COMMISSION INTERNATIONALE
DES GRANDS BARRAGES

VINGT TROISIÈME CONGRÈS
DES GRANDS BARRAGES
Brasilia, Mai 2009

TURBIDITY CURRENTS AT THE ORIGIN OF RESERVOIR SEDIMENTATION, CASE STUDIES [*]

Jolanda M.I. JENZER ALTHAUS
Research Associate, Ing. Civ. Dipl. EPF

Giovanni DE CESARE
Senior Research Associate, Dr. ès. Sciences, Ing. Civ. Dipl. EPF

Jean-Louis BOILLAT
Senior Research Associate, Dr. ès. Sciences, Ing. Civ. Dipl. EPF

Anton J. SCHLEISS
Director, Prof. Dr., Ing. Civ. Dipl. ETH

Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL)

SWITZERLAND

1. INTRODUCTION

Sedimentation is a subject of major importance in reservoirs worldwide and is - in large and deep reservoirs - mainly related to the phenomenon of sediment transport by the means of turbidity currents. Turbidity currents are the governing process in reservoir sedimentation by transporting fine materials in high concentrations and following over long distances the reservoir bottom along the thalweg through the impoundment down to the deepest point in the lake normally near the dam. At the dam the transported sediments settle down. Sediment deposition in reservoirs not only reduces storage capacity, but also increases the risks of blockage of intake structures. The state of the art in respect of turbidity

---

[*] *Courants de turbidité à l'origine de la sédimentation des réservoirs, études de cas*

currents is presented and illustrated with the help of several Swiss case studies. Possible solutions preventing or reducing sedimentation are exposed.

2. THE PROBLEM OF RESERVOIR SEDIMENTATION

Reservoir sedimentation is a problem that will keep those responsible for water resources management occupied more than usual during the decades to come. All sorts of impounding structures are concerned. Impounding facilities are always costly, but this is justified by their various potential uses.

Although the aim behind the efforts to create reservoirs is storing water, other substances are carried along by the water and are usually deposited there. This is a result of dam construction, dramatically altering the flow behaviour and leading to transformations in the fluvial process with deposition of solid particles transported by the flow. Each reservoir created on natural rivers, independent of its use (water supply, irrigation, energy or flood control), can have its capacity decreased due to deposition over the years. In an extreme case, this may result in the reservoir becoming filled up with sediments, and the river flows over land again.

A reservoir, like a natural lake, silts up more or less rapidly. In actual fact, reservoirs may completely fill with sediments even within just a few years.

Reservoir sedimentation reduces the value of or even nullifies the dam construction investment. The use for which a reservoir was built can be sustainable or represent a renewable source of energy only where sedimentation is controlled by adequate management, for which suitable measures should be devised. Lasting use of reservoirs in terms of water resources management involves the need for de-sedimentation.

The planning and design of a reservoir require the accurate prediction of erosion, sediment transport and deposition in the reservoir. For existing reservoirs, more and wider knowledge is still needed to better understand and solve the sedimentation problem, and hence improve reservoir operation.

2.1. CONSEQUENCES OF RESERVOIR SEDIMENTATION

The accumulating sediments successively reduce the water storage capacity [1]. Consequently, at long-term the reservoir operates only at reduced functional efficiency. Declining storage volume reduces and eventually eliminates the capacity for flow regulation and with it all water supply, energy and flood control benefits [2]. Reservoir sedimentation can even lead to a perturbation of the operating intake and to sediment entrainment in waterway systems and hydropower schemes [3, 4, 5]. Depending on the degree of sediment accumulation, the outlet works may be clogged by the sediments. Blockage of intake and bottom outlet structures or damage to gates that are not designed for sediment passage is also a severe security problem [6, 4, 7]. Other consequences are sediments reaching intakes and greatly accelerating abrasion of hydraulic machinery, decreasing their efficiency and increasing maintenance costs [6].

2.2. SEDIMENTATION RATE

The worldwide average annual sedimentation rate of all the reservoirs due to sedimentation are estimated to be 1 to 2 % of the storage capacity [8, 9], whereas the annual increase of storage volume due to construction of new reservoirs is close to 1 % [10, 11]. If there are no effective measures undertaken, until the end of the 21st century, the major part of the worldwide useful volume will be lost.

The sedimentation rate of each particular reservoir is very variable. It depends more particularly on the climatic situation, the geomorphology and the conception of the reservoir including its outlet works. Based on an analysis of data of 14 reservoirs, Beyer et al. [12] showed that on average in Switzerland only about 0.2 % of the storage capacity is lost annually due to sedimentation. The lower sedimentation rate in the Alps is due to the geologic characteristics, mainly rocky mountains, of the catchment areas at high altitudes [13, 10]. Nevertheless, sedimentation is also a subject of major importance in Alpine reservoirs, and after 40 to 60 years of operation, the sedimentation process may become a real threat for safe operation of intakes and bottom outlets.

2.3. RESERVOIR SEDIMENTATION BY TURBIDITY CURRENTS

In long and narrow Alpine reservoirs, turbidity currents are the governing process in reservoir sedimentation by transporting fine materials in high concentrations.

The erosion of the soil within a catchment area is at the origin of the material transported by a river. The erosion process starts in the high mountainous regions, and continues in the highlands and plains and ends in the lakes or in the sea respectively where it comes - due to the decreasing flow velocity - to sedimentation. Depending upon the sediment supply from the watershed and flow intensity in terms of velocity and turbulence, rivers usually carry sediment particles within a wide range of sizes. During flood events the fraction of sediments smaller than sand reaches 80 to 90 % of the total sediment carried by the river [14, 15], and the total sediment discharge is usually significant. If the sediment concentration is high enough it may come to turbidity current.

The turbidity currents belong to the family of sediment gravity currents. These are flows of water laden with sediment that move downslope in otherwise still waters like oceans, lakes and reservoirs (. Their driving force is gained from the suspended matter (fine solid material), which renders the flowing turbid water heavier than the clear water above. When a sediment laden river flows into a big reservoir, the coarser particles deposit gradually and form a delta in the headwater area of the reservoir that extends further into the reservoir as deposition continues. Finer particles, being suspended, flow through the delta stream and pass the lip point of the delta. If after the lip point of the delta, the difference in density between the lake water and inflowing water is high enough, it may cause the flow to plunge and turbidity current can be induced. During the passage of the reservoir, the turbidity current may unload or even resuspend granular material. Subsequently the sediments are deposited along the path due to a decrease in flow velocity caused by the increased cross-sectional area. Fine sediments (clay and silt sizes) are usually the only sediments that remain in suspension long enough following over long distances the reservoir bottom along the thalweg through the impoundment down to the deepest point in the lake normally near the dam to reach the outlets. At the dam the sediments form a muddy layer and settle down.

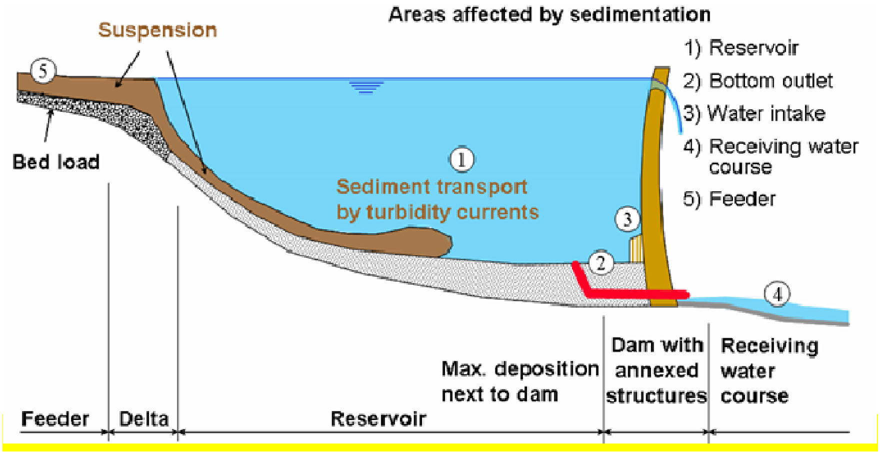

Fig. 1
Areas affected by sedimentation along a reservoir
Zones le long d'un réservoir touchées par la sédimentation

2.4. MEASURES AGAINST RESERVOIR SEDIMENTATION

Over the years several measures against reservoir sedimentation have been proposed [16]. But not all of them are sustainable, efficient and affordable. For example the raise of dams and outlet works doesn't provide a long-term solution [9].

There is a strong need to limit sediment accumulation in reservoirs in order to ensure their sustainable use. Management of sedimentation in Alpine reservoirs cannot be apprehended by a standard generalized rule or procedure. Furthermore, sediment management is not limited to the reservoir itself, it begins in the catchment areas and extends to the downstream river. Every situation has to be analysed for itself in order to determine the best combination of solutions to be applied. An overview of possible measures is summarized in Fig. 2 and grouped according to the areas where they can be applied:

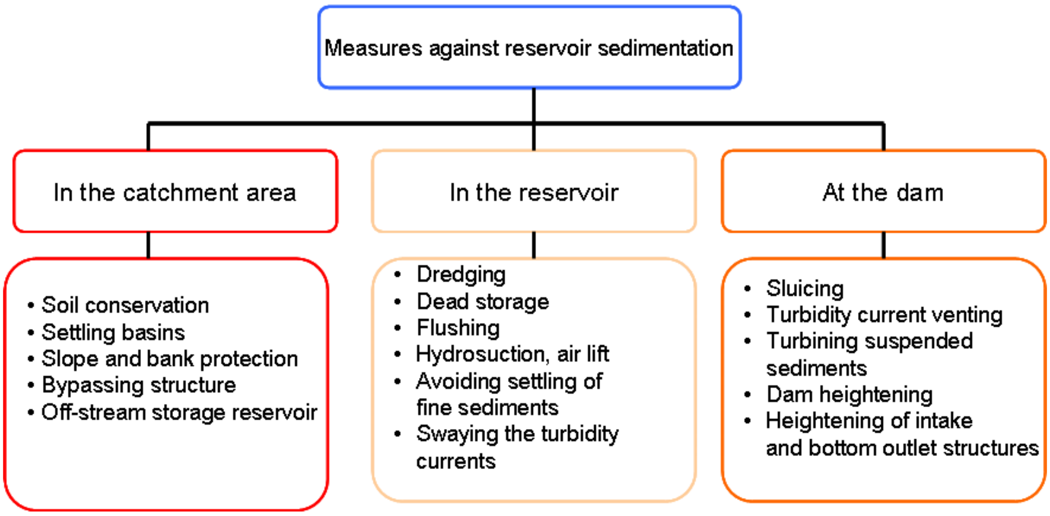

Fig. 2

Inventory of possible measures for sediment management

Inventaire de mesures possibles pour agir contre la sédimentation [16]

An integrated approach to sediment management that includes all feasible strategies is required to balance the sediment budget across reservoirs [17]. Integrated sediment management includes analysis of the complete sediment problem and application of the range of sediment strategies as appropriate to the site. It implies that the dam and the impoundment are operated in a manner consistent with the preservation of sustainable long-term benefits, rather than the present strategy of developing and operating a reservoir as a non-sustainable source of water supply [18].

A sustainable sediment strategy should also include the downstream reaches; therefore monitoring data should also include downstream impacts as well as sedimentation processes in the reservoir [19].

2.5. AWARENESS OF THE PROBLEMATIC

A glance on the historical development regarding reservoir sedimentation tells us about the evolution of the reservoir sedimentation awareness and the historical efforts in science and achievements in knowledge in the same topic over the intervening years and decades [20]. Although the phenomenon is not new and there are several observations recorded in the past, its importance is still underestimated or simply neglected. Studies that started in the late eighties brought in a much broader view on the transportation and sedimentation processes, better simulation techniques both in the laboratory and numerically allowed an insight view on turbidity currents, considered since the end of nineties as the major medium for moving sediments insight large reservoirs and therefore hindering long term operation of bottom outlets and water intakes. It is interesting to see that in the same epoch the notion of sustainability started to boom in any ecology related topic. And since then also efforts are done to find long-term solutions for sedimentation problems.

Based on a large literature review, particularly in ICOLD congresses, publications on specific reservoir sediment management techniques, in total 79 papers, appear only after the eighties in a significant number [20]. Only 6 papers exist before 1960, with Hill [21] as well as Visentini in 1936 [22] and Brown in 1943 [23] being the first ones, three articles were published in 1951 in New Delhi during the 4th ICOLD congress. The increase after 1990 is spectacular with a jump from 18 before to 61 papers after. This clearly indicates the enlarged awareness of the necessity to master reservoir sedimentation and to present the required competences in the field.

3. CASE STUDIES

Based on fundamental research and on former studies with field measurements [5], Oehy [10, 13] conducted numerical simulations and hydraulic experiments and studied various possibilities preventing turbidity currents proceeding to the dam. With obstacles such as submerged dams and screens made out of geotextile, with bubble layers and water jets he succeeded to partially or totally block the turbidity currents and to hinder them reaching the dam with its outlets. His methods were used in case studies outlined in the following chapters. Case studies of obstacles retaining turbidity currents as well as measures for venting are presented.

3.1. SUBMERGED OBSTABCLES IN LAKE GRIMSEL

3.1.1. Introduction

In Lake Grimsel, in Switzerland, an ongoing design project consists of heightening the two existing dams by 23 m (Spitallamm Arch Dam 114 m; Seeuferegg Gravity Dam 42 m). The excavation and demolition works necessary for the planned heightening generate approximately 150'000 m^3 of rock material. This large amount of materials has to be stored somewhere near the construction site. This led to the idea of building some kind of obstacle in the form of a submerged embankment dam to prevent sediment deposition due to the turbidity currents in the area near the intake structures. Thus, the occurrence and impact of turbidity currents on the reservoir sedimentation were investigated and the efficiency of such submerged obstacles sediment retention was evaluated (Fig. 3; see also [24, 13]).

The reservoir is approximately 5.5 km long and 300 m wide. The depth is regularly increasing from the inflow to the middle of the lake where a hollow upstream of the canyon exists. The intake and bottom outlet structures are located in the deepest area, approximately 90 m deep, downstream the canyon.

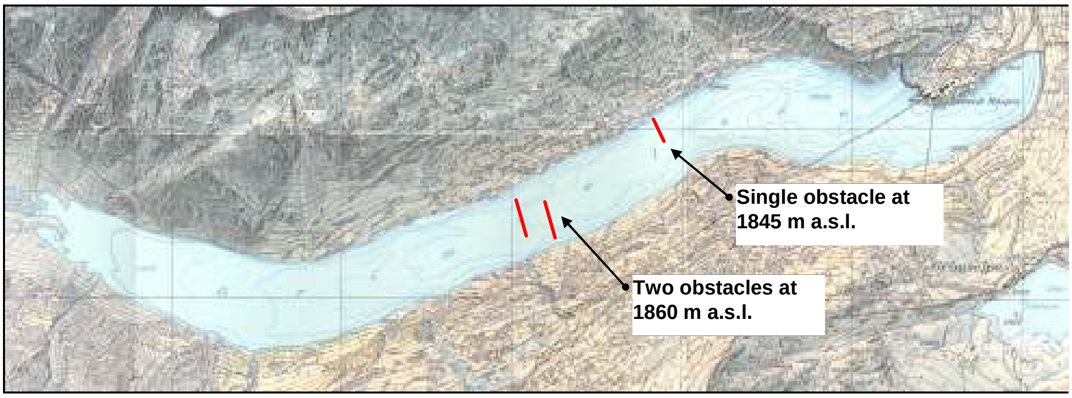

Fig. 3
Overview of the investigated obstacles in a 1:25'000 map
Aperçu des obstacles étudiés dans une carte géographique d'échelle 1:25'000

3.1.2. Turbidity current simulation of the October 2000 flood event

Numerical simulations modelling the high flood event occurring in October 2000 revealed that a turbidity current develops and propagates to the deepest area of Lake Grimsel close to the dam. During such an event considerable sediment deposits are created in the area of the intake and bottom outlet structures.

The canyon with the negative slope causes a slowing down of the current and deposition takes place upstream of this place. After passing the ridge the current accelerates again and finally dies out in the deepest area of the lake with maximum deposit heights of approximately 0.10 m each event. The turbidity current develops with increasing sediment and water discharge. After the peak the driving force of the current decreases and the turbidity current starts to die out until it finally disappears. The concentration decreases continuously from the inflow to the deepest area.

3.1.3. Turbidity current passing over submerged obstacles

Two possible configurations for these obstacles built as submerged embankment dams were numerically evaluated. The first configuration consisted of a obstacle, 15 m high and 150 m long, situated upstream of the canyon in a counter-slope of the lake. The second configuration consists of two submerged obstacles placed in the middle of the lake one after each other in a displaced manner, so that the current needs to turn around or overflow them. In this case, the height of the two obstacles was 10 m with a length of 210 m each. Both configurations do not extend over the whole width of the valley to keep a free passage for the water flow during emptying of the reservoir.

The obstacle clearly blocks the flow and reflects the major part of the turbidity current while some of the fluid of the turbidity current flows over the obstacle. A considerable amount of sediment deposits occurs, therefore, upstream of the obstacle (Fig. 4).

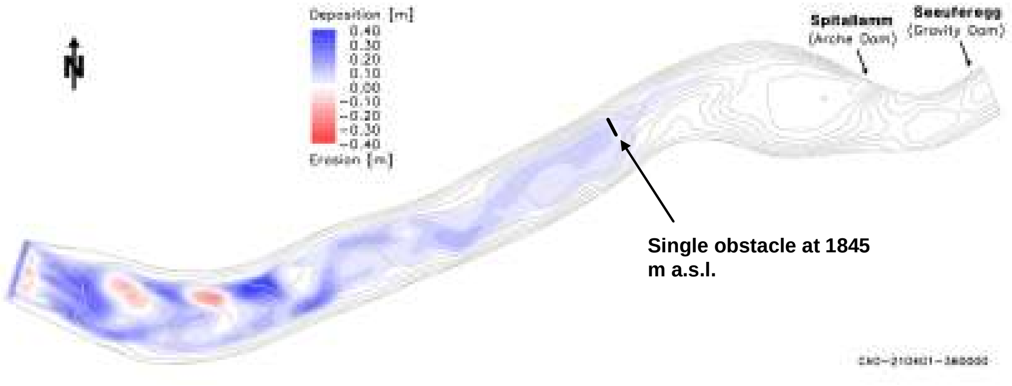

Fig. 4

Sedimentation after the flood in October 2000 with a single obstacle at 1845 m a. s. l..

Dépôts de sédiments après la crue d'Octobre 2000 avec un obstacle singulier à l'altitude 1845 m s.m. (Q = 40 m^3/s and cs =15 g/l)

The investigation of the effect of an embankment dam, built of demolition and excavation materials from the heightening of the Grimsel dams showed in agreement with the physical experiments, that the height should at least extend to twice the height of the approaching turbidity current to block the flow efficiently. A height of the dam of 15 m is sufficient and ensures that the elevation of the dam crest is below the minimum operation level of the reservoir. It is estimated that the retention of sediments behind the dam lasts for at least 20 to 50 years.

It can be concluded that the recycling of the demolition and excavation materials to build a submerged embankment dam gives an excellent example to control reservoir sedimentation due to turbidity currents.

3.2. OBSTACLES: LIVIGNO RESERVOIR

3.2.1. Evaluation of the reservoir sedimentation in the Livigno Reservoir

The actual sedimentation behaviour of the reservoir was analysed by means of 3D numerical simulations of the annual flood event, the October 2000 flood event, the highest flood event (1960) ever measured in the catchment area and the 100 years return period flood event. Once the effects of turbidity currents on the sedimentation process had been identified, further simulations were conducted to propose technical solutions against sedimentation due to turbidity currents in the Livigno Reservoir.

Two types of alternatives at two different sections were considered for the reduction of the effects of sedimentation studied for the Livigno Reservoir:

- Section 1: The implantation of pervious obstacles with three different heights located 3.0 km downstream of the inlet of the reservoir for the maximum operation level.
- Section 2: A measure consisting of a geotextile screen placed approximately 2.5 km upstream of the Punt dal Gall dam.

The Livigno reservoir, created by the Punt Del Gall dam built in 1968, is mainly located on Italian territory with the dam half in Italy and half in the Canton of Grisons, in Switzerland. The capacity of the reservoir is 164.6 million m^3, with the maximum operational level at 1’804.7 m a.s.l. The minimum operational level is at 1’700.0 m a.s.l. Currently, the water surface is never lower than 1’740 m a.s.l. The total catchment area is 295 km^2. The dam with 130 m high and 540 m of crest length forms a lake with two arms. The principal west arm of the reservoir, the object of this study, is approximately 9 km long and is formed by the Spöl River. The longitudinal average slope along the west arm of the reservoir is about 1.2 %.

The computational domain for the calculations is shown in Fig. 5. The discretisation of the grid is different for the simulation of the current situation and the simulations with technical measures.

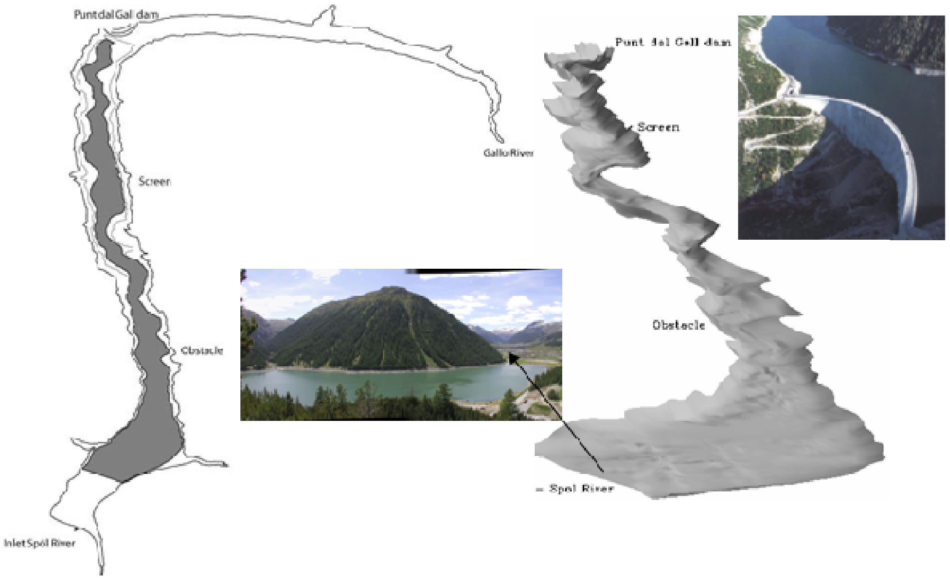

Fig. 5
Computational domain for the study. Current situation.
Domaine de simulation numérique, situation actuelle

It can be highlighted that the present situation of the reservoir does not present a major sedimentation problem in the vicinity of the dam. Approximately 60% of the sediment deposits during a flood occur in the first 3.0 km of the reservoir which acts as a natural desilting basin, and about 90% settle upstream of a proposed geotextile screen for all analyzed events. The maximum thickness of the deposits is less than 10 cm, even for the 100 years flood with a 30 g/l maximum inflow concentration.

This can be explained by the weak slope of the inlet bottom (1.2%) and the width of the inlet trumpet, which both decrease the velocity of the inflow and facilitate the deposition. The length of the reservoir is another factor reducing sedimentation close to the hydraulic outlet structures and the Punt dal Gall dam. The current looses its forces while flowing downstream due to water entrainment.

At the envisaged location of the screen, the peak of the current occurs 16h after the start of the flood and attains maximum concentration of 0.54 g/l with a maximum velocity of 0.30 m/s (Fig. 6).

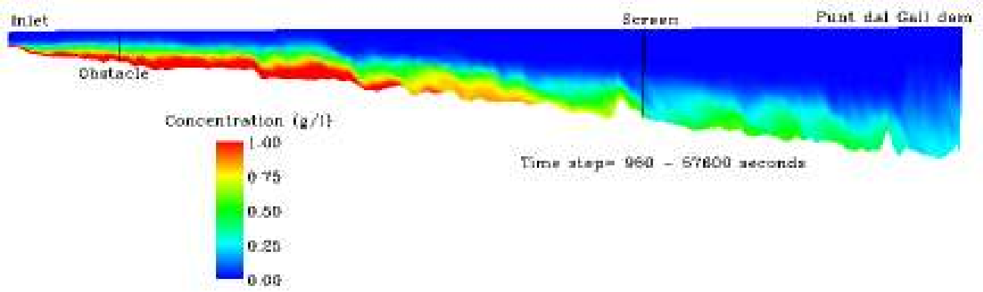

Fig. 6

Longitudinal cross section 16 hours after the start of the flood without the effects of the obstacle and screen

Profil en long 16 heures après l'arrivée de la crue sans tenir compte des effets de l'obstacle et du géotextile.

According to this analysis of the present situation, the alternative of installing a geotextile screen was dismissed, since more than 90% of the sediments are settling upstream of its proposed location for all cases and the current is almost completely dissolved in the reservoir at this section.

3.2.2. Technical measure

For the simulation of a pervious obstacle in the reservoir, three heights are considered. The obstacles with 4, 8 and 12 m height are simulated based on the October 2000 flood event with the maximum concentration of sediments reaching 15 g/l.

The performance of an obstacle against turbidity currents starts to be significant for the obstacles higher than 8m. In this case, the sedimentation upstream of the location of the obstacle increases from 63% to 76% for the obstacle with a height of 8 m and from 63% to 87% for the obstacle with a height of 12 m. The maximum deposition attains some 5 cm upstream the obstacle for a single event.

Due to the accessibility of the upstream area of the obstacle, removal of the sediment deposits can be organised if necessary over the years. A topographic survey before and after the implementation of the obstacle enables monitoring its efficiency, this is even simplified due to the annual lowering of the water level in the reservoir.

A longitudinal cross section in Fig. 7 at the invert of the reservoir shows the distribution of concentration at the peak of the current in the Section 1 for the different studied heights.

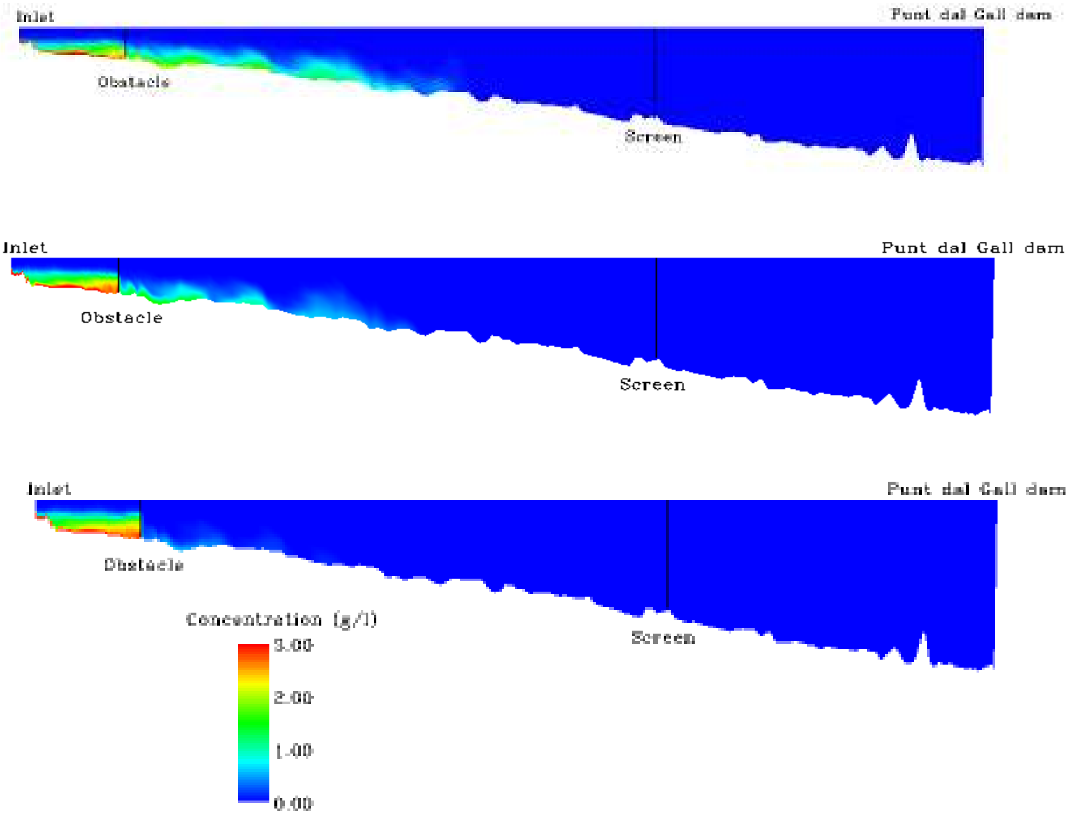

Fig. 7

Longitudinal cross section 9 hours after the start of the flood with the effects of obstacles of 4, 8 and 12m height (up to down)

Profil en long 9 heures après l'arrivée de la crue avec les effets d'obstacles de 4, 8 et 12 m de hauteur (du haut en bas)

It is important to remark that even the implantation of the obstacles seems not necessary with a maximum operation level of the reservoir, it can become crucial during the emptying of the Livigno Reservoir, once it blocks the flow of the sediments already settled to downstream.

3.3. Venting of turbidity currents: Reservoir Mapragg, Hydro Power Sarganserland

Müller [26] studied the sedimentation problem of the Kraftwerke Sarganserland. He aimed to find economically and ecologically feasible measures that could be taken to prevent sedimentation in the reservoir Mapragg created by a approx. 70 m high concrete gravity dam. Therefore he analysed bathymetric measures, the annual sedimentation and turbidity measurement data, and he identified possible measures to prevent sedimentation.

The sedimentation volume in the two reservoirs at the hydroelectric operation "Kraftwerke Sarganserland" increases annually by 75'000 m^3, which is equal to a loss of 0.2 % of the volume of the reservoir Gigerwald and 0.4 % of the reservoir Mapragg. The main problem is the increasing level of the sediments close to the bottom opening at the dam. In Mapragg the sediments are already above the base level of the bottom outlet. Turbidity measurements in Mapragg have shown that the main solid inflows occur during a few heavy rain events during the summer period. Several turbidity currents were measured, which transported solid material to the foot of the dam. Applying this knowledge, possible measures to prevent sedimentation were checked and compared. As an immediate measure for Mapragg, a concept for venting turbidity currents was developed, recommended and implemented. For Gigerwald the automation of the water intakes in the Weisstannental will have to be installed quickly, so that during flood events water with high suspension concentration levels will no longer be taken and diverted to the Gigerwald Reservoir.

3.4. LUZZONE

3.4.1. Introduction

Turbidity current flow in a laboratory flume as well as field measurements during two summer seasons at the Luzzone Reservoir in the Swiss Alps were used to validate a 3D numerical model. User-defined erosion and deposition modules that take into account the interaction between the current and the existing sediment deposits were used to simulate the balance between sediment deposition and erosion in the model.

The Luzzone arch dam of the Blenio Hydropower Company (OFIBLE) was built from 1958 to 1963 near the village of Olivone in the southern part of Switzerland in the Canton Ticino. The maximum crest height is 208 m and the crown is 530 m long. It is equipped with a power intake, a bottom and an intermediate outlet as well as an overfall spillway. From 1995 to 1998 the dam crest was raised by 17 m from 208 m to 225 m to bring the water level 15 m higher which increased storage from $87x10^6 m^3$ to $107x10^6$ m^3, allowing additional production of 60 Mio. kWh of energy in the wintertime.

The initial geometry of the reservoir in the deeper part is characterized by a V-shaped valley that has accumulated sediment for more than 30 years. The mean bottom width is now around 50 m. A trapezoidal section approximately characterizes the reservoir geometry with side slopes between 1:1 and 1:2. The bottom shape is nearly symmetrical in the reach near the dam. The average longitudinal slope along the reservoir bottom is about 4 %. The annual mean sediment inflow is approximately $38x10^3$ m^3 (based on measured deposit volume), and the total sediment volume in the lake is $0.90x10^6$ m^3 or 1.03 % of the pre-heightening total storage capacity in 1994. Major sediment deposits cover approximately 0.1 km^2 of the lake bottom, or around 8 % of the total lake surface.

During 1985, the reservoir was emptied (see Fig. 8), allowing the release of approximately 0.3x10^6 m^3 of alluvial deposits through the bottom outlet over a period of 7 weeks. At present, regular short-term flushings keep the intake of the bottom outlet free from sediments. These flushings create an almost 18 m deep cone in the sediment deposits around the bottom outlet structure. Dredging in 1995 removed sediments from the upper part of the power intake. The intake has been recently raised to minimize potential blockages by sediments.

Fig. 8

Luzzone Reservoir during emptying in 1985, looking upstream.

Réservoir de Luzzone pendant la purge en 1985, vue vers l'amont

In order to clarify the flow mechanism of river-induced turbidity currents in an artificial lake, field observations of turbidity currents were carried out in the Alpine reservoir of Luzzone and its main inflow river in the Val di Garzora (see Fig. 8). In 1992 and 1995, extended measuring campaigns took place in the mentioned test reservoir.

During the two years of on site investigations in 1995 and 96, no significant floods were observed. It was possible, however, to show the relationship between precipitation, water and sediment flow and turbidity current in the reservoir even for minor events. The inflow measurements showed large variations in water discharge, sediment concentration and water temperature.

3.4.2. Numerical simulations of Lake Luzzone

Simulation of a Flood Event

Based on the pre-construction topographic map and on bathymetric measurements of the reservoir bottom from 1982 to 1994, a mathematical model of the reservoir topography was prepared. Based on existing hydrologic analysis, a hypothetical 1000-year flood event was prepared as input to the numerical model. The maximum concentration, based on extrapolation from in-situ measurements, was set at $C_{sp} = 10\ \%_{vol}$ or 265 g/l. The selected single sediment size was $d_{50} = 0.02$ mm, mean value based on samples taken from the inflow river, from the reservoir bottom, and from flushing.

Results

The plunging of the tributary occurs just after the inflow patch of the computational domain. The underflow turbidity current then accelerates downstream along the bed. After about 40 minutes the current arrives at the dam. It is reflected and returns upstream, interacting with the still downstream moving body of the turbidity current. The returning current travels upstream over a distance of about two thirds of the total reservoir length. The global motion inside the lake becomes insignificant after approximately 4 hours while sediment inflow stopped already after 1.5 hours. A sediment-laden underwater "muddy lake" is formed, which will then settle its granular material over several hours or even days.

Due to particle entrainment from the existing sediment deposits, concentration increases as the current moves on. The current is globally erosive and thus becomes stronger during the first two hours, but becomes depositing later on. The volume of sediment entrained from the bottom is around 35'000 m^3, compared to 9'000 m^3, contributed by the inflow river. The maximum erosion depth of 0.35 m takes place in the centre of the lake; and the maximum deposition of 0.50 m is located close to the dam. Fig. 9 illustrates the location of the global erosion and deposition for the simulated turbidity current over a total duration of 4 hours and 10 minutes.

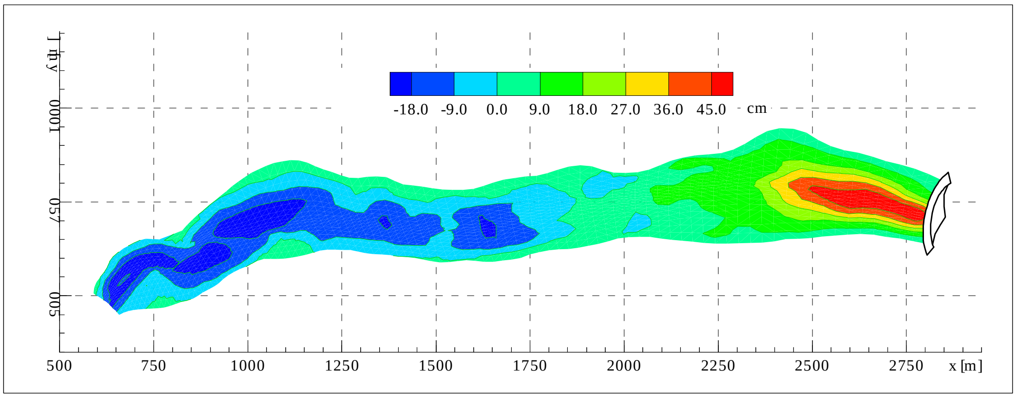

Fig. 9

Calculated sediment depth change due to a simulated 1000-year flood on the bottom of the reservoir

Profondeurs calculées des sédiments déposés sur le fond du réservoir résultant d'une simulation d'une crue milléniale

3.4.3. Links to Observations

Observation and numerical simulation show that turbidity currents are not only the main transport medium for the incoming fine granular material, but can also redistribute sediments inside the reservoir by entraining bed material and transporting it closer to the dam. After stopping, the current will deposit its entire sediment load almost uniformly across the deepest part of the lake. The surface covered with sediments brought in by turbidity currents can be seen in the detailed bathymetric map in Fig. 10 showing the deepest deposits near the dam. Ultrasonic bathymetric measurements of the reservoir bottom made in 1994, after 31 years in service, showed deposit depth increasing from 5 m in the upstream part of the lake, to 30 m in front of the dam.

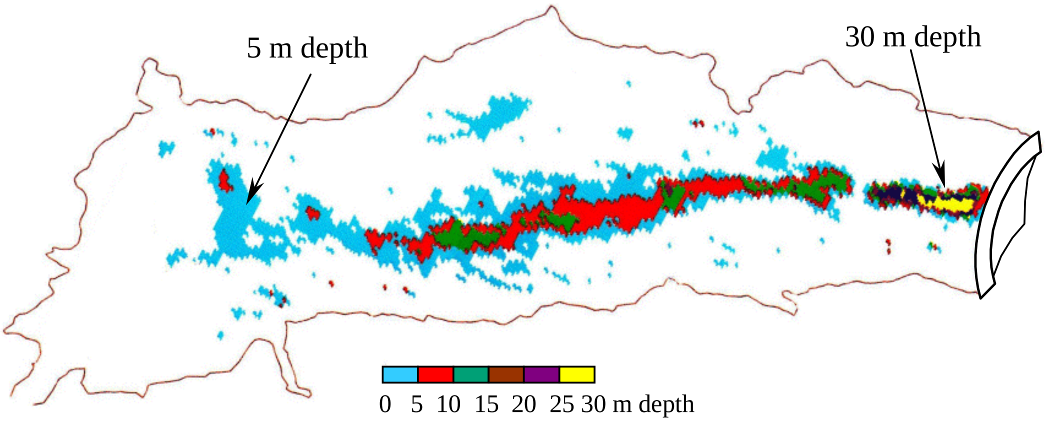

Fig. 10

Qualitative representation showing the location and magnitude of measured sediment deposits after 31 years in service

Représentation qualitative des dépôts de sédiments mesurés après 31 ans d'exploitation

The numerical simulation showed that turbidity currents from a large flood could entrain a substantial amount of bed sediment into suspension. The entrained sediment increased the density and accelerated the velocity of the current, causing even more entrainment to occur. Similar observations were made during experiments by Garcia and Parker [26].

Sedimentation prevails over entrainment for minor turbidity currents, the density of the turbidity current decreases in the downstream direction. Therefore turbidity currents induced by small floods and snowmelt seldom reach the dam, and when they do then only at low speeds and concentrations. They will deposit their granular material in the upper part of the reservoir in the form of temporary deposits, which can be eroded by larger flood events and carried into the deepest part of the lake.

Based on the numerical simulations, not only general conclusions can be drawn, but the precise behaviour of turbidity currents can also be predicted. The numerical model can be used as a strategic evaluation tool for reservoir management analyzing various technical solutions to prevent sedimentation in the most vulnerable parts of the reservoir, the bottom outlet and the water intake. Based on this simulation the optimal timing of the opening of the bottom outlet can also be determined to pass an important part of the sediment yield beyond the dam during floods (venting).

REFERENCES

[1] FAN, J. AND MORRIS, G. L. (1992). "Reservoir Sedimentation. II: Reservoir Desiltation and Long-Term Storage Capacity", *ASCE, Journal of Hydraulic Engineering*, Vol. 118, No. 3.

[2] INTERNATIONAL COMMITTEE ON LARGE DAMS (ICOLD). Sedimentation control of reservoirs – Guidelines, Bulletin Vol. 67 (1989).

[3] BOILLAT, J.-L., DE CESARE, G. (1994). "Dichteströmungen im Bereich des Grundablasses des Stausees Luzzone – Modellversuche". Tagungsband (proceedings) des Symposiums "Betrieb, Erhaltung und Erneuerung von Talsperren und Hochdruckanlagen", pp. 183-192, Graz, Austria

[4] SCHLEISS, A., FEUZ, B., AEMMER, M. UND ZÜND, B. (1996). "Verlandungsprobleme im Stausee Mauvoisin. Ausmass, Auswirkungen und mögliche Massnahmen ", Proceedings of Internationales Symposium «Verlandung von Stauseen und Stauhaltungen, Sedimentprobleme in Leitungen und Kanälen», *Mitteilungen der VAW* Nr. 142, Teil 1, pp. 37-58, Zürich, Switzerland.

[5] DE CESARE, G. 1998, Alluvionnement des retenues par courants de turbidité. Communication No. 7 of Laboratory of Hydraulic Constructions (LCH), EPFL.

[6] BOILLAT, J.-L., DELLEY, P. (1992), "Transformation de la prise d'eau de Malvaglia, étude sur modèle et réalisation". "Wasser – Energie – Luft", 84. Jhg. 1992, Heft 7/8, p. 145 – 151.

[7] HUG, CH., BOILLAT, J.-L., LIER, P. (2000). "Hydraulic model tests for the new water intake of the Mauvoisin hydroelectric scheme (Switzerland)", Proceedings of HYDRO 2000 - Making Hydro more Competitive, Session III: Sediment Management, 2-4 October, Berne, Switzerland, pages 161-170.

[8] JACOBSEN, T. 1999. Sustainable reservoir development: The challenge of reservoir sedimentation, Conference Proceedings "Hydropower into the next century", Gmunden, Austria, pp.719-728.

[9] BATUCA, D.G. AND JORDAAN, J.M., (2000). "Silting and desilting of reservoir", A.A. Balkema, Rotterdam.

[10] OEHY, CH. (2003). Effects of obstacles and jets on reservoir sedimentation due to turbidity currents. Communication No. 15 of Laboratory of Hydraulic Constructions (LCH), EPFL.

[11] OEHY, CH.; DE CESARE, G.; SCHLEISS, A. (2000). "Einfluss von Trübeströmen auf die Verlandung von Staubecken". Symposium Betrieb und Überwachung wasserbaulicher Anlagen, 19.-21. Oktober 2000, Graz, Österreich, Mitteilung des Instituts für Wasserbau und Wasserwirtschaft Nr. 34, 2000; p. 413-422

[12] BEYER, N., SCHLEISS, A. (2000) "Bodenerosion in alpinen Einzugsgebieten in der Schweiz", Wasserwirtschaft", 90. Jahrgang, Nr. 3, pp. 88-92.

[13] OEHY CH., SCHLEISS A. (2007) "Control of Turbidity Currents in Reservoirs by Solid and Permaeable Obstacles", Journal of Hydraulic Engineering ASCE, Vol. 133, No. 6, June 2007, pp. 637-648

[14] ALAM, S. 1999. The influence and management of sediment at hydro projects, Hydropower & Dams 3:54-57.

[15] SINNIGER, R.O., DE CESARE, G., BOILLAT, J.-L. 1999. Propriété des alluvions récentes dans les retenues alpines, Wasser, Energie, Luft, 91. Jahrgang, Heft 9/10, pp. 255-258.

[16] SCHLEISS, A. and OEHY, C. 2002. Verlandung von Stauseen und Nachhaltigkeit, wasser, energie, luft 7/8: 227-234.

[17] MORRIS, G. L. (1995), “Reservoir Sedimentation and sustainable development in India: problem scope and remedial strategies. Sixth International Symposium on River Sedimentation, Management of Sediment: Philosophy, Aims, and Techniques, New Delhi, 7-11 November, Balkema, Rotterdam, pp. 53-61.

[18] MORRIS, G.L. (1996), “Reservoirs and integrated management”, Reservoir Sedimentation, Proceedings of the St Petersburg Workshop May 1994, S. Bruk and H. Zebidi, eds, IHP-V, Technical Documents in Hydrology no. 2, UNESCO, Paris, pp. 135-148.

[19] MORRIS, G.L. and FAN J. (1997), "Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoir and Watersheds for Sustainable Use", McGraw-Hill, New York.

[20] DE CESARE G., LAFITTE R. (2007) "Outline of the historical development regarding reservoir sedimentation", 32nd IAHR Congress, Harmonizing the Demands of Art and Nature in Hydraulics, Venice, Italy, 1-6 July 2007.

[21] HILL, R. A. (1936). "Silting of reservoirs formed by large dams: its measurement and prevention". Communication 5 The silting of reservoirs formed by large dams; its measurements and prevention, Proc. of 2nd Congress on Large Dams, Vol. 5, Washington, USA, 1936. US Government Printing Office, pp. 203-206

[22] VISENTINI, M. (1936). "Alluvial deposits in reservoirs, their importance and the means to lessen or prevent them". Communication 5 The silting of reservoirs formed by large dams; its measurements and prevention, Proc. of 2nd Congress on Large Dams, Vol. 5, Washington, USA, 1936. US Government Printing Office, pp.169-176

[23] BROWN, C.B. (1943),"The Control of Reservoir Silting", United States Department of Agriculture, Miscellaneous Publication No. 521, Washington D.C., 166 pp.

[24] OEHY, C. and SCHLEISS, A. (2001). "Numerical modelling of a turbidity current passing over an obstacle – Practical application in the Lake Grimsel, Switzerland", Proc. of the 2001 Int. Symposium on Env. Hydraulics, Tempe AZ, USA.

[25] MÜLLER, P., DE CESARE, G., SCHLEISS, A. (2009). "Sedimentation problems in the reservoirs of the Kraftwerke Sarganserland", xxiii ICOLD Conference, Q89, Brasilia

[26] GARCIA, M. H. AND PARKER G. (1993). "Experiments on the entrainment of sediment into suspension by a dense bottom current", Journal of Geophysical Research (Oceans) 98(C3): 4793-4807

SUMMARY

The problem of reservoir sedimentation is pointed out, highlighting all the aspects accompanying the continuous process of loosing storage volume. The sedimentation process is described and its dependency on the various parameters regarding the reservoir catchment and the reservoir itself. The diversity of the watershed and the reservoir characteristics explains the differences in sedimentation rates and the variety of applicable and appropriate measures against reservoir sedimentation. An overview of the different measures currently in use is given. From the case studies it can be drawn, that a combination of several measures might provide the best solution.

An outline of the historical development regarding reservoir sedimentation is included. It can be concluded that even though the phenomenon is not new and there are several observations recorded in the past, its importance is still underestimated or simply neglected.

The situation of deep and long, seasonal storage reservoirs is discussed. The phenomenon of the governing process in reservoir sedimentation, the turbidity currents, transporting fine materials in high concentrations, is explained. Case studies investigating the effects of obstacles, screens and venting are exposed.

Today, most of the existing artificial lakes are still not operated in a sustainable way. With the current knowledge and technology regarding reservoir sedimentation, it is possible for future hydropower project with storage reservoirs to be operated more efficiently and productively, ensuring their sustainability. For any new hydro power scheme it is recommended to consider all the aspects related to reservoir sedimentation in early stage of design. Especially technical measures and devices for the management of turbidity current should be foreseen from the beginning.

RÉSUMÉ

Le problème de la sédimentation des réservoirs est présenté, notamment les aspects accompagnant le processus continu de la perte de volume de rétention. Le processus de sédimentation est décrit dans le contexte des paramètres du bassin versant et du réservoir lui-même. La diversité des bassins versant et les caractéristiques des réservoirs expliquent les différences en taux de sédimentation ainsi que la variété des mesures applicables et appropriées qui sont actuellement connues et pratiquées. Les études de cas montrent que des fois la combinaison de plusieurs méthodes fournit la meilleure solution.

Un extrait du développement historique concernant la sédimentation des réservoirs est inclus. On peut y conclure que même si le phénomène ne soit pas nouveau et qu'il y ait plusieurs observations effectuées dans le passé, son importance reste sous-estimée ou simplement négligée.

La situation des réservoirs profonds et saisonniers est discutée. Le phénomène du processus moteur, les courants de turbidité, transportant des matériaux fins dans des hautes concentrations est expliqué. Des études de cas investiguant les effets d'obstacles, de rideaux et de purge de courants de turbidité sont exposées.

Aujourd'hui, la majorité des lacs artificiels existants ne sont pas encore exploités d'une façon durable. Avec les connaissances et la technologie actuelle concernant la sédimentation des réservoirs, il est possible dans des futurs projets d'aménagement hydrauliques de les faire opérer de manière plus efficace et plus productive, tout en assurant leur durabilité. Pour tous les nouveaux aménagements il est recommandé de considérer tous les aspects liés à la sédimentation à temps. Spécialement des mesures techniques et des

installations pour maîtriser les courants de turbidités devraient être prévues depuis le départ de la planification d'un aménagement hydraulique.