Rehabilitation of artificial reservoirs and environmental utilization of sediment

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Abstract

Analysis of data relating to artificial reservoirs rehabilitation, in order to remove the sediments due to the solid transport, is useful for a correct water supply management. The present study analyses the effects of the concomitant emission of the siphoned water-sediment mixture and water discharged through dam drains. It has three main objectives:

- rehabilitation of artificial reservoir in close relationship to environmental balance;
- the reduction of sediment in the mixture emitted into the river bed to levels compatible with environmental regulations;
- the definition of hydrodynamic conveyance, which is able to guarantee the transport of released sediment.

The proposed analysis has been applied in the pilot reservoir Camastra (Potenza, Southern Italy). Ten years of observational data regarding rainfall, discharge and flow rate discharged through drains are available for this site. Grain size distribution analysis of sediments deposited on the lakebed was carried out and the geometric and hydraulic characteristics of the riverbed down valley from the dam are known. The first results obtained show that this method, in this study case, enables the carrying out of the rehabilitation of the reservoir within environmental compatible parameters.

1 Introduction

The cause of littoral recession is determined by a number of processes. Some are of global scale such as the rise in average sea water levels due to the melting of the polar glaciers as a result of the rise in average land temperatures. Others are
of local origin and include hurried and unthought out works, uncontrolled extraction of inert materials from the river bed and damming of water courses. The present work looks at this latter factor with the aim of establishing the positive effects of a controlled increase in the solids transported downstream from a dam.

The building of a river bed barrage determines an alteration in the balance achieved by the system constituted by the water course and the river bed: the accumulation of water resources upstream from the barrage reduces the quantity of flow and solid transport downstream with consequent erosion processes downstream and silting up upstream. To compensate for the phenomenon of silting up in artificial reservoirs and allow for a correct programming and management of available water resources it is necessary to draw up a plan which includes rehabilitation and sediment utilization.

The present work examines the problem of rehabilitation in the Camastra (PZ) reservoir with the recuperation of capacity through syphoning [Molino, 1998] and solid transport following the immission in the river bed downstream from the dam of the water sediment mixture coming from the the bottom of the artificial reservoir (environmental use). Of particular interest is the process of solid transport in suspension both in the Camastra bed going from the dam to the confluence with the Basento river and in the Basento water course flowing to the sea. The aim of the study is to establish the river bed flow conditions wherein the water sediment mixture coming from the dam can totally or partially reach the sea.

2 Rehabilitation through syphoning

The recuperation of capacity of an artificial reservoir is often sought through "one off" solutions coinciding with particular anomalies in the functioning of the reservoir-dam system which call for its emptying. One possible intervention which allows a link between the phases of rehabilitation and sediment utilization is "syphoning".

This method, defined "SEPS" ("Sediment Evacuation Pipeline System"), is one of the most economical and efficient passive defence methods in the recuperation of useful reservoir capacity and is based on the utilization of a syphon which, as a result of the difference in hydraulic head between the initial and final sections, removes the water sediment mixture from the reservoir. The initial section of the syphon is positioned upstream of the barrage near the bed area covered by the volume of sediment to be transferred; the final section is placed downstream from the dam near the site of the deposit which in some cases is the water course itself (figure 1).

In this way the part of the river bed concerned is subjected to a process of "unmuddying" ie the capture of solid volumes which, mixed with water, flow through the syphon and beyond the dam to the release site. [Molino, 1998].

The utilization of the syphon produces the following effects:

• removal and transfer of sediments with low plant and execution costs;
possibility of intervention with full reservoir, without interference in storage execution tasks;

- possibility of productive utilization of solid materials deposited downstream if suitably accumulated (agrarian and industrial uses);

- possibility of utilization for environmental recuperation purposes obtained through the eventual release of water sediment mixture in controlled concentrations in the bed; in this way it would be possible to contribute to the containment of erosive phenomena and the attenuation of coast line recession (environmental use).

![Syphoning Diagram](image)

Figure 1: syphoning

This study focuses on the last effect. Italian legislation in the area of environmental protection [Molino and Masi, 1999] establishes highly restrictive values for sediment mixture concentration left in river beds. The aim of this study is the combined programming of reservoir capacity recuperation through syphoning with sediment utilization for the containment of erosive phenomena downstream from the dam, paying attention to the contribution which could arise from a possible change in existing norms. To this end a plan for the artificial reservoir at Camastra containing potential contributions to the phenomena of downstream coastal erosion is put forward.

3 The hydrodynamic and sediment transport model

In order to simulate flow behaviour and water sediment mixture transport the "Mike 11" DHI Software, in particular the following modules, were chosen: HD, "hydrodynamic", AD, "advection-dispersion", and ST, "sediment transport". The hydrodynamic module is able to simulate the motion of any type of free surface flow in steady or unsteady conditions basing on the De Saint-Venant equations implemented with schemes of finite differences. The ST module immediately resulted as unsuitable because it was more useful for the study of transport on the bed of sediments of sand or superior dimensions. The AD module is the most suitable because it simulates the transport of fine sediment in suspension, on the basis of the principle of the conservation of mass.
The working hypotheses at the base of the application of the HD module are the following:

- incompressible homogeneous fluid;
- velocity closely parallel to the direction of motion and hydrostatic distribution of the pressure in the transversal section;
- quasi-cylindrical current.

The downflow phenomena included in this scheme are characterized by slight slopes and curves of water surface.

The principles of the conservation of mass and the quantity of motion can be expressed in this way:

\[
\frac{\partial S}{\partial t} + \frac{\partial Q}{\partial x} = q_2;
\]

\[
\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left( \alpha \frac{Q^2}{S} \right) + gS \frac{\partial h}{\partial x} + \frac{gQ|Q|}{\chi^2SR^*} = 0;
\]

where "S" is the area of the transversal section, "Q" is the flow, "q_2" represents the lateral inflow per unit of river length dx examined, "t" represents time, "\alpha" is the momentum coefficient (for absolutely turbulent motion it is equal to one), "\chi" is the Chezy resistance coefficient, "g" is the acceleration of gravity, "h" is the piezometric head and "R*" is the hydraulic radius.

The equations are resolved using a scheme of finite differences in which, in order to obtain a stable solution, the following conditions must be satisfied:

- velocity:
  \[
  \frac{v \cdot \Delta t}{\Delta x} \leq 1 + 2;
  \]

- number of Courant:
  \[
  Cr = \left( \sqrt{\frac{v}{gY}} \right) \frac{\Delta t}{\Delta x} \leq 10 + 15;
  \]

where "Y" is the water depth.

The transformation of the equations of the conservation of mass and of the momentum in a set of implicit equations to the finite difference is obtained using a grid of calculation where h and Q are computed alternatively for each point, and for each instant of time. Such a grid is generated from the model on the basis of conditions established by the user: the scheme adopted is that of Abbott in six points [Abbott e Jonescu, 1967; Mike 11, Scientific Documentation, DHI].

The module AD requires in input:

- the results of the hydrodynamic module;
- a single upstream boundary condition, data on the value of concentration in the first section for the duration of the simulation;
- an initial condition, ie the concentration of the sediment in the whole bed for only the initial instant;
two parameters relative to the sediment: the density and the velocity of free fall;

- specific parameters of transport in suspension:
  - the factor and the exponent of diffusion;
  - the (eventual) constant of decadiment;
  - the critical shear stress (or the velocity) for deposition and erosion;
  - the coefficient and the exponent of erosion;
  - the density of the layer of sediment on the bed (or, where it exists, the density such a layer would have if material were to be deposited).

The use of the model includes two steps: the simulation with the model HD, used for fluid motion, and that with AD, necessary for the transport of solid material. The results of the hydrodynamic model provide, for each section and for each instant of time, the values of flow, average velocity, area, water depth, hydraulic radius and width of free surface; in the same way the results of module AD are constituted, for the same sections and instants, of the values of concentration and thickness of the layer of sediment deposited or eroded.

Because it is based on the hydrodynamic module, the AD module utilizes the same geometric and planimetric input of the water course and calculates, using the initial boundary conditions, the distribution for every section of the concentration through an integration of the equation of the conservation of mass. It also determines the resulting conditions of erosion, deposition, and equilibrium in relation to the bed shear stress; where there are deposits or shifts in bed materials it calculates the consequent depth of the layer deposited or shifted.

The monodimensional equation of conservation of the mass of a substance in solution or suspension, called "advection-dispersion equation", is the following:

$$\frac{\partial SC}{\partial t} + \frac{\partial QC}{\partial x} - \frac{\partial}{\partial x} \left( SD \frac{\partial C}{\partial x} \right) = -SKC + C_2q_2;$$

where "S" represents the area of the section, "C" the concentration, "Q" the liquid flow, "D" the coefficient of diffusion (contemplating both turbulent and the molecular diffusion) and "x" and "t" the spatial and temporal dimensions. The quantities "C_2" and "q_2" represent the concentrations and the unitary discharge of lateral inflow, while "K" represents the decadiment constant, with dimension "T^{-1}\)", relative to the hypothesis of exponential decadiment of the mass and defined by the following equation:

$$\frac{dC}{dt} = -KC.$$  

Two fundamental measures of transport in suspension are flows of erosion and deposition which relate the mass present in the hydric body with the mass which separates out or is deposited on the bed. These measures represent, therefore, the boundary conditions in the conservation of the solid mass. Their calculation is linked to a parameter which expresses the erosive force of the water course: bed shear stress.
In the case of module AD the critical shear stress values should be examined in relation to those calculated using the hydrodynamic model: if the latter are superior to the critical shear stress of erosion it means that the water course causes erosion and, consequently, the flow of materials separating from the bed should be calculated and united with those transported in suspension; if the bed shear stress is inferior to the critical shear stress of deposition it means that the water course allows for the sedimentation of a part of the transported material and consequently the relative flow should be calculated.

In both cases the adopted model calculates the new thickness of the deposited layers, on the basis of the density of the bed sediments. If there is no erosion or sedimentation found, it means that the bed is balanced; in this case both the thickness of deposits and the solid transport flow are invariable.

For the calculation of the flow of deposits the model uses the concept of the "probability of deposition" which depends on the critical shear stress of deposition \( \tau_{CD} \) and on that obtained from hydrodynamic calculations \( \tau_0 \); in particular if \( \tau_0 < \tau_{CD} \) it is calculated like this:

\[
p = 1 - \frac{\tau_0}{\tau_{CD}} = \frac{\tau_{CD} - \tau_0}{\tau_{CD}} ;
\]  

(7)

in such cases the deposition flow is positioned as:

\[
F_D = w_0 p C = w_0 \cdot \left(1 - \frac{\tau_0}{\tau_{CD}}\right) \cdot C ;
\]  

(8)

where "C" is the volumetric concentration and "\( w_0 \)" is the free fall velocity.

If \( \tau_0 > \tau_{CE} \) the erosion flow is calculated according to the law:

\[
F_E = E \cdot (\tau_0 - \tau_{CE})^n ;
\]  

(9)

where "E" and "n" are the coefficient and the exponent of erosion.

4 Rehabilitation plan and environmental utilization of sediments for the Camastra-Basento

In order to demonstrate the effects of the proposed methodology (rehabilitation through syphoning) it was applied to the Ponte Fontanelle dam, on the Camastra river, a right tributary of the Basento river, with successive re-immissions of the water-sediment mixture in the river bed. On this basis, a work hypothesis was proposed which included superficial discharge of the dam in concomitance with the syphoned release in the river. In particular, given that from observation of available data, it results that superficial overflows equal to or greater than 5.8m³/s are found on average 53 days per year, combining these overflows with the flow in the syphon which, in conditions of maximum hydraulic load, is equal to approx. 1.3m³/s, a total flow equal to approx. 7.1m³/s is found downstream. In the syphon transporting the mixture coming from the river bed there is an average sediment concentration of 257g/l; this value is reduced to 49g/l when mixed with the water coming from the superficial overflows, whose sediment concentration has been measured to be on average equal to 0.5g/l.
The simulations relative to the Camastra section between the dam and the Basento confluence, carried out with HD and AD modules show that the sediments taken from the river bed and re-inserted downstream, are transported by the current of 7.1 m³/s at least until the confluence.

Simulations were also carried out downstream of Camastra-Basento confluence with the aim of examining the eventual arrival in the sea of the discharged mixture or the deposits along the Basento river bed. They were carried out with diverse flow values, in conditions of permanent motion, on 101 transversal sections of the Basento, taken from the study of flood areas arising from the effects of Ponte Fontanelle dam breakage. The sections were subjected to correction in several points following numerous observations and data collection on site.

For the parameters required by the hydrodynamic and transport models, the following values were taken into consideration:

- critical shear stress for erosion equal to 1.3 N/m²;
- critical shear stress for deposition equal to 0.4 N/m²;
- Manning parameter equal to 29 m⁹/³/s.

The HD module was calibrated on the Manning number using the experimental width and depth current data taken along the course of the Camastra stream in the sections of calculation with known input hydrogram; the used boundary conditions are: the hydrogram upstream and a Q-h relation downstream.

With flow variation, different possible conditions were observed and the value of the concentration along the section of the river examined was obtained.

5 Analysis of the results

As already stated, no deposits with a flow reference of 7.1 m³/s were found in the section between the dam and the Basento confluence; in the section of the Basento between the confluence and the mouth (for flow values comparable to the yearly average daily Basento discharge equal to approx. 10 m³/s) significant deposits of cohesive materials were observed in a single zone (section B), approx. 20 km from the mouth. This is a section which presents a bridge on the Basento river; at this point the bed is particularly slight: upstream of the section it is equal to 0.7 per thousand, while downstream it decreases to 0.1 per thousand.

The minimum flow value without deposits, defined as the "critical flow value for deposition" is equal to 53 m³/s; below this threshold the bed shear stress is lower than the critical value for deposition. Through simulations carried out with flow values less than the critical levels it can be observed that there are no material deposits until 8 m³/s is reached whereas if the flow falls below 8 m³/s deposits are observed in many other sections. These results are reported in table 1.
Parallel to the application of Mike 11 a comparison between the AD model and several other empirical models present in the literature was carried out to test obtained results. These models include: Celik and Rodi [Celik and Rodi, 1988 and 1991], Biggiero et al. [Biggiero et al., 1994] and van Rijn [van Rijn, 1984 and 1986]. The first two gave analogous results to those obtained with the AD model, while the van Rijn model gave very different results because it is more suited to simulate the transport with non-cohesive materials. As expected, many of the fundamental parameters of that model, calculated for this case study, went beyond the limits studied by the author himself.

6 Conclusions

In order to correctly evaluate the values of the specified flows, it was considered necessary to carry out a comparative analysis between these values and the average daily flow values recorded by the SIMI in past years (even though available data refers to the period between 1927 and 1971).

The SIMI data collection stations concerned are located at Gallipoli (downstream the confluence) and Menzena (near to the section B). For both these stations the frequency of excess was calculated. The average annual number of times when the critical flow value was exceeded; this frequency was found to be equal to 10 at Gallipoli and 16 at Menzena. This data indicates that the flow of 53 m³/s is rarely found in the Basento and is even more rarely exceeded.

In the figure 2 the (yearly average) number of days per month when the flow in the Camastra exceeds the threshold level of 5.8 m³/s is compared with those when the Basento (at Menzena) exceeds the values of 53 and 8 m³/s.

The distribution of cases of excess of the flow threshold in the course of a year lead to the proposal of a work hypothesis based on the utilization of the syphoning method in conjunction with two events: the overflow in the Camastra above 5.8 m³/s and a flow in the Basento above 8 m³/s.

In this case the number of days wherein it is possible to remove the sediment from the bed of the Ponte Fontanelle dam reach a maximum of 50-60; for these days, however, it is not certain that all the solid flow will reach the Basento mouth, it could be deposited in correspondence with the above mentioned section B.

The amount of such deposits could be quantified by calculating the flow sedimentation reached at that point with a discharge of 8 m³/s; the flow sedimentation is obtained dividing the volume of sediment accumulated in a time period of an hour by the entity of the time period itself. Such a flow is equal to 0.25 g/s and corresponds to a flow volume of approx. $10^{-4}$ l/s.
This means that, in the work hypothesis specified, given a removal of bed sediment equal to approx. 1,590,000t/y (calculated as 30,000t/g for 53 days), there would be a material deposit of not more than 1.14t/y, equal to 0.00007%.

Figure 3 reports the quantity of deposits found in the area surrounding section B one hour after the beginning of the simulation.

Table 2, shows the comparison between two diverse work hypotheses with the average number of days annually when it is possible to carry out the operations of capacity recuperation and the consequent solid deposit flow which would be obtained in section B.
Table 2: Discharge in the Basento river

<table>
<thead>
<tr>
<th>Threshold level (m³/s)</th>
<th>53</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days with discharge exceeding</td>
<td>16</td>
<td>128</td>
</tr>
<tr>
<td>Discharge of deposition (t/g)</td>
<td>0</td>
<td>0.022</td>
</tr>
<tr>
<td>Removed volume (t)</td>
<td>480,000</td>
<td>3,840,000</td>
</tr>
</tbody>
</table>

From an examination of the data it results that, even in the most limited hypothesis of a flow in excess of 8m³/s, there is a deposit in a single section, which is moreover subject to strong erosion phenomena in periods of flood, and that almost the entire amount of the sediment deposited downstream from the dam reaches the mouth contributing to the re-establishment of a natural equilibrium altered by the presence of the barrage.

7 References

- Biggiero, Del Giudice and Della Morte, "Trasporto solido nei tratti fociali", XXIV Convegno di Idraulica e Costruzioni idrauliche, University "Federico II" of Naples, Italy, september 1994.
- Molino, "Riabilitazione degli invasi artificiali ed utilizzo dei sedimenti: difesa economica", Environmental Engineering and Physics Department, University of Basilicata, Italy, april 1999.
- Molino, "Interrimento e riabilitazione degli invasi artificiali mediante rimozione intubata di sedimenti: il caso dell' invaso del Camasta (PZ)", XXVI Convegno di Idraulica e Costruzioni Idrauliche, Catania, september 1998.
- Molino e Masi, "Rilasci in alveo di sedimenti: un quadro della normativa ambientale", Environmental Engineering and Physics Department, University of Basilicata, Italy, 1999.