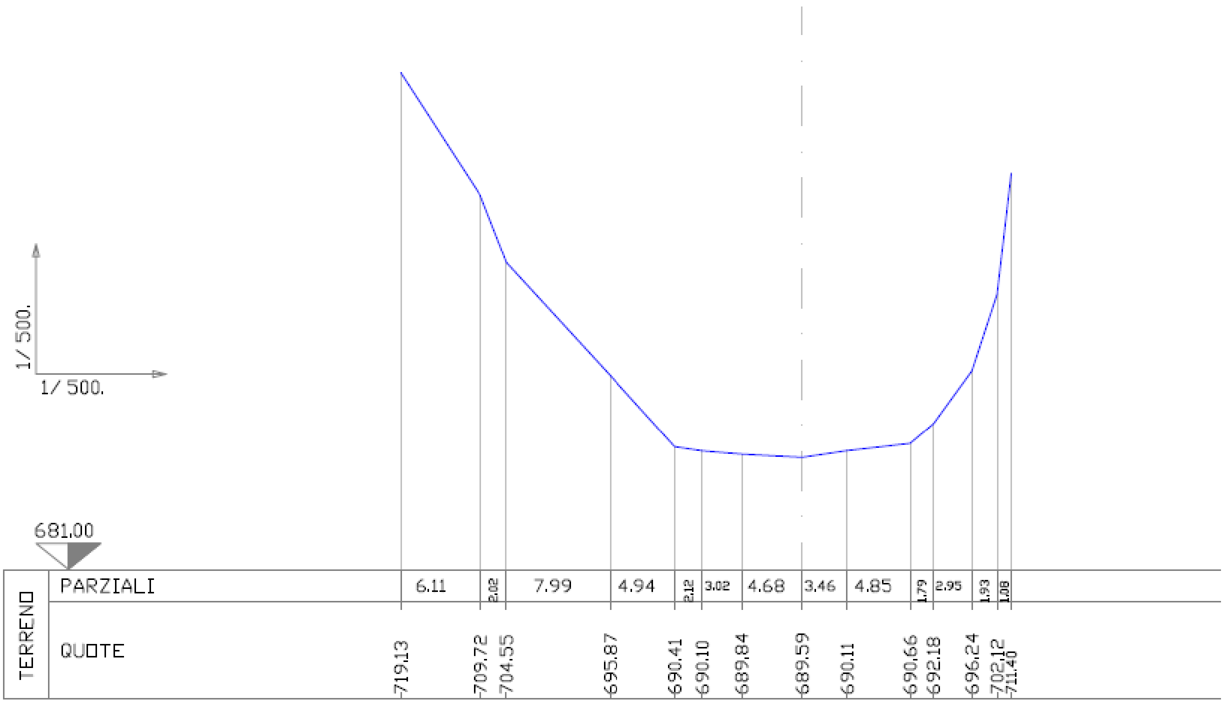

Figure 51 – Cross section of the Piave river, progressive 5840 m.

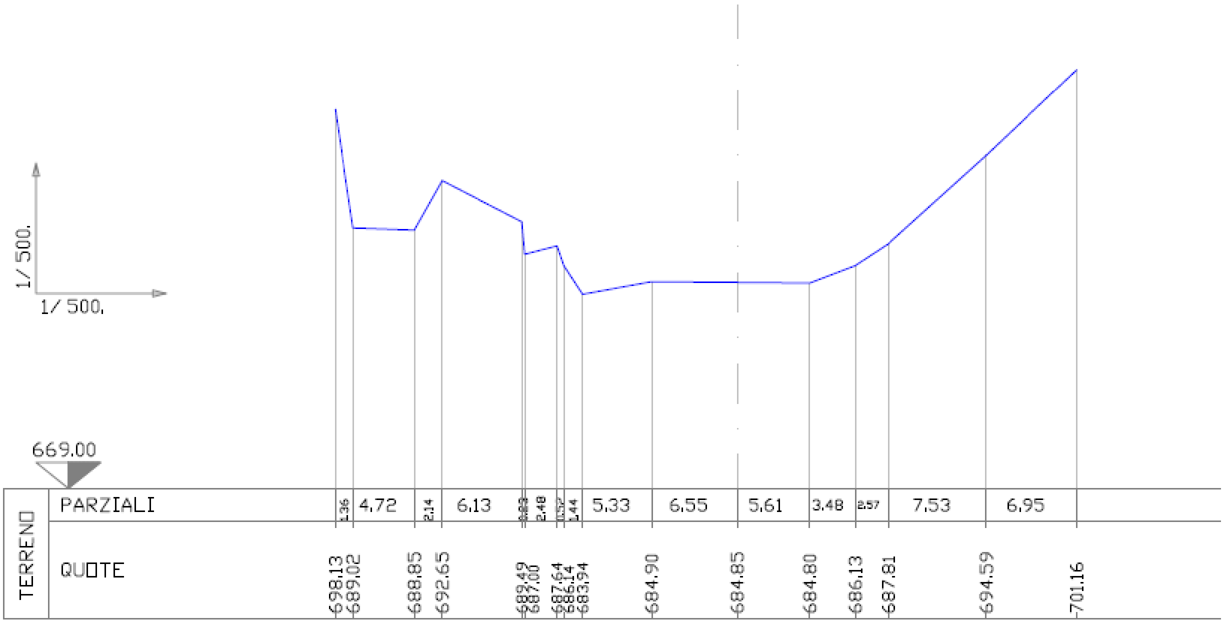

Figure 52 – Cross section of the Piave river, progressive 6390 m.

Annex 2: pictures of the granulometric survey

In September 2012, a granulometric survey has been performed to define the grain size distribution in the Piave river (from the Comelico dam to the Centro di Cadore lake). Pictures of the investigation are reported below.
For the location of the survey points, please refer to the map of Figure 13.

Figure 53 – Overview of the survey point G1.

Figure 54 – Upstream view from G1.

Figure 55 – Downstream view from G1.

Figure 56 – Overview of the survey point G2.

Figure 57 – Upstream view from G2.

Figure 58 – Downstream view from G2.

Figure 59 – Overview of the survey point G4.

Figure 60 – Upstream view from G4.

Figure 61 – Downstream view from G4.

Figure 62 – Excavation related to the survey point G4.

Figure 63 – Overview of the survey point G6.

Figure 64 – Upstream view from G6.

Figure 65 – Downstream view from G6.

Figure 66 – Excavation related to the survey point G6.

Figure 67 – Overview of the survey point G8.

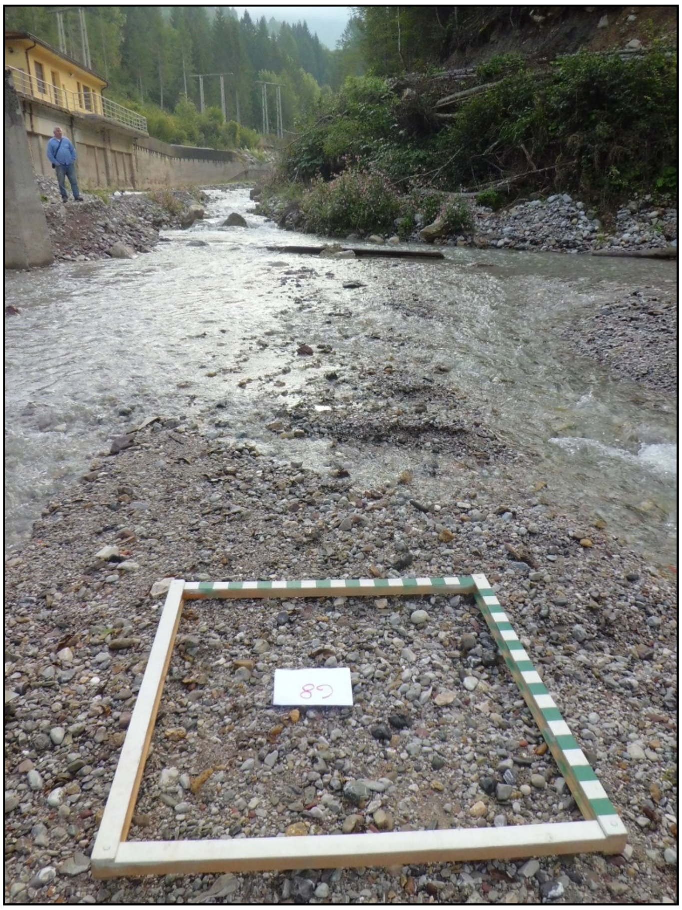

Figure 68 – Upstream view from G8.

Figure 69 – Downstream view from G8.

Figure 70 – Excavation related to the survey point G8.

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