Sustainable Sediment Management of Alpine Reservoirs considering ecological and economical Aspects

Sediment Management in Alpine Reservoirs - Recommendations and Best Practice Guide
Sven Hartmann

ALPRESERV
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1 Introduction

Sediments are part of the geomorphological cycle which has shaped the earth’s surface ever since. Exogenic processes such as precipitation, wind, temperature as well as vegetation are the agents causing the weathering, loosening, fragmentation and, finally, transportation of the materials making up the earth's surface. This starts in the high mountains, then continues at the medium levels and in the river plains, ending in a lake or ocean, where the material carried along by running waters usually settles as a result of the reduced flow velocity.

Man has created numerous reservoirs to equalise the natural variations of water flow in the rivers to make intensive use of the water for e.g. irrigation purposes, drinking water storage, hydro power use, navigation or flood protection. There are, however, not only advantages to the above uses of impounding facilities. They also involve problems, mainly due to the interruption of the flow continuum of the stream, and thus the natural geomorphological cycle. As a stream enters a reservoir, its velocity decreases depending on the type of reservoir, so that it starts depositing the solids it is carrying along. This may go as far as a reservoir filling completely with sediment. In addition, the properties of a stream are affected by the reduction or elimination of its flow characteristic, which in turn risks having detrimental effects on e.g. stream ecology, especially for fisheries. Other negative consequences may come from rising water tables. Negative effects are also likely to result for the sections immediately upstream and downstream of a reservoir.

All lakes and reservoirs created on natural rivers are subjected to reservoir sedimentation. There are no accurate data on the rates of reservoir sedimentation worldwide, but it is commonly accepted that about 1 - 2 % of the worldwide capacity is lost annually. Analysis of data of 14 reservoirs in Switzerland showed that this percentage is only about 0.2 % in Alpine reservoirs. The lower filling rates are results of geologic characteristics of these basins at high altitude. Impounding facilities are always costly, but this is justified by their various potential uses. Reservoir sedimentation, however, reduces the value of or even nullifies this 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.

Sedimentation problems and management techniques vary widely from one site to another with additional and often more tighten problems in alpine environment. Due to the complexity of sedimentation processes governed mainly by hydrologic, geologic, topographic, and geographic characteristics, neither an all-embracing description of the problem nor an analytical approach exits to predict or accurately manage sedimentation. The best way to face occurring problems is to study specific sites and best practice examples.

The project ALPRESERV is based on an initiative of research institutes in Germany, Austria and Switzerland working on the field of sediment issues since many years and overlooking scientific, ecological, economical, legal and operational facettes of reservoir sedimentation in different scales of space and time. Within the EU Interreg IIIB project ALPRESERV 17 project partners from 5 alpine countries worked together to develop and evaluate a sustainable sediment management program for impoundments. The activities were not focussed on technical and economic issues only but addressed the ecological consequences of sedimentation as well as de-sedimentation options, too.

The partnership published a series of technical reports with specific information regarding Sediment Sources and Transport Processes (Volume 2), Reservoir Sedimentation (Volume 3), Sediment Management Methods - Technical and legal aspects (Volume 4), Pilot Actions and Database (Volume 5), and Impact Analysis and Recommendations regarding Sediment Flushing (Volume 6). Volume 7 can be regarded as a compendium to present the most important outcomes of the project.
The Problem of Reservoir Sedimentation

2.1 Influencing factors

The sedimentation process in a reservoir is governed by a wide variety of highly complex factors. Sediment influx, reservoir geometry and flow are considered as the determining factors. These in turn depend on a number of parameters and conditions such as catchment, reservoir management and climate. In addition, the upstream river morphology is important; in particular, other reservoirs, dams, retention basins or lakes may substantially reduce sediment delivery to the reservoir under study. Other man-made measures, such as sewers, may also have a direct effect on the sedimentation process.

2.2 The mechanics of sedimentation

Flow conditions change substantially as the water travels from the end of the upstream reach in the direction of the dam. As the cross-section increases, the bottom shear-stress as a factor governing sediment transport decreases, and the solids start settling. Bedload is deposited near the upstream end of the reservoir, while the suspended particles settle further downstream.

Another important factor influencing the sedimentation process, in particular its morphology, is reservoir geometry. In a long, narrow backwater reach (above a river barrage) and under idealised constant conditions (water level, inflow, sediment influx), the bedload deposit progresses relatively evenly from the upstream end of the reservoir in the direction of the dam. By contrast, the sedimentation process is irregular in reservoirs of major width. Even small bedload bars, sudden widenings of the channel (such as lakes), etc. may generate unexpected sedimentation conditions. Other factors of some importance are the changes over time in inflow, water level and sediment supply, resulting in a constant alternation between sedimentation, a state of equilibrium and erosion. Stream bends intensify the difference in transport capacity of the current between the inner and the outer bends, the sedimentation tendency being higher on the inner side.

The hydraulic and sedimentological processes are even more complex and irregular in wide reservoirs (lakes) with rapidly widening inflow cross-sections. The bedload is deposited in delta-shaped formations (Mangendorf, Scheuermann, Weiss, 1990) which, at a later stage, become traversed by several distributary streams transporting the settling particles to the channel edges. These distributaries keep migrating, causing the delta to spread approximately radially from the inlet (Mertens, 1987).

In rivers developed by a series of dams, the location of the reservoir under study is another influencing factor, and so is the commissioning year, which is important for the sedimentation condition (initial sedimentation followed by erosion and then sedimentation in the downstream reservoirs, state of equilibrium).

In practice, sedimentation processes are also influenced by changes in time of inflow, water level (in the basin) and sediment supply, which results in an alternation of sedimentation, state of equilibrium and erosion of already deposited solids. While the transport behaviour of non-cohesive sediment obeys the limit curves of the diagram by Shields (1936) or others, considerable changes in the critical erosion and sedimentation shear stresses may result for inorganic fine material with aggregation and flocculation properties. Thus, the sedimentation shear stress for fine sediment with a high mineral percentage in the clay fraction may be 100 times higher than suggested by the Hjulström criterion (1935) or even above the erosion limit.

After settling, such fine sediment undergoes a major consolidation phase during which the erosion shear stress may increase by more than a factor of 10. In consequence, in reservoirs
with a high inflow of inorganic and organic fine sediment, once this is consolidated, the sediment may fail to be carried along even by floods.

2.3 The sedimentation process of reservoirs

Reservoirs differ from natural lakes by the morphological peculiarity that their lowest point is almost always situated at the dam and, thus, near the outlet gates. In addition, it is possible to some extent to control discharge from a reservoir and, hence, the reservoir water level. In many reservoirs, the outlet gates permit almost complete water level drawdown or reservoir emptying. These special morphological and hydrological features of reservoirs, as compared with natural lakes, enable increasingly efficient sedimentation-control (Vischer, 1984).

The deposition process of sediment carried into a reservoir can be described, in hydraulic-sedimentological terms, by the relationship between discharge, flow velocity or bed shear stress and particle diameter or settling velocity, both for bed load and suspended sediment. It thus becomes clear that the sedimentation pattern is a function of the type and rate of sediment delivery and of discharge and reservoir geometry as well as of the type of reservoir management. Figure 2.3-1 below is a graph illustrating the sedimentation pattern characteristic of a reservoir lake.

![Diagram of sedimentation](Delta formation through bed load and suspended load)

Figure 2.3-1: Sedimentation pattern for a reservoir basin (Vischer, 1981)

Whereas coarse sediment settles as bed load directly in the inflow zone, suspended particles are carried farther into the reservoir. They may travel as far as the dam itself to be deposited there, which is mainly a result of density currents. 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. If 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. Turbidity currents are encountered in fluvial hydraulics, most prominently if a sediment-laden discharge enters a reservoir, where, during the passage, it may unload or even resuspend granular material.

More detailed information is provided by Volume 3 - Reservoir Sedimentation of the ALPRESERV Publication Series.
3 Sediment Management

Reservoirs are intended to store the inflow for a certain period - on a daily, weekly, monthly, seasonal or year-to-year basis - to bring about a temporal and quantitative balance between water yield and water needs as well as to control the flow regime. Resort is made to the stored water during periods of insufficient flow for the purposes of electricity generation, drinking water supply, or supply to waterways. Retention of flood flows through storage may prevent inundations, and disastrous droughts may be avoided, or at least mitigated, through irrigation.

Accepted practice has been to design and operate reservoirs to fill with sediment, generating benefits from remaining storage over a finite period of time. The consequences of sedimentation and project abandonment are “left” to the future. These consequences can be summarized as: sediments reaching intakes and greatly accelerating abrasion of hydraulic machinery, decreasing their efficiency and increasing maintenance costs; blockage of intake and bottom outlet structures or damage to gates that are not designed for sediment passage (Boillat and Delley, 1992), etc. Considering reaches downstream of the dams, one important problem can be the augment of the erosion risk in the river since the sediment equilibrium was affected. This ‘future’ has already arrived for many existing reservoirs and most others will eventually experience a similar fate, thereby imposing substantial costs on society (Palmieri et al., 2001).

The average annual loss in storage volume due to sedimentation in the world's reservoirs has come to exceed the annual increase in storage through the construction of new facilities for such purposes as irrigation, drinking-water supply and hydro power. Sustainable use of the reservoirs is thus not always ensured in the long term. Although the sedimentation rate in Alpine reservoirs is not more than about 0.2%, which is much below the world-wide average, sedimentation constitutes a serious hazard, as turbidity currents sporadically transport large sediment volumes like avalanches down to the dam, where concentrated deposits jeopardise the operation of gates, power intakes and bottom outlets.

Under the aspect of sustainability, which should dictate any future action, reservoirs should be designed and operated so as to function as sustainable resources. This requirement will be met in the long term only by combining appropriate reservoir design with sediment management and/or desedimentation activities. To ensure availability and proper use of the installations as well as to limit the consequences of impounding facilities to the river morphology a sediment management strategy is needed which has to be adopted to each single installation taking into account the special boundary conditions of the local situation.

Action against reservoir sedimentation can be classified into preventive and retroactive measures. The former are intended as a precaution intended to prevent sedimentation from the outset, the latter are to remove at least part of the sediment once deposited. Another distinction can be made between measures in the catchment, in the reservoir and at the dam (Fig. 3.1-1).

More detailed information is provided by Volume 2 - Sediment Sources and Transport Processes of the ALPRESERV Publication Series.
3.1 Measures in the catchment area

The most effective precaution against reservoir sedimentation is erosion protection in the catchment. Climatic conditions permitting, surfaces should be planted as a protection against erosion. Afforestation in the catchments above the great number of reservoirs with a sedimentation hazard, especially in Asia, will be one of the main tasks to be faced by mankind in this century. Unfortunately, afforestation will take long to show its effect against sedimentation. Yet this is essential for conserving valuable cultivated land for agricultural uses and as a protection against floods, debris flows and landslides.

In vegetation-free catchments, such as found at high levels in the Alps, erosion control is possible only by technical means, such as stabilisation of valley slopes as well as of stream beds and banks.
3.2 Measures in the reservoir

Once sediment has entered a reservoir, only retroactive (Fig. 3.1-1) or passive measures are possible, which remove sediment or at least mitigate their adverse effects.

Sedimentation can be delayed or prevented by routine evacuation of the deposits. This may be achieved by dredging with a full reservoir as well as with the water level drawn down, from the shore or from barges. Depending on the granulometric grading of the sediment and dredging depth, suction dredgers or purely mechanical, conventional dredging equipment may be used for this purpose.

A special application of hydraulic clearing is sucking sediment from the reservoir through piping placed at the bottom of the lake. This is provided with special openings on the underside through which sediment is sucked in as soon as a gate is opened at the end of the pipe (SPSS - Slotted Pipe Sediment Sluicer) (Jacobsen, 2000).

An extremely efficient measure of clearing a reservoir is by flushing, which - where possible - should completely empty the basin. But this may involve ecological problems and sedimentation downstream from the dam. The potential effects of such a measure will depend on the amount of sediment charge passed during the relatively short flushing process (Boillat et al., 2000a and 2000b).

Suspended sediment is an important factor in reservoir silting. Where it is possible to prevent suspended particles from settling, they could be continuously discharged through the outlets. Passage of a certain level of sediment concentration through the turbines is in fact acceptable. Thanks to novel materials, turbines are becoming increasingly abrasion resistant (Grein et al., 1992). Fine sediment can be kept in suspension permanently by providing for sufficient turbulence. This may be achieved in Alpine reservoirs by taking advantage of the energy coming from stream diversions. Another conceivable method would be by purely mechanical turbulence produced from a "large-scale mixer".

Another method of minimising the adverse effects of sedimentation is by controlling the turbidity currents, provided these constitute the dominant process as is the case for a large proportion of the Alpine reservoirs.

3.3 Measures at the dam

A method commonly practised worldwide for preserving the usable storage of a reservoir lake is overdimensioning its volume. This provides for a certain amount of space where sediment is allowed to collect for a given period, typically 50 years. Where this space is not amenable to utilisation, it is termed dead storage.

Where only the outlet works of a dam have been affected by sedimentation, and if moreover efficient flushing is not feasible, these structures need to be relocated at a higher level in order to ensure continued operation. A recent project of this kind is the reconstruction of the outlet and power intake structures at the Mauvoisin Dam (Hug et al., 2000; Schleiss et al., 1996).

Pressure flushing to clear the outlets will normally evacuate but a cone in front of the outlet, with slopes corresponding to the angle of internal friction of the deposited material. In the case of fine sediment, the feasible cone angle will not reach more than about 30° at best (Sinniger et al., 2000). Where an outlet is already entirely covered up with sediment, opening of the gate may cause the material to consolidate altogether and prevent the erosion of a cone. This may be remedied by sinking an injector shaft to admit sufficient water during the initial flushing phase (Krumdieck et al., 1981). At least sporadic evacuation of a cone in front of a power intake is possible by combining this structure with a flushing outlet located immediately below (Hug et al., 2000; Schleiss et al., 1996).
Bottom outlets of sufficient capacity are theoretically capable of "sucking in" and passing density currents during floods. The outlet capacity of an Alpine reservoir, however, is normally too small to permit this type of sediment passage. Moreover, frequent operation of outlets against the extremely high pressures they are subject to involves certain risks, such as vibration and jamming of the gates. Finally, Alpine reservoirs often serve for flood protection, which implies that opening the bottom-outlet gates during floods is undesirable.

When a large proportion of the usable storage has been lost, this may be compensated for by heightening the dam where feasible. This has been practised at several dams in North Africa (Cornut, 1992) and in Bavaria on the Sylvenstein reservoir in 1997 (Fig. 3.3-1)

![Figure 3.3-1: Cross section of the Sylvenstein dam with the dam heightening (maximum operation water level 767 m.a.s.l., normal operation water level 752 m.a.s.l., minimum water level 736.40 m.a.s.l)](image)

More detailed information is provided by Volume 4 - Sediment Management Methods - Technical and Legal Aspects of the ALPRESERV Publication Series.
4 Decision making process for suitable sediment management strategies

4.1 General aspects

Measures should be designed and implemented according to aspects of water resources management, ecology and economy as well as technical feasibility. The aim of any such action should be to minimise the detrimental effects in all relevant respects. As each installation has a different requirement specification, the measures have to be designed to suit each specific case. Thus a definition of standard limits (sediment concentration, oxygen concentration, chemistry, duration of a measure, discharge etc.) is not appropriate. Standard values should only be defined as part of a specific legal procedure.

The design and assessment of a measure should in particular include the following main parameters:

- Type and configuration of the plant, the reservoir and the tailwater section,
- Discharge,
- Drag,
- Season,
- State of sedimentation - grain-size distribution of the sediment,
- Duration of the measure,
- Substances contained in the water and sediments (organic, anorganic, oxygen etc.),
- Solids concentration.

Apart from these, additional parameters designed to suit the respective plant may be needed, such as morphology and type of land use in the catchment area, co-ordination with upstream and downstream riparians etc.

4.2 Mechanical Excavation

Mechanical excavation is only desirable where conditions such as flow, gradient, particle size distribution, duration of peak flow etc. make other reservoir desedimentation measures appear inefficient.

Based on the respective requirement specification, the evacuation method should be selected with due allowance for the type of plant under consideration, while weighing advantages against disadvantages.

Dry dredging:
Advantages: economical, short duration of work, equipment available
Disadvantages: restricted to low-flow period (especially in winter), partial filling necessary, greater adverse ecological impact

Wet dredging:
Advantages: continuous evacuation at top water level, less adverse ecological impact, flexible timing possible
Disadvantages: higher costs, longer duration of work, special equipment required

Suction dredging:
Advantages: continuous evacuation at top water level, less adverse ecological impact, independent timing
Disadvantages: higher costs, special equipment needed, intermediate storage and drainage facilities required
4.3 Flushing

Generally, flushing is regarded as the most favourable method for desedimentation of a reservoir given the appropriate requirement specification and boundary conditions. Flushing activities can be performed close to natural flood situations, allowing fish and other species to escape to protective areas and thus limiting the negative consequences. However, flushing events often result in a short-term resuspension of fine sediment which has been stored over a long period in the impounded area. Such discharges commonly are associated with high turbidity in the downstream reaches. The increased turbidity can directly impact aquatic organisms negatively (fish, benthic fauna) and can also lead to indirect effects through the change of habitat conditions. Large regions of the riverbed can be covered by sand and fine sediment (colmation of gravel interstices through the settlement of fine sediment), resulting in a loss of habitat area for typical riverine aquatic species and suitable spawning area for gravel-spawning fish key species. In extreme cases, this can even lead to a reduction or total loss of food supply. In all, a very complex set of problems with high interdependency arises. More detailed information is provided by Volume 6 - Impact Analysis and Recommendations of the ALPRESERV Publication Series.

Flushing should be carried out with allowance for the following aspects:

- Sufficient flow to initiate the flushing process (50% to 70% of HQ1 - present threshold value in the German-speaking region)
- Consideration of the forecast inflow from the upstream sections
- Reservoir draw-down with allowance being made for:
  - Aggravation of the flood situation
  - Start flushing during the ascending branch of the flood wave
  - Stability of reservoir slopes (pore water pressure and stabilisation structures)
- Flushing process with allowance being made for:
  - Controlling particle concentration on the basis of continual monitoring in the tailwater
  - Monitoring inflow (forecast inflow from the catchment area)
  - Constant checks of reservoir slopes (stability, erosion attacks)
  - Cessation of the flushing process if flow falls below threshold value and inflow forecast is negative
- Reservoir filling with allowance being made for:
  - Rated discharge of downstream hydro power plants
  - Follow-up flushing for diversion-type power plants

Flushing strategies are generally limited to Run-of-River installations as they are capable to provide high discharge rates by opening the gates of the weir construction.

From the economic point of view flushing activities are favourable, too, as almost no machinery is necessary and the sediments transferred from the reservoir to the downstream area by the natural forces of running water. If flushing is performed in the context of a minor flood event the loss of power output can be limited and the reservoir can be refilled within short periods of time.

Generally the costs of a flushing activity can be divided into 3 main categories: preparation costs, flushing costs and post-processing costs (Fig. 4.3-1).

For preparation, planning is a sub-category as well as the preparation works like operation instructions or meetings with stakeholders. Depending on how many flushings are appropriated by the government, a report for the notification is necessary as well.

The flushing costs are divided into energy losses, external controlling and monitoring. The monitoring includes flood forecast, echo-soundings and measurements of various parameters at different locations along the river. The post-processing costs consist of general post-
processing costs due to damages at the banks or at the power plant as well as the reporting. Further categories are the ecological monitoring to assess the damages on fish and to find an agreement on restitutions to the fishery.

<table>
<thead>
<tr>
<th>Preparation Costs</th>
<th>Flushing Costs</th>
<th>Post-processing Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planning</td>
<td>Energy losses</td>
<td>General post-processing Costs</td>
</tr>
<tr>
<td>Notification</td>
<td>External Controlling</td>
<td>Ecological Monitoring</td>
</tr>
<tr>
<td>Preparation Works</td>
<td>Monitoring</td>
<td>Restitutions to fishery</td>
</tr>
</tbody>
</table>

Fig. 4.3-1: Cost categories of a flushing activity

For the pilot action Bodendorf (more information is provided by the ALPRESERV publication Volume 5 - Pilot Actions and Data Base), the costs of each category were worked out with assistance of the operator AHP. Fig. 4.3-2 shows the percentage of sub-categories on the total costs. As it can be seen, the flushing operation causes only 31% of the total costs. All together, the preparation costs are calculated with 14%. Also restitutions to fisheries downstream of the reservoir are a main fraction in the analyses (28%). This category is a varying cost-category and depends on the ecological impact of the flushing but also on negotiations between operator and fishery. The main share of the costs are related to ecological monitoring activities.

![Cost Categories Pie Chart](image)

Fig. 4.3-2: Cost categories for a flushing event (in percent)

4.4 Combined methods

Combined processes should be used if neither flushing nor evacuation alone is capable of producing the required amount of reservoir desedimentation. The two measures must be
implemented separately, both in time and space. Experience gathered during previous flushings and evacuations should be used to optimise the overall result. For reasons of ecology and water resources management, care should be taken to ensure that the maximum possible proportion of the sand and gravel fractions lending themselves to flushing are passed through during the flushing process. Coarse fractions that cannot be flushed should be evacuated in not more than absolutely necessary quantities.

Additional measures may be needed to achieve this aim.

### 4.5 Additional measures

The main means of improving bedload transport are groynes and training works, which increase or concentrate the drag forces (Fig. 4.5-1). Suitable sites will have to be selected on the basis of experience gained from past flushing measures, while aiming at improving the efficiency of future flushings. If technically feasible, an artificial “ripping open” of the top layer at the reservoir floor should be considered in order to accelerate the bedload drift.

#### Fig. 4.5-1: a.) Construction works of a groyne and b.) constructed groyne at pilot action Bodendorf

Fig. 4.5-2 shows the excavation of an initial erosion channel (view from downstream to upstream).

#### Fig. 4.5-2: Excavation of gravel (a.) and construction of an initial erosion channel (b.) at Bodendorf

All other additional measures serving to remove material (upstream basins, sedimentation basins, etc.) can be considered as being of secondary importance.
5 Planning requirements for sediment evacuation

Generally it must be distinguished between river-run-of installations and dams. Dependent on the discharge high flow velocities may occur in river-run-of installations, exceeding to almost natural flow conditions during flood events. In contrary impoundments with dams can be compared more or less with lakes with very small discharge rates and flow velocities compared to the total volume of the reservoir.

5.1 Planning phase

Fundamental data has to be collected during the planning phase comprising sediment transport rate, sediment composition, degree of compaction, and ratio of bedload and suspended load. As these parameters vary significantly depending on hydrological conditions and seasonal effects, measurements have to be performed over several years to gain adequate accuracy. Sampling techniques are described in detail in chapter 10 of the ALPRESERV Publication Volume 2 - Sediment Sources and Transport Processes. If depositions of hazardous substances (e.g. heavy metals) can be assumed due to industrial or mining activities or other possible point sources upstream of the reservoir specific chemical investigations have to be performed accordingly.

The reservoir itself requires a detailed survey to establish its topography. A sedimentation survey for a reservoir is carried out by determining the position and elevation of a multitude of individual points. Comparison of conditions recorded at different times shows the progress of sedimentation. Reservoir sedimentation is recorded by means of profiles so as to allow two-dimensional representation. The distance between two consecutive profiles should not exceed 200 m to allow proper analysis of the topographic data.

The individual cross-sections of the reservoir are surveyed by position-finding. This includes simultaneous echo-location and sounding (geometric position of the measuring point; water depth). Position-finding is usually carried out from floating vehicles (Fig. 5.1-1). Depth measurement is usually by echo sounding. The survey has to be related to a regional or higher-order contour system.

Fig. 5.1-1: Survey boat of Verbund Austrian Hydro Power AG in the River Drau
It has been stated already that there are certain requirements for successful sediment flushing which are related to the amount of water available. Hence historical and present river flow records have to be collected. Additionally sound hydrological knowledge is necessary for planned flushing activities to be able to estimate or calculate the run-off from the catchment areas upstream related to rainfall or specific weather conditions.

Physical as well as numerical models may be used as basis for evacuation activities in reservoirs. Such models determine the minimum flow requirements for flushing operations (incipient motion), the amount and size distribution of transported sediments as well as bottom level elevations. However, it must be emphasised that restrictions and limitations apply regarding the application of models. Inaccuracies come from simplified, often empirical, assumptions for the flow equations and in particular the transport equations. They also come from the numerical treatment necessary for solving this system and from the necessity of making assumptions for the great number of parameters, which in many cases do not reflect reality with sufficient truthfulness. Thus, the variation of individual parameters, as roughness, along with discharge and season is often left out of account.

Nowadays, significant effort is necessary to properly consider environmental concerns and to limit the ecological risks. The ecological effects of sediment management practices vary highly from site to site. More recently, the consequences associated with sediment flushing, especially concerning the often-occurring degradation of ecological systems downstream, have been openly debated both, in the professional community and largely in the media. Moreover, this problem gains specific topicality due to new requirements for water protection according to the EU Water Framework Directive. It is strongly recommendable to integrate ecological expertise into the planning process as soon as possible to be able to start a suitable monitoring program which helps to document the present state which should be re-established after applying evacuation measures. A broad documentation of an extended monitoring program can be found in the ALPRESERV publication Volume 6 - Impact Analysis and Recommendations regarding Sediment Flushing.

Part of the planning process is to identify the best option out of different sets of variations and techniques. Beside all technical issues the operator of the reservoir is mostly interested in costs related to the expected financial benefit due to the extension of the reservoir life time. Multiple scenarios have to be developed and compared including the “no action”-option. On that basis, priorities may be defined regarding the most preferable strategy which has to be communicated to authorising authority as well as the stakeholders.

5.2 Operational phase

If an evacuation measure needs a permission by authorities, which is mostly the case, it must be ensured during the execution of all activities that the legal framework resp. obligations are strictly fulfilled. Proper monitoring and documentation of all relevant actions is therefore strongly recommended.

Flushing activities can be predominantly conducted by the operator itself with little assistance of external experts. No major contracts are necessary limiting the efforts for issuing tenders and analyse offers. However, as the flushing by natural flood events is difficult to predict the organisational efforts are not marginal to have all actors ready and prepared for immediate response. As meteorological forecasts have a limited accuracy and are subject to change with changing weather conditions, especially in alpine regions, it might happen that the evacuation action has to be aborted while already in operation. If it becomes obvious, on basis of updated forecasts, that the amount of water of a minor flood wave is not sufficient to transfer the material and to further flush the relocated sediments widely in the downstream section, the
event has to be abandoned. Such scenarios happened at the pilot action Bodendorf during the ALPRESERV project.

Starting a flushing of a reservoir must simultaneously initiate monitoring activities. To ensure a proper and effective sediment transfer the meteorologic and hydrologic data is fundamental and must be in focus all the time. The most relevant parameter, however, is mostly turbidity of the water-sediment-mixture downstream of a reservoir. Also if it is not regulated by the permitting public agency it is recommended to engage external experts to measure, monitor, document and report turbidity constantly before, during and after the flushing event to ensure fulfilment of the obligations. An immediate communication between the monitoring teams in the downstream section and the operators of the weir must be ensured to be able to react if the maximum allowed concentration is exceeded. Closing the gates can reduce the transfer of sediments within a short period of time to adjust the turbidity to an acceptable level again. Figure 5.2-1 shows an example of adjusting the gate during the flushing operation at the pilot action Bodendorf in June 2004. During the start-up phase the suspended sediment concentration exceeded the recommendations of the authorities of 4.5 g/l which was counteracted by a proper adjustment of the weir. During the peak flow the turbidity threshold had been exceeded, too. As organisms have had several hours to react to the raising water level, discharge and velocities such peaking turbidity is less relevant as during the start-up phase.

**Fig. 5.2-1:** Flushing in June 2004. Gauge during drawdown at the weir Bodendorf in comparison with the Suspended Sediment Concentration in St. Georgen.

More detailed information of monitoring concepts and actions during flushing operations can be found in the ALPRESERV publication *Volume 5 - Pilot Actions and Data Base*.

Sediment evacuation strategies in reservoirs backed up by dams significantly differ from flushing activities in river-run-off installations. As the natural inflow into such reservoirs is very low compared to the total storage volume, flushing strategies are generally not applicable to transfer all depositions to the downstream section. Additionally the outlet structures are not capable to ensure hydro dynamic conditions which would be suitable to remove sediments on a wider range and extent. Flushing operations are therefore limited to transfer those sediments which are situated close to the outlet structures to prevent their disfunction due to sedimentation.

In contrary to flushing strategies excavation measures in a reservoir are not dependent on specific and rare flood events and can be planned in much more detail. Planning periods normally counts for several years.
Excavation of sediments normally needs extended contracting of dredging equipment as well as transport capacity. Due to significantly higher costs of such activities intensive work on alternatives and cost reducing options results in a much bigger share of the planning efforts. Especially transportation becomes a critical issue as soon as public roads and urbanised areas are affected. Alternatives, like slurry pipelines, should be taken into consideration, too.

Excavation activities normally are strictly local actions resulting in significantly lower turbidity. Consequently monitoring efforts to limit ecological impacts are far less. Additionally environmental protection efforts are normally focussed on the downstream section to minimise disadvantages for the populations in these normally not affected areas. Practitioners state that there are normally no specific interests of environmentalists concerning actions in the reservoir itself as the excavation process by technical means generally eliminate the local populations and living conditions completely.

Relevant for the operational phase is the further use of the excavated material (see chapter 6). Different logistic efforts, equipment, personnel and intermediate storage areas are necessary dependent on the strategic approach. Few efforts are necessary if the excavated material can be just loaded on trucks and delivered for an immediate re-use. Fine sediments may need dewatering treatment first to reduce mass and costs.

Fig. 5.2-2: Excavation activities in reservoirs: Suction dredger and floating pipeline at the pilot action Margaritze (left) and conventional hydraulic excavator at the pilot action site Sylvenstein (right).

Fig. 5.2-3: Logistic details of excavation activities: Tranport of suction dredger and floating pipeline by truck to the pilot action Margaritze (left) and washing installation for truck tires to limit contamination of public roads (right).
5.3 Review and documentation

Evacuation measures do need some attention and efforts also after their execution, whether they had been successful or not. It must be distinguished between reporting obligations to authorities on the one hand and internal analysis on the other hand.

Generally reporting obligations are part of the permission issued by the relevant authorities. Main focus is to document the most important data as well as the fulfilment of all technical and ecological obligations. As the planning process included intensive preparation of the claim for permission the involved personnel of the operator does know which documents have to be issued to fulfil the requirements. Additionally they should have implemented a monitoring and documentation strategy to be able to collect all necessary data.

The operator itself should critically review the evacuation measure internally. As the sediment supply of the Alps can be regarded as unlimited it can be assumed that further activities will be necessary in the future. To limit the efforts during upcoming actions and to be able to assess the effectiveness of the present activity adequate resources should be reserved for reviewing and documentation purposes.

The internal reviewing process may address different topics:

- Target achievement: Did the activity fulfil the achieved goals?
- Evaluation of effectiveness: Had the activity been effective?
- Proof of causality: Was the result affected by the measures?
- Cost benefit analysis: Could the activity be finalised within the planned budget?

The most relevant parameter to evaluate the result and effectiveness is the topographic information. The comparison of profiles prior and after the evacuation allows the calculation of a mass balance and the volume of recovered reservoir storage. The reviewing process therefore needs at least another measurement of profiles.

Further analysis may include proper investigation of discharge measurements, suspended sediment concentrations, and morphologic changes together with their dependencies for future optimization of weir operation and duration of flushing activities. This kind of analysis is not immediate essential and therefore very much dependent on capacities. However, if further activities are necessary proper analysis and documentation within the reviewing process may save much more time and resources than have to be invested in future.

The evaluation of the ecological impacts should be considered carefully to avoid legal disputes with fishermen or environmentalists and to ease permissions for future activities.

All reviewing processes are strongly dependent on accurate data. Consequently the requirements for the different reviewing options must be communicated within the planning process already to ensure proper data collection and involvement of relevant personnel.
6 Reuse and Deposition of Sediments

6.1 Re-introduction into the river

Sediments are part of the natural geomorphological cycle and an important part of natural rivers. Sediments are the contact zone of groundwater and surface water and do play a key role regarding the fluvial system. Sediments are the basis for the morphologic shape of the rivers and an essential living zone for numerous species. Almost all fauna species are dependent on an adequate sediment composition within their life cycles. Consequently excavated material should be re-introduced into the river system if applicable to avoid negative consequences resulting from a lack of gravel material like erosion of the downstream river bed or armouring processes (details of these phenomena can be found in ALPRESERV Publication Volume 2 - Sediment Sources and Transport Processes). Some preconditions must be considered concerning a possible re-introduction of bed material. The proposed river section must be a free-flowing reach of sufficient length with an adequate transport capacity and a cross section width allowing the run-off of flood discharges.

Hydraulic structures in a river backing up the water interrupt the natural flow of the sediments and the dynamic balance of water flow and sediment transport. Depending on the hydrological and hydraulic condition of the downstream river section deposited material in the reservoir should be transferred to it by by-passing the structure or sluicing the material through the structure. Numerous applications proofed the benefit of such strategies. However, specific knowledge is needed to plan a re-introduction and to avoid possible negative effects. If sediments of a bigger reservoir should be relocated it must be considered that a sorting process had been effective resulting in the deposition of the coarse material in the upstream area of the lake and of the fine material close to the hydraulic structure. Most beneficial for river systems are the coarse fractions while the fine material often causes problems to ecosystems by clogging the sediments. A further problem is related to the changed hydraulic and sedimentological conditions in the downstream river section. Therefore total mass and composition of the re-introduced material has to be adjusted very carefully. One good example had been the relocation of more than 100,000 m³ of gravel material in the river Isar at the Oberföhringer Wehr.

Fig. 6.1-1: Re-introduction of gravel material into the river Isar at the Oberföhringer Wehr: Transport of excavated material by truck and deposition in the river bed as depots (left) and naturally distributed gravel material after minor flood event after 3 months (right).

A further example of re-introduction of sediments is documented for the pilot action Forni in the ALPRESERV publication Volume 5 - Pilot Actions and Data Base.
6.2 Commercial use

Sediments are generally suitable as construction material for roads, dams, noise reduction structures and concrete production. Specifically coarse material is demanded by industry in those areas where intensive construction projects are under way. Normally, a commercial use of these fractions can be ensured. In some areas with only few gravel sources construction companies compete for river sediments. It must be ensured that the needs of a river to balance its sediment budget is not threatened by commercial interests.

6.3 Deposition

Often neither a re-introduction nor a commercial use of excavated material is applicable. Reasons might be that the total quantity of sediments exceed the possibilities for relocation strategies, that the sediment composition is not matching with the requirements or that the sediments are contaminated. Deposition should always be the last option and reuse preferred as space and financial resources are limited.

One possibility for deposition could be the reservoir itself. If the reservoir volume is big related to the managed water volume sediments from critical locations could be transferred to those sections where negative impacts are not visible. Critical sections are mainly the inflow into the reservoir as sediment deposits significantly increase flood risk as well as the areas close to the hydraulic structure and the outlet installations as deposits may block these.

If the excavated material has to be deposited on land surface often extensive handling is required for dewatering, transport, decontamination and final storage. Depending on the grade of treatment costs for deposition in land fills are much higher than all other methods. Preferred locations are abandoned gravel pits or quarries. More specific information can be found in the ALPRESERV Publication Volume 2 - Sediment Sources and Transport Processes.

Fig. 6.3-1: Re-introduction of gravel material into the river Isar at the Oberförhringer Wehr: Transport of excavated material by truck and deposition in the river bed as depots (left) and naturally distributed gravel material after minor flood event after 3 months (right).

A further example of re-introduction of sediments is documented for the pilot action Forni in the ALPRESERV publication Volume 5 - Pilot Actions and Data Base.
7 The Ecological Impact of Desedimentation

Reservoir desedimentation means dredging with heavy equipment, and this involves severe interference with the ecosystem of the stream. Another desedimentation method is reservoir flushing. Such measures affect both the reservoir itself and downstream river sections.

Desedimentation affects to some degree all the biocenoses of a river; these include

1. Organisms living at the surface of the river bottom:
   - macroinvertebrates
   - microscopic growth
   - underwater vegetation

2. Fishes

3. Organisms living in the interstitial system of sediment. The interstitial is a fringe biotope, where there is interchange between surface water and ground water as one of the main components of the natural water cycle:
   - juvenile stages of surface-water organisms
   - interstitial population proper
   - groundwater organisms.

Disturbance through desedimentation extends over the period of the measure itself as well as the following period of recovery and varies according to the type of river and the other uses, such as sewage pollution, navigation etc.

7.1 Desedimentation and its impact on the fauna and flora

Dredging sediment from a reservoir causes local interference with the organisms living there, through mechanical destruction and drifting as well as through parts of the lake bottom falling dry. Repopulation after termination of the measure is from unaffected zones and through drift from the upstream river section. The ecological damage being caused to the reservoir defies control and cannot but be accepted.

Flushing means that sediment is carried away by the evacuating effect of the flowing wave. This occurs already during major natural flows. What has to be discussed, however, is operationally supported reservoir flushing taking advantage of major flows. This includes opening bottom outlets and partial or complete water-level drawdown. Artificially enhanced sediment transport, the primary aim of such measures, at the same time counteracts bed load deficits. The merits and demerits in terms of stream biology of this method of dealing with sediment is very much dependent on particle size and the material components involved. Evidence from mountain streams with natural bed load transport during flood events shows the invertebrate fauna is adapted to such conditions in that it escapes to the interstitial of the bed. Flushing followed by addition of the coarser bed load to downstream river sections is regarded as positive in terms of stream biology. The greater problem is the fine sediment. Turbulence produced by flushing causes fine sediment deposited in the reservoir to go into suspension and then find its way downstream as suspension load. This may even remobilise contaminants and cause oxygen depletion. As flow velocity decreases further downstream, the fine sediment is redeposited and finally covers the entire riverbed. As a result, repopulation of the solid substrate is practically prevented. In addition, colmation may clog interstitial spaces, which form a biotope for aquatic invertebrates. Frequent reservoir flushing is nearer to natural processes and should be preferred over rarer and, hence, more massive transports. Flushing frequency is a function of operational requirements as well as sedimentation intensity and natural flow regime.
The impact from reservoir flushings is heavily dependent on the season in which they take place. Many bottom-fauna species have stages outside the stream or highly resistant stages during the period of natural flood flow, usually in spring. The consequences of flushing in winter (low-flow period) are much severer than during the natural flood period. The same is true of the fish fauna, especially in streams of the trout region (epi/metarthial) with brook trout as the main species. This fish species lays its eggs, late in autumn, in the gravel interstitial, where these remain through the winter. The fish larvae hatching from the eggs remain in the gravel interstitial for about a fortnight. Colmation of the interstitial during that period, as through reservoir flushing, causes the death of the fish eggs or larvae.

7.2 Monitoring strategy

Disturbance resulting from desedimentation is complex and unspecific. Analysis as for water pollution on the basis of a prevailing factor through biological indicators (e.g. saprobia) is not possible. There is no such as thing as a "desedimentation factor". This would be the wrong approach, since the organisms themselves, rather than what they may indicate, are the objects of protection efforts. In fact, the entire biocenosis should be examined for potential changes.

The biocenotic analysis is carried out according to the following steps:

1. Biocenotic status as compared with a reference status typical of the natural habitat
   Knowledge of the original ecological conditions is of great importance for assessing disturbance. This refers in fact to the degree of naturalness of the ecosystem and the extent to which the naturalness and completeness of the biocenosis were affected already prior to or upstream from the point of disturbance. A degraded biocenosis containing few and tolerant species may perhaps suffer little from further disturbance. Inversely, biocenoses typical of a natural habitat containing a high proportion of delicate species will clearly reflect such disturbances.
   Note: Reference sections or reference water bodies for large rivers have ceased to exist in Central Europe, they are all more or less heavily modified as defined in the European Water Framework Directive. Not only are water individuals affected, but the type itself is extinct. No river is left in the Alpine foothills or the plains that might serve as a reference, this could at best be reconstructed from old data.

2. Comparison of the results
   Based on the ecological reference condition, the results from the various tests carried out at one location, or the data from the various test locations, are compared in respect of the disturbance; comparisons are made between before and after as well as between upstream and downstream.

Disturbance is of ecological relevance only in so far as it manifests itself through the biocenotic structure. An examination should include:

- type and magnitude of changes in biocenosis
- affected river section
- period of restoration after termination of the measure.

This forms the basis for selecting the suitable investigation method:

- Survey of the ecological framework, i.e. the abiotic (physiographic) factors as well as the biological situation by use of the standard methods of analysing running waters.
- Interpretation of the data obtained in the form of a biocenotic analysis by means of parameters describing the biocenotic structure.
- Assessment of the results with due attention to the need for protection and the sensitivity of the respective biocenosis.
Biological analysis of a water body followed by interpretation of the results yields numerical and possibly also quantitative data which provide a comprehensible basis for assessing disturbance levels.

The upstream/downstream principle is applied where disturbance already exists; "upstream" serves as a reference location. Where changes are planned - disturbance or elimination of disturbance as part of rehabilitation or renaturing projects - the before/after principle comes in; "before" refers to the present condition.

Three or four dates, distributed over the year, are needed to survey the biocenosis satisfactorily. Perpetuation of evidence for desedimentation measures should provide for analyses

- prior to
- during and
- after termination of the work.

The number of test locations should be selected according to the population differences in respect of current and substrate within the section under study.

In the optimal case manual sampling from the bank will suffice. Where the interstitial as a biotope is affected by potential colmation, more sophisticated sampling techniques will be needed, such as production of freeze cores or underwater sampling from a barge by use of heavy grabs or sampling in diving bells as practised along national waterways. Seasonal effects and the flow situation are of great biocenotic importance and should govern both sampling schedules and the assessment of the results.

The amount of time to be devoted to a sampling site is governed by the principle that rich biocenoses call for more time than degraded biocenoses. Any minimum test schedule should be tailored to the needs of the case under study. It can generally be said:

| Few in-depth investigations provide better information than a large number of merely informative surveys. |

### 7.3 Measures for minimising the ecological impact from flushing

- Continuous discharge of fine sediment through the turbines may prevent the deposition of large quantities in the reservoir. But care should be taken to avoid low-flow periods, when, normally in winter, there is little natural turbidity. In the rhithral (trout region), this is the reproduction period for book trout and thus holds a high damage potential (Eberstaller et al. 2001).
- The flow conditions during flushing should largely correspond to the natural flood regime. This is normally in spring and early summer in the Alpine region and foothills. A differentiation should be made between the various fish regions to account for their differing requirements.
- Regular and frequent flushing (once or twice a year where possible) acts to reduce the level of turbidity concentration and, on the other hand, to reduce the total amount of sediment. Such a periodicity is recommended from the ecological point of view.
- Flushing, along with water-level drawdown, should start already during minor floods in order to arrive at the desired flushing frequency (the work group on desedimentation of the ÖWAV - Austrian Water and Waste Water Union, (2000) - recommends flushing should commence at 50% HQ1 in case a major flood is predicted). This does, however, not apply to first flushings.
- The increase and decrease of the flushing wave should be gentle rather than abrupt. This prevents fish and bottom fauna from drifting off along with the first surge and falling dry during flow reduction.
- Especially in by-pass and residual-flow sections, gradual flow reduction in the residual-flow section when the flow is directed back to the headrace after flushing is recommended in order to prevent bank zones from falling dry and enable the formation of a low-flow channel.
- Flushing should be controlled as a function of turbidity concentration, using a standard value depending on the type of water body and on the region. This calls for continuous suspended sediment measurement downstream from the reservoir and for measuring gate openings.
- Secondary flushing with low turbidity concentrations are recommended after flushings with high sediment concentrations or major sedimentation levels in the streambed. Such "clear-water flushings" wash away the fine sediment deposited during the main flushing process and also aid decolmation in the gravel interstitial. Such action substantially reduces the ecological damage and enables ready repopulation of the affected sections (cf. the example of the River Mur).
- Training structures at the reservoir head, intended to ensure bed load transport (including gravel) through the reservoir, are recommended from the ecological point of view. At the same time, training works may structure the reservoir so as to ensure habitat diversity. Moreover, such structures may serve as shelters during floods and flushings.

7.4 Measures for minimising the ecological impact from dredging activities

When assessing potential impacts from sediment evacuation, excavation with at least partial water-level drawdown should be differentiated from dredging in the reservoir with or without water-level drawdown.

Partial water-level drawdown causes shore and shallow-water zones to fall dry and dry out. As the drawdown is usually of long duration, remaining ponds and the substrate dry out completely, so that not only the remaining fish and bottom fauna die, but also water plants (submerse macrophytes) in the shallow-water zones dry. Large important shore structures and, thus, the main spawning substrate for many plant-spawning fishes are lost especially in reservoirs with pronounced shallow-water zones at the transition between the grayling and barbel regions (e.g. Inn, Drau …), the more so as aquatic plants occur almost exclusively in shallow-water zones where they find the appropriate light conditions.

Excavation also directly removes animals from the water body and shallow-water zones.

Turbidity during such a measure is substantially lower than in the case of flushing, or even dredging provided only dry sediment is dredged.

Great attention should be given to a well structured near-natural design of the reservoir head, which is a zone of particular ecological value.

The best possible time for such a measure is autumn and winter to allow for the development phases of a large proportion of the aquatic organisms. But in water bodies of the trout region, it should be remembered that this coincides with the reproduction and egg-development period of brook trout, and reservoir heads are often the only spawning grounds left.

More detailed information is provided by Volume 2 - Sediment Sources and Transport Processes and Volume 6 - Impact Analysis and Recommendations of the ALPRESERV Publication Series.
8 Best Practice Examples

8.1 Pilot Action Sylvenstein Lake: In-depth analysis of surveying data and different sediment management strategies

The Sylvenstein Reservoir is situated approximately 60 kilometres south of Munich/Germany. In addition to the river Isar the reservoir also retains the lateral inflow of the rivers Dürrach and Walchen. Thereby a fjord-like lake was formed, which fits in the mountainous scenery as if it is a natural leftover from the ice-age. Since its start of operation in the year 1959 the Sylvenstein reservoir provides flood protection to the Isar valley. During the low flow season it feeds additional water to the downstream section of the Isar river as most of the discharge of the Isar is withdrawn from its original river course and by-passed to Lake Walchen to run a hydro power station there. The multipurpose installation also serves as a recreation area and attracts local people as well tourists. Last but not least two small-scaled hydro power turbines generate environment-friendly electricity.

The Karwendel and Wetterstein are distinctive parts of the northern Alps and provide significant amounts of denudated rock material. Due to steep slopes the erosion products are often immediately delivered to the rivers at the valley bottom. The morphology of the Isar river therefore had been determined by bed load processes mainly.

The delivery of bed load material to the downstream section of the Isar river was almost cut off through the construction of the Sylvenstein reservoir resulting in an armouring of the river bottom as well as sedimentation in the reservoir itself. By means of check dams in the tributaries transport of gravel and sand into the lake can be avoided to a great extent. At the different check dams each year about 85,000 m³ of bed load material is excavated and used for concrete production as well as construction of roads. However, finer material as sand and silt is almost not affected by the check dams and transported into the lake. Most of these suspended sediments are deposited within the reservoir while a small fraction leaves it again as part of a density current released by the outlets. The depositions mainly take place in those areas of the reservoir storing the water to feed the Isar river during low flow conditions. This increasingly affects the useful storage volume.

The State Office for Water Management Weilheim which is operating the reservoir is very well aware of the problem and its consequences and therefore initiated different investigations already to ensure a sustainable use of the reservoir.

8.1.1 Validation and correction of surveying data

Information about topography are crucial for proper planning of evacuation measures. Great efforts are necessary to collect and analyse historical as well as actual data to provide an accurate basis for decisions concerning when and where evacuation measures are necessary.

Surveying data of the Sylvenstein reservoir exist for a time period of almost 50 years. However, as technology had changed significantly during these years the accuracy and reliability is very different. While the first surveying data set of 1958 is based on manual surveying techniques the latest data was gained by means of an echo-sounding system with high data sampling rate and accuracy. Additionally a Digital Terrain Model (DTM) is available based on aerial surveying covering the adjacent shore and slope areas. This DTM, called DGM10 Alpenraum, may have an estimated accuracy of 1 m regarding elevation. The combination of the latest echo-soundings with the DGM10 is called DGM 2003 and acts as the base for calculating the difference of volume related to the original cross sections of the reservoir immediately after construction of the dam.
Through the combination of aquatic and terrestrial surveying data, profiles for the different years could be generated and compared to calculate the changes of the lake bottom elevation. The bottom elevation was calculated on basis of averaged elevations for the different years which were determined using two different approaches: The so called “Msohle” was calculated as the averaged bottom elevation for all data points of the cross sections while the “Gsohle” represents those data points situated on the sediment transport active part of the river/ lake bottom only. The difference between Msohle and Gsohle can be regarded as variations of the banks.

Based on the two different approaches the total loss of storage volume could be calculated. It turned out that the original estimation based on recent surveying data was not accurate enough and overestimated the already sedimented material. Instead of 5.1 Mio m$^3$ for the time span 1961 - 1983 the accumulation was determined to be 3.6 Mio m$^3$ for the period span 1958 - 2003. As the difference between Msohle and Gsohle is only marginal sedimentation/ deposition processes at the banks are only of minor importance.

To be able to plan measures in the reservoir itself (e.g. extraction or relocation of sediments) it is essential to locate areas of sedimentation resp. erosion. As averaged bottom elevations are not accurate enough a different strategy had been performed. Each profile was divided into 25 m-sections and an associated average bottom elevation calculated. These values were compared and finally illustrated by connecting neighbouring data points. Fig. 8.1-1 represents the graphical output of the bottom elevation differences between 1958 and 2003.

![Fig. 8.1-1: Changes of local bottom elevations in the Sylvenstein reservoir for the time period 1958 - 2003 based on averaged cross section data for 25 m increments (red colour: erosion, yellow colour: no changes, purple colour: deposition).](image)

### 8.1.2 Assessment of different Sediment management strategies

Extended investigations had been performed to judge different preventive as well as retroactive measures to reduce the sedimentation of the reservoir resp. to remove already accumulated material.

Preventive measures in the catchment area are limited as most of the land area is covered by vegetation and sediment yield not to be influenced significantly by further afforestation. Plans
do exist and will be checked in detail now to erect a further check dam in the Dürrach tributary. A diversion tunnel to bypass sediments around the reservoir is not suitable and possible costs extraordinary.

Different options exist for measures in the reservoir. As most of the sediments settle already in the upstream parts of the tributaries and are mostly not transported close to the dam where the dead storage volume is situated a relocation of sediments by means of dredging techniques might be applicable. However, as the Sylvenstein lake is a natural reserve and accumulated sediments in the dead storage zone might negatively affect the penstock inlets and the bottom outlet that kind of strategy is presently abandoned, too. Mechanical removal of depositions in the lake area with floating devices and dredging equipment is critical due to restrictions for the natural reserve as well as regarding transport and final storage of the huge amounts of sediments. The specific manipulation of density currents to transport a higher share of the fine sediments through the reservoir and into the downstream river section during flood events might be an option; however, knowledge about existence and formation at the different tributaries is too poor at the moment. Additionally effects on the power plants downstream had to be taken into consideration and communicated with the residents and operators.

Measures at the dam itself had been applied already. The heightening of the dam and extension of the storage volume in the late 1990ies increased the flood protection capability of the Sylvenstein reservoir significantly. Another heightening seems to be too expensive at the moment. Flushing operations can not be performed as the outlets are not powerful enough and not designed for such a strategy. Additionally, all flushing operations during major flood events interfere with the purpose of the reservoir to secure the downstream areas from devastating floods.

Since the implementation of the check dams in the tributaries and their regular maintenance by extracting gravel and sand a total volume of 2.3 Mio m³ of bed load material had been removed from the tributaries by mainly constructing companies. The legally binding regulations for the safe and sustainable operation of the Sylvenstein reservoir could be maintained without costs by the Free State of Bavaria so far based on the economical reuse of the extracted material for concrete production and street construction.

The check dams in the tributaries as well as the reservoir itself are retaining the coarse fractions of the sediments which are naturally transported by the rivers Isar, Dürrach and Walchen. While the depositions accumulate in the upstream section of the dam a severe lack of bed load material can be observed in the downstream reach of the Isar resulting in an erosive tendency of the river bed. A possibility to balance the transport capacity of the Isar consists of extracting gravel material from the check dams, transport it to the downstream section by truck and reintroduce it into the river. This procedure is called as “feeding” and may stabilise the river bottom by establishing an equilibrium condition between the erosive forces of the running water and the resistance of the transported gravel material. The State Office for Water Management Weilheim performed according tests in the years 1995 - 1998 and relocated extracted gravel from the Isar check dam to different downstream locations. The extracted volumes were increased from 5,500 m³ (1995) to 7,800 m³ (1996) and finally to 17,000 m³ in 1998. Additionally the grain size distribution was changed during the tests to estimate the transport capacity of the Isar river downstream of the dam. In general the feeding material was transported by the river shortly after reintroducing it into the water body. Only the biggest grain sizes remained at their location until a significant flood moved them downstream. Due to complaints of residents concerning severe truck traffic and undesirable gravel depositions the tests were suspended.
8.1.3 Summary and Recommendations

The Sylvenstein reservoir is a key structure for flood protection of the cities downstream of the Isar like Bad Tölz and Munich. Therefore the preservation of storage volume is a major goal of the applied management strategy. However, the priority of flood protection is limiting sediment management strategies, too, as flushing operations during major flood events are not applicable. Additionally the Sylvenstein lake is a valuable nature reserve and intensively used by the tourist board. Technical measures as relocation or extraction of sediments by means of dredging equipment and trucks are therefore hardly favourable. At present only slight changes of the management strategy can be applied like erection of additional check dams to limit the sedimentation to a minimum. Further investigations concerning the possible existence and manipulation of density currents do need much more time and additional scientific efforts and are recommended to use the natural transport mechanism for small sized particles.

With the in-depth analysis of recent and present topographic data it turned out that the so far existing estimations about yearly sedimentation rates and total loss of storage volume had been significantly incorrect. By means of up-to-date technology (laser-scanning surveying, application of Geographic Information Systems) different data sources could be combined, corrected and used to build up an integrated Digital Terrain Model. Based on the corrected numbers it had been decided that the loss of storage volume of 3,6 m³ for the period span 1958 - 2003 related to the total volume of 124 m³ does not call for immediate actions.

Nevertheless the distribution of depositions within the lake is affecting flood protection abilities. Based on the actual data a strategy has to be developed to manipulate further sedimentation by variations of the water level to force future sediment input to be transport to deeper sections of the lake closer to the dam.

The intensive assessment of sediment management alternatives discarded most of the options which are generally available (Fig. 3.1-1). On that basis further discussions with the stakeholders and authorities can be focussed on the remaining strategies, especially the favourable relocation of coarse bed load material to the downstream section of the river Isar and the sluicing of portions of the fine material.

More detailed information is provided in chapter 4 of Volume 5 - Pilot Actions and Database of the ALPRESERV Publication Series.
8.2 Pilot action Forni: Optimization of sediment transfer to the downstream section by applying numerical models

The Valtellina is one of the biggest valleys in the Lombardia Italian Region and it is located at the north of the city of Milan; the Adda river is the main course of the valley.

The Forni barrage is located in the Valfurva Municipality and it is the biggest of the thirteen intake structures realized to derivate the water of the watersheds connected to the San Giacomo and Cancano reservoirs, part of the Premadio Hydroelectric System. The reservoir collects the water from the own upper basin and the Gavia reservoir by means of a link gallery and is then discharged to the Braulio gallery and exploited in the system by the hydroelectric plant. The large quantity of sediments that comes from the upper basin compromises periodically the little Forni reservoir capacity.

During the spring and summer season, the Forni Glacial melts and the water flow erodes the soils and the moraines and a great volume of sand and gravel incomes into the Forni reservoir remaining trapped inside. Forni is constructed with particular attention to ensure enough desanding capacity of the water that comes form the Forni glacial; indeed two sand trap reservoirs were constructed on the right bank.

The gravel trap channel, with the entrance below the inlet structure, is provided by two flat gates with 4 m width and 1.8 m height. It has an ovoid section and a bottom coated in granite masonry in order to avoid the wear and tear produced by the rolling of the solid material transported by the water. The gravel trap channel collects also the sand that comes from the 10 gates, 0.53 m width and 0.6 m height, connected with the upper sand trap. The following figure shows a cross section of the sand trap structure in the upper part and the gravel channel in the lower part.

![Fig. 8.2-1: Cross sections of the sand and gravel traps](image)

8.2.1 Original reservoir sediment management strategy

The accumulated gravel and sand in the Forni reservoir is flushed downstream the barrage taking advantage of the drag capacity of the water when it enters the gravel channel with the gates opened. This operation, normally achieved twice a year during the high discharges season, is accomplished when the incoming discharges vary from 10 to 16 m$^3$/s, to ensure a good drag of the water and an efficient cleaning of the reservoir.

The decision of the flushing operation day is made after the identification of the near exhaustion of the reservoir capacity due to the sedimentation, and it is chosen between the forbidden-fishing days during the week. If possible, the flushing operations are not accomplished during the intense rainfall events that produce floods in the torrents.
This management strategy, ever achieved by AEM SpA, should be optimized during flood events, increasing also the discharges derived to the Braulio gallery to reduce the Frodolfo river discharges and then decrease the flood damages in the downstream Santa Caterina Valfurva village. The flushing operation, that globally keeps on 6 to 8 hours, is normally achieved during the night to reduce the risk of presence of people in the river margins. During the previous days, information regarding the increase of the discharge in the rivers is provided to the companies that operates in the Frodolfo and some branches of the Adda rivers. During flushing operations an average of about 200,000 to 350,000 m$^3$ of water are released and about 2,000 to 4,000 m$^3$ of sediment removed. The total loss in energy production is estimated about 650,000 to 1,200,000 kWh.

### 8.2.2 Field measurements

One of the main aims within the ALPRESERV project had been to understand the mechanism of the sediment accumulation in reservoir, the way the sediments are conveyed in the downstream reaches of the river during a flushing or sluicing operation and the environmental impact of the sediment downstream. This information will be useful to study a more efficient and economical way to perform the flushing operation and to minimize the downstream environmental impacts. To reach these objectives the following actions were carried out related to the Forni barrage pilot project:

- A controlled sand and gravel flushing operation,
- measurements of the sediment transported flow,
- topographic surveys of the Forni reservoir bottom bed, before and after the controlled flushing operation,
- evaluation of the main parameters of the flushing operation,
- simulation of the solid transport process with de MORIMOR GIS mathematical model,
- comparison of the measured and calculated data sets,
- optimization of the operations from the point of view of the efficiency of the operation, the economical point of view and the environmental impact.

To estimate the efficiency of the flushing process a field topographic survey of the bottom bed of the reservoir was achieved prior and after the flushing operation. The topographic and bathymetric data were processed with ARC GIS to calculate a triangulated irregular network (TIN) surface of the reservoir bottom and, as a difference, the flushed volume (Fig. 8.2-2).

*Fig. 8.2-2:* 3D graphic of the reservoir bed TIN representation prior (left) and after (right) the flushing operation
Based on the field measurements and data analysis the total volume of transported material could be determined at 4,528 m$^3$.

### 8.2.3 MORIMOR model

To simulate the sediment flushing scenarios of the Forni reservoir, MORIMOR GIS a monodimensional sediment transport simulation model was developed and used. The model was precise enough to take into account the deposition-erosion phenomena in the Frodolfo River, due to the sediment release activities.

In this project two historical events and one measured event were simulated with success. The aim of the whole study is to construct a useful managing tool which will permit the best combination of gate parameters: time intervals and rules.

The MORIMOR model was developed in order to allow the simulation of strong non-uniform sediments and relatively large 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. 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.

### 8.2.4 Results of the MORIMOR model application

The MORIMOR model was applied to two historical events as well as to the field study with extended data. Fig. 8.2-3 illustrates the erosion - deposition pattern in the whole branch of the Frodolfo river downstream of the barrage approx. 3 hours after the flushing action. The simulation results could be proved with observations and surveying data.

Fig. 8.2-3: Erosion - deposition patterns in the whole branch of the Frodolfo river downstream of the barrage 3 hours after the flushing action as simulated with the MORIMOR model
8.3 Conclusion

Due to sediment detachment processes in the basin, coming from surface erosion and large mass movements (bank erosion, debris flows, etc.), commonly mountainous reservoirs have to deal with a considerable sedimentation. To guarantee the correct operation of the system, the sediment trapped inside the reservoir might be flushed to the downstream rivers. Sediment transport capacity, suspended sediment concentrations and morphological changes in the river are the major issues to be assessed, in order to avoid the risk of flooding and irreversible environmental problems.

The MORIMOR GIS model (MOuntain RIver MORphology GIS), permits to evaluate all those parameters and to analyse different flushing operation scenarios in order to minimize the undesirable effects in the downstream river.

The Pilot Action describes the basis of the morphodynamic mathematical model, which is employed for the computations of sediment transport capacity and bottom changes, at basin space scale and for short and long-term calculations. The Forni barrage pilot application in Valtellina (Italy) is described, using the MORIMOR model to simulate the morphological effects in the Frololfo river, due to programmed and synthetic flushing operations.

The flushing process parameters are tested and then optimized using the so-called “overflow hazard index”, an indicator which takes into account the relationship between the used and the overall conveyance of each cross section. Finally the best operation flushing practice for the barrage was chosen.

Within the pilot action at the Forni reservoir it could be proved that the application of mathematical models can be recommended to test and assess strategies for flushing operations. By means of the MORIMOR model, which is capable to deal with alpine boundary conditions as steep slopes and widely distributed grain size distributions, a best fitting operation mode can be obtained through the variation of multiple parameters ensuring a proper transport of the sediments while minimizing the quantity of water which can not be used for hydro power generation.

More detailed information is provided in chapter 7 of Volume 5 - Pilot Actions and Database of the ALPRESERV Publication Series.
8.4  Pilot Action Tourtemagne: Sustainable sediment management strategy at a glacier-induced reservoir

8.4.1  Location and sedimentation problem history

The Moiry-Mottec and Turtmann-Mottec power plants are in activity since 1960. They are part of the Gougra hydroelectric power scheme owned by the Gougra Hydropower Company (in French Forces Motrices de la Gougra SA - FMG). The hydroelectric power scheme is located on the South side of the Rhone Valley between Sion and Brig, in Val d'Anniviers and Turtmanntal. The original storage volume of the Turtmann Reservoir of 780,000 m³ has been reduced to some 623,000 m³ in 2002. From the very start of Gougra's exploitation, the aggradation of the Turtmann Reservoir with very fine material from the glacier-induced catchment was very high (Fig. 8.4-1). In the seventies, after only ten years of exploitation, the adopted solution was to build a sediment retention basin upstream of the Turtmann Reservoir. With the years, the sediment trap became almost full of materials. It is thus necessary to find another solution taking into account the concession end in 2039.

The currently used solutions such as annual sediment flushing through the bottom outlet and dump of extracted sediment from the sediment trap cannot be used much longer because of the following reasons:

- lack of place for additional dump areas in a very sensitive environment
- necessity to keep the remaining available volume in the vicinity of the reservoir for urgent desilting measures for landfill in case of "force majeure" such as rapid glacier retreat, avalanches or landslides into the reservoir
- the sediment flushing as a very concentrated event has considerable impacts on the downstream river reaches
- it is not a long term solution, but one has to favour sustainable sediment management methods allowing the transit of the material.

Fig. 8.4-1: Sediment deposits in the Turtmann Reservoir during emptying in 2004

Although the Turtmann reservoir is very small it contributes a significant share of the water for power generation. The net energy production of the Gougra hydro power scheme amounts to some 350 GWh/year and the produced energy in the catchment area of the Turtmïnna River amounts to 170 GWh/year, which represents almost half of the total energy production.
In order to evaluate the annual sediment input into the Turtmann Reservoir, five bathymetric surveys have been made since the commissioning of the reservoir. These investigations have been performed in 1959, 1970, 1978, 1997 and 2002, thus allowing calculating the annual volume loss of the reservoirs. Assuming a constant aggradation rate since the construction of the dam, the average sediment filling rate of the whole system is 5,000 m$^3$/year. Some 40,000 m$^3$ have been extracted from the sediment trap, either to be used to heighten the dam of the sediment trap, or to be dumped at nearby landfill areas. Annual flushing operations are performed since 1970, the average flushed sediment volume amounts to some 1,500 m$^3$ per operation.

### 8.4.2 Investigation of suitable sediment management alternatives

In order to find a long term, sustainable and economic solution to the sedimentation problem, some 13 alternatives have been evaluated, taking into account the concession end in 2039, future exploitation rules (minimum flow requirements) and financing possibilities. The main goal was to prevent the complete loss of the storage capacity respecting the eco-morphology of the hydro-system by a global approach.

The evaluated alternatives can be more or less classified into 4 major categories as follows:

1. Removal of the deposited sediments from the sediment trap and reservoir and nearby disposal
2. Removal of coarse material, nearby deposit, and transit of fine sediments
3. Transit of "all" sediments
4. Other solutions

There is a clear distinction between fine particles (< 1mm) and coarse material (> 1 mm). The various alternatives taken into account had been exposed and evaluated based on 5 main criteria:

- **Efficiency** - Distinction between fine and coarse particles, reduction of the overall sediment trap efficiency
- **Sustainability** - Effectiveness of the solution over the long term, autonomy, continuity
- **Uncertainty and flexibility** - Especially new and innovative solutions may have an unknown performance, and there is lack of precise hydrological, hydraulic and sediment data
- **Environmental and landscape friendliness** - Distinction between upstream, reservoir region and downstream, over the long term and during construction or work
- **Economy** - Initial investment, annual exploitation costs, water (respectively energy production) losses, storage volume loss, short, mid and long term view

All alternatives have been thoroughly evaluated with respect to economy, efficiency for evacuation of fine and coarse particles, sustainability and environmental and landscape friendliness upstream and downstream of the dam.

The analysis is based on an ordinal multi-criteria decision aid method (similar to the ELECTRE approach) to assess the performance of each solution. Fig. 8.4-2 shows the result of the overall analysis. It can clearly be seen, that there is no exceptionally good solution, but there is a clear tendency towards alternatives that allow the transit of the sediment.

A particular view has been put on the analysis taking into account only the three major criteria (economy with investment and exploitation costs, environmental and landscape impact and sustainability), the grades went from 0 to 6 and have been summed up. It can be seen in Fig. 8.4-2 that the most sustainable solutions which are the ones with sediment transit and desanding, are also the least economical ones. The most economical options are the ones without any constructive measures, but with a very limited sustainability.
Fig. 8.4-2: Result of the analysis taking into account only the three main criteria (economy, environmental and landscape impact and sustainability), it can be seen that the most sustainable solutions are also the least economical.

All the alternatives have been pre-designed and their construction and exploitation costs approximately evaluated. The solutions with nearby landfills are from a purely financial point of view the most interesting ones. The analysis has been performed for a time span up to the concession end in 2039, 2100 and even up to 2200 with an assumed 2% capitalisation. For longer time periods and with assumed increasing transport and landfill costs, the solution providing sediment transit, while storing the clean waters become more and more economical. This result will be achieved much earlier considering increased sediment input in the reservoir due to climate changes with glacier retreat and amplified heavy rainfall events. In that case the only viable solutions are the ones allowing the sediment to bypass the reservoir.

8.4.3 Description of the retained solution

The evaluation showed the alternative C2 to be the best solution. This option includes a water intake on the sediment trap dam, a desander and flushing gallery to bypass the Turtmann Reservoir (Fig. 8.4-3). The nowadays clear sediment trap basin (after the emptying in 2006) will again be filled-up with sediment, mainly coarse particles. The Turmanna River will again create its own river bed in its alluvial deposits. The flow will be evacuated through a Tyrolean weir located on the right side of the dam. Up to a 10 m$^3$/s discharge, all water from the Turmanna River, will be captured by the weir. The rack already performs a separation of gravel (> 30 mm) and finer material. After desanding, the clean water is diverted through a channel directly into the Turtmann Reservoir. The 4 desilting chambers, installed right after the intake, will be flushed regularly through the bypass gallery. The discharge exceeding 10 m$^3$/s during flood events will be diverted up to the 100-year flood of 59 m$^3$/s; larger exceptional flood events are still retained in the Turtmann Reservoir for downstream flood protection. This alternative has no life time limitation. For economic reasons the desanding devices removes particles except the very fine material, and pressure flushing of the Turtmann Reservoir is still needed. The water loss through flushing of the desanding chambers is estimated some 6% to which the losses of the discharges exceeding the intake and desanding capacity has to be added.
The bypass of flood events will reactivate a dynamic morphology of the downstream Turtmänna River. The numerical sediment transport simulation (both suspended and bed load) of the downstream Turtmänna River shows that fine sediments will transit the entire river reach down to the Rhone Valley in suspension, while bed load will accumulate in the alluvial zone and thanks to major flood events, also with additional discharge from lateral torrents, transported further downstream at each event. Possibly the mainly fine sediments remaining in the reservoir may be evacuated through the pressure gallery and the turbines so that the sediment problem can be solved integrally. In case that the sediment yield of the watershed should increase significantly, the desanders will basically work more often and thus remove and flush downstream the additional sediment input.

The retained alternative still has some optimisation potential, both to reduce construction and exploitation costs and enhance its efficiency.

8.4.4 Summary

The important retreat of the glaciers of Turtmann and Brunegg liberated a large quantity of materials which are transported by Turtmänna River and ineluctably fills up the Turtmann Reservoir, created in 1960. In order to ensure the long-term exploitation of the reservoir, 13 sediment management alternatives were studied. Among others, the following main evaluation criteria have been taken into account: efficiency of desanding of fine and coarse particles separately, sustainability, environmental and landscape impacts, as well as construction and exploitation costs.

The bypass measure diverting major flood events and sediment downstream the Turtmann dam was selected. To set-up such an installation raises many questions regarding its technical feasibility (design of the spillway, the Tyrolean weir and the desanding basins), its impacts on
the environment (flushing and diverting of floods), its socio-economic consequences (profitability and costs), or its security impacts (flushing and flood protection) which were analysed in detail within the framework of this preliminary study. In conclusion, a bypass solution to divert sediments and floods, according to the selected optimization alternative, is sustainable from all standpoints, it is technically feasible and economically viable, the environment and the hydroelectric scheme of Gougra are revalorized and the investment costs give added value in the long term.

The project partners of ALPRESERV involved in that study designed a sustainable solution in that way that the natural way of the sediments from the origin in the high alpine regions to the natural sink in the Lake Geneva can almost be re-established. Thus negative consequences to environment can be limited to a small extent.

Additionally an innovative approach is in discussion regarding the share of costs. As the concession is still valid the operator can not be forced to implement an option which is, from an economic point of view, disadvantageous. To convince the operator to choose an option of category C (see Fig. 8.42) rather than of category A the regional government checks the possibility to finance part of the project as investment in the future as the proposed solution ensures full operation of the scheme also at the end of the present concession period. This leaves more options for future use.

More detailed information is provided in chapter 5 of *Volume 5 - Pilot Actions and Database* of the ALPRESERV Publication Series.
9  Pilot Action Bodendorf: Ecology-friendly flushing strategy and extended monitoring program

9.1  Introduction

The run-off-river hydro power plant Bodendorf is the head reservoir of a chain of power schemes at the river Mur in Austria. At the head of the reservoir there are mainly gravel deposits, while close to the dam fine sediments are silting. All in all, a mean yearly sediment input of about 53,000 m³ was measured, which is 17% of the original storage volume of the plant. To counteract reservoir sedimentation the operator decided to flush the reservoir regularly. Flushing has been the main management strategy for the last 10 years.

Although in the case of Bodendorf flushing is the best way to manage the sediments in an economical point of view, the sensitive ecological situation in the river Mur requires restrictions to each flushing. These restrictions were written into a notification of the government of Styria and should avoid a high impact on the ecological system of the downstream river. Especially an upper limit on suspended sediment concentration (4.5 g/l), and a minimum discharge of 0.62% of the yearly flood was defined. However, the impact on the ecological system of the river was not clarified until now.

Furthermore, and due to hydraulic reasons, it was not possible to transport the deposited gravel at the head of the reservoir. This was the main criticism of the fishery that only fine sediments were flushed, but the essential gravel for spawning was being deposited in the reservoir. Secondly, a decrease of the fish population immediately after a flushing was observed. The question about managing this situation was one reason for the reservoir operator to join the ALPRESERV project. On one hand, the impact on the ecological system of the river (ecological aspect) should be minimised, on the other hand, the sediment output during the flushing should be optimised (economical aspect). Thus, a new flushing strategy should be developed to find a satisfying solution for all stakeholders. At a first view, these objectives are competing and it is needless to say that compromises will have to be made. A detailed study should help to find opportunities for a best practise state-of-the-art flushing strategy for the run-off river plant Bodendorf.

In a first step of the project several groynes were installed at the head of the reservoir. Furthermore, a flushing channel was excavated in order to improve erosive processes at the beginning of the reservoir. In a second step, the setup of an extensive monitoring during 2 flushing events within the ALPRESERV project duration should form the basis for improvements in the flushing procedure, particularly concerning the effects of the measures, discharge times and minimal water supply. Finally, the monitoring of fish and invertebrates, bed clogging and the setup of a habitat model for the downstream section of the reservoir becomes the basis for optimising flushing intervals with regard to their economical and ecological compatibility.

9.2  Reservoir sedimentation history and recent flushing actions

In 1982, the reservoir had a water storage capacity of 900,000 m³. Detailed analysis of echo-soundings in the last years makes it possible to verify the yearly deposits within the reservoir. The average amount of sedimentation in the reservoir was calculated to be about 53,000 m³ a year. The sedimentation rate strongly depends on the discharge conditions during a year. Generally, the bed load and suspended load at a high flood exceed the load at a mean discharge over a year. In the dry year of 2003, the sedimentation in the reservoir was only 64% of the average rate, while in 2005 it was 147 %. All in all, the reservoir of HPP Bodendorf loses about 17% of its original storage capacity in one year. Compared to the bed
load material, which deposits in the reservoir, most of the suspended load passes the weir. Bed load and suspended sediment load deposit at a rate of about 3:1 to 5:1.

In the year 1994, the capacity was reduced to about 1/3 due to sedimentation of silt, sand and gravel. Fig. 9.2-1 shows a section of the reservoirs thalweg with the bed levels in 1980 and 1994.

![Fig. 9.2-1: Thalweg of the reservoir, bed levels in the years 1980 (before construction of the HPP) and 1994.](image)

The situation in 1994 made it necessary to reduce sedimentation. Two years later in 1996, the first flushing at the run-off-river plant was performed. Even though a small flood was used for the flushing, high sediment discharges had a great ecological impact on the river.

A flushing of the reservoir Bodendorf must be performed in the context of economy and the ecosystem but also has to satisfy the Austrian legislative and nowadays the EU Water Framework Directive is already implied in Austrian laws. Therefore, the flushing of the reservoir Bodendorf is coupled to a notification of the water managing authority of the province of Styria. The notification regulates the boundary conditions for a flushing. As an example, the main regulations for the flushing 2004 had been:

- Flushing only can be performed within the period of 15th of May and 31st of September to avoid high losses in spawn and juvenile fish populations,
- 80 m³/s minimum water discharge (62% of the yearly flood),
- 0.5 m/hour maximum drawdown of the reservoir water level,
- no exceed of 15 ml/l or 4,5 g/l in suspended sediment concentration downstream of the reservoir and
- a minimum duration of the flushing of two days.

The performance of flushings was the main sediment management strategy at the reservoir Bodendorf during the past 10 years. The operator AHP defines the aims of flushings at the reservoir as:

- Minimising sedimentation at the turbine inlet,
- minimise limitations on reservoir operation due to the reduction of water storage capacity and
- minimise sedimentation at the beginning of the reservoir to avoid negative effects of high water levels during flood events.
The deposited material in the reservoir consists of sand and gravel with a small amount of silt near to the plant. Beside the aims of the operator, a flushing at the HPP Bodendorf might result in positive effects onto the river morphological and ecological system. The basic positive effects for the river Mur are:

- Transportation of gravel into the downstream section of the HPP - new substrate for spawning of fish species,
- transportation of gravel into the downstream section of the HPP - avoiding the lowering of the river bed due to the lack of sediments,
- activation of sediment dynamics in the downstream river section of the reservoir - new habitat structure for the ecological system and
- in comparison to other reservoir management methods, flushing is the “cheapest” way of de-siltation of the HPP Bodendorf.

Up to now, about 460,000 m³ of sediments have been transported to the downstream river section during five flushings.

As a sensible water body, the river Mur is an Alpine river with high stocks on fish. Negative effects of flushings stated by the fishery are:

- high losses on invertebrates,
- high losses on fish stocks due to high sediment concentration rates,
- bed clogging due to sedimentation of silt and sand at the river bed with the consequence of less habitats for spawning,
- less reproduction of fish stocks in the following years and
- restoration costs due to silted banks along the river.

The reservoir operator have decided to establish an extensive monitoring programme to meet the problematic of the negative ecological effects with the goal of a new flushing strategy which should be sensible to the river’s eco-system.

9.3 The monitoring program

In Austria it is usual to prove the effectiveness and impacts on the river’s ecosystem with a monitoring program during the flushing. In the case of the upper Mur river this program consists of an abiotic and biotic monitoring, for the ALPRESERV project, however, an extended program was applied.

Fig. 9.3-1: HPPs, suspended sediment (SS) concentration measuring points and gauging stations along the Upper Mur river.
Fig. 9.3-1 shows a map of the location of the reservoirs and it gives an overview of gauging stations for measuring suspended sediments and water levels/discharges along the Mur river. Beside the mapped gauging stations, a bed load sampler was used to measure the bed load input to the reservoir Bodendorf (Wandritsch Bridge). Detailed echo-soundings of the Bodendorf reservoir make it possible to evaluate the effectiveness of a flushing.

9.4 Water ecologicy aspects

9.4.1 Aim and problem definition

A highly important factor, in view of an ecologically optimised flushing management, is the supply of coarse gravel to the free flowing river stretches downstream from hydropower plants, as this enables the formation of new and loose non-clogged gravel banks, which constitute a major prerequisite for the preservation of a river-type-specific fish and benthic fauna. The reported activities also concentrated on the fine sediments that are mobilised in a flushing operation. The aim is to understand the impact of the fine sediment load flushed into the gravel interstices and the resulting alteration of the fish fauna’s habitat. Since the fish larvae and juvenile fish of the key species in the River Mur (grayling and Danube salmon) strongly depend on gravel interstices during the first months of their life, alterations in the gravel body can significantly impact the successful development of larvae and the feeding rate during later stages of development.

The purpose is to understand key ecological factors which have an influence on flushing, such as the sequential course of flushings, time of year, and eroded fine sediment load. The results are then transformed into recommendations for optimising future sediment management at the Bodendorf hydropower plant, which should cater for the needs of both the plant’s operation and of aquatic ecology and should serve as model for other impoundments. The overall aim is to preserve a sustainable, self-sustaining fish stock in the area.

9.4.2 Methodology

Substrate conditions were surveyed by means of freeze-core sampling (see Fig. 9.4-1). The frozen core (diameter approx. 20 - 30 cm) was cut up into 6 compartments (layers: 0 - 10 cm, 10 - 20 cm, 20 - 40 cm, 40 - 60 cm, 60 - 80 cm and 80 - 100 cm). The individual frozen layer samples were then weighed and desiccated in a lab drying chamber (105°C). After drying, the samples were sieved and weighed by their grain size classification. To ensure statistical certainty, 5 freeze cores samples were taken per site and the results averaged.

Fig. 9.4-1: Substrate extraction using the freeze core sampling method (left: injecting liquid nitrogen. right: sawing the core into compartments using a diamond saw).
In order to document the natural reproduction rate, regular surveys of fish larvae and juvenile fish fauna (0+ individuals) were conducted along selected gravel bars. Catching started with the hatching of larvae mid-June/July and took place every fortnight, later in the year once every month, until November.

The fish were caught with an electric catching device and a specially adapted pole bar using point-abundance sampling (Persat & Copp 1990). For each sampled stretch 5 sampling points had been defined and the average number of individuals per point (expressed as CPUE = catch per unit effort) was calculated. In each sampling campaign, a total of 90 points were sampled. In addition the nutrition of larvae based on the filling level of their stomach, distinguishing three classes (full-up, filled, barely filled), was determined. Furthermore, juvenile fish catches were conducted in extended areas during autumn 2004 and 2005, thereby enabling to assess the current fish ecology conditions as part of long-standing fishery evidence (Steiner et al., 2004 and 2005).

9.4.3 Habitat Modelling using CASiMiR

Ecological systems such as surface waters and their habitats are complex systems, which contain a multiplicity of connections between biotic and abiotic components. Habitat models serve as a suitable instrument in illustrating the important parts of these connections. They are based upon the required living conditions of indicator species and their developmental stages. Indicator species are used because their occurrence indicates the concurrent presence of a larger number of other ecosystem-specific species. Detected changes in their presence or behaviour can therefore be used as a reference to monitor important structural or material factors of influence. These factors are in turn connected with the effects on subordinate species (Lutze et al., 1998).

The advantages of using habitat models to answer questions about the ecological conditions of surface waters can be seen through the following relations:

- The ecological condition of a surface water system is directly coupled with the living conditions of the inhabitant organisms.
- With habitat modelling, the influence of discharge and structural changes can be forecast for fish, invertebrates and macrophytes.
- Numerical models can be used to simulate variations in discharge and changing morphologic conditions. This in turn can be related to water depths, flow velocities, surface wetness, and substrate variability. These parameters are all main factors of the habitat quality.
- Through the use of a habitat model’s ability to use varying discharge and morphologic scenarios, a quantitative basis is created to simulate ecological effects.

Due to these advantages, the use of habitat models in North America have been accepted for use in common practice for quite some time. When questions arise requiring the examination of minimum discharges and their potential ecological impacts, the range of application for such models can be further extended. Currently habitat models are used commonly for the following applications:

- Discharge regulation
- Renaturization projects
- Effects of structural measures
- Catchment management

More recent applications have used the Schwall-Sunk (Hydro Peak)-Approach or, as in the Bodendorf case study, colmation as it relates to the capture of fine sediment and morphodynamic changes resulting from structural installations. (Baptist et al., 2002)
The case study used the habitat modelling program CASiMiR developed at the Universität Stuttgart (Jorde, 1996, Giesecke et al., 1999, Schneider et al., 2001). Riverine geometry and structure information is used by the program to simulate habitat suitability for the river reach in question. Through the use of preference functions and fuzzy logic programming, the model is able to directly incorporate expert knowledge into the habitat simulation model (Jorde et al., 2000, Schneider, 2001). Fig. 9.4-2 shows the principle of fuzzy-rule based habitat modelling.

![Image of fuzzy-rule based habitat modelling](image)

**Fig. 9.4-2: Principle of fuzzy rule - based fish habitat modelling**

The fuzzy logic formulation of habitat requirements is implemented through the use of inference rules. These rules are dependent on the parameters flow velocity, water depth, and dominant substrate. For the case study additional parameters were included to describe colmation. The rules used included the previously mentioned linguistic quantities of “large” water depths or “small” flow velocities. An example of one of the rule used is:

```
WHEN the flow velocity is “small” and the water depth is “big”
AND the dominant substrate is “medium” AND colmation is “small”,
THEN the habitat suitability is “large”
```

This fuzzy formulation is made possible through the use of so-called fuzzy sets. The edges of the sets are also referred to as membership functions, which provide how much a parameter belongs to a particular fuzzy set.

In alpine rivers such as the Mur, high bed load transport and large flow dynamics result in continuously changing morphology. Especially considering the effects of the groynes, it can be expected that for high flow rates with increasing sediment loading and aggressive flow conditions will result in more rapid morphologic processes. Therefore using the 2d numerical model MIKE 21C, the impact of a one-year flood event was analyzed. The model was run considering a partial mobilization of the substrate top layer and fractioned bed load transport. Results of the freeze core samples were used as the basis for the sediment composition. A simplifying assumption was that the substrate had uniform properties and was evenly distributed over the entire reach investigated.
The relative changes to the bed geometry, as predicted by the model, are shown in Fig. 9.4-3 left. The left side of the river reach was especially impacted through settlement due to its low water depth. This is expected since the widening of the river will result in overall lower flow velocities. Erosion at the bottom end of the investigation reach show higher water depths and changes in the substrate composition. Fig. 9.4-3 shows the results of CASiMiR when comparing the newly implemented structural measures to those just after the one-year flood event. It is clear that the areas which were previously suitable for spawning have been noticeably reduced. This is mainly due to erosion and deposition of coarser substrate material in these areas, found mostly below both groynes. However, slightly improved spawning area conditions are still to be found. These are present in the centre of the investigation reach, where the combination of hydraulic and morphologic conditions was already determined to be favourable. According to the model results, the amount of suitable habitat area in comparison to the case without structural mitigation measures (but not considering colmation effects) has almost doubled.

### 9.4.4 Proposed flushing strategy for Bodendorf - Compromise between water management and ecology

The analyses and interpretations of the extended investigations performed within the pilot case study Bodendorf enable the ecological requirements for a flushing strategy to be defined. Key parameters include, in addition to discharge levels, the interval between the last flushing and the season of the flushing. The proposal comprises a multi-annual flushing strategy based on the time of the last flushing (hereafter referred to as “year 0”). In the year directly following the last flushing (year 1), ecological needs have the highest priority. Priority is given to avoid flushing in the sensitive months from April to July, which corresponds to spawning and the larval phase (Fig. 9.4-4). The sole exception is major flood events ($\geq$ HQ5), during which flushing can take place year-round. This is designed to enable bed load transport through the impoundment and to establish loose unclogged gravel banks as spawning habitats along reaches downstream of the power stations.
Every year without a flushing promotes fish reproduction and therefore helps stabilise the grayling, Danube salmon and brown trout populations. Accordingly, in subsequent years the ecological priority decreases and the sediment management priority increases. The ongoing sedimentation in the reservoirs increases the pressure to empty them. Therefore, the time slot for flushing is extended to include the spring months of April and May. Ultimately, if several years passed without a flushing, flushing should be allowed from April until late September. Due to the hydrological conditions in the Upper River Mur, the probability to be successful in autumn/winter is very low. Moreover, effective post-flushing during the low-water phase is unlikely and would cause the siltation of fine sediments on the riverbed. This time period proves to be critical for the benthic fauna and for brown trout, which spawn in late autumn/early winter. Unless major floods occur, flushing during these months is ruled out.

<table>
<thead>
<tr>
<th>Date of flushing</th>
<th>Year 0</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4+ later</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>high</td>
<td>ecological compatibility</td>
<td>high</td>
<td>ecological compatibility</td>
<td>high</td>
</tr>
</tbody>
</table>

**Fig. 9.4-4:** Flushing strategy from an aquatic ecology perspective.

The above-mentioned requirements of water management and ecology provide the basis for an interdisciplinary proposal on sustainable flushing along the Upper River Mur. These basic considerations are combined to yield the following flushing strategy (Fig. 9.4-5).

<table>
<thead>
<tr>
<th>Date of flushing</th>
<th>Year 0</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4+ later</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (April-May)</td>
<td>--</td>
<td>&gt;80/130 m³/s</td>
<td>&gt;80/130 m³/s</td>
<td>&gt;90/160 m³/s</td>
<td></td>
</tr>
<tr>
<td>Early Sommer (June-July)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>&gt;90/160 m³/s</td>
<td></td>
</tr>
<tr>
<td>Late Sommer (Aug.-Sept.)</td>
<td>&gt;80/130 m³/s</td>
<td>&gt;80/130 m³/s</td>
<td>&gt;90/160 m³/s</td>
<td>&gt;90/160 m³/s</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 9.4-5:** Sediment management strategy combining the needs of water management and ecology. Specified discharges are for the beginning of draw-down and for predicted peak discharge at the Bodendorf facility.
9.4.5 Discussion of results and recommendations for effective ecological monitoring

The fish stock sampling in the Bodendorf case study provide due to the relatively long time series (sampling from 1998 to 2006) a good data basis to assess the long-term impacts of impoundments and sediment management practices on fish coenosis. The collection of data spanning such a long period of time is more the exception than the rule, but in order to best understand the complex nature of the problem, it is certainly recommended. Ultimately, the time series analysis together with the newer larvae sampling data serves to provide a strong background for the creation of an optimized sediment management plan for the Bodendorf case study.

Should the sampling, (for example through the collection of annual larvae sampling) provide only the long-term development of the fish population, a multi-year sampling cycle would be sufficient. In regions where the grayling is the key species, a three to maximum four-year sampling cycle is recommended. An approved sampling time in transition from trout to grayling region is autumn (October), and sampling should begin in any case before the spawning season of the brown trout. In order to obtain comparable data over several years, it is important that the sampling locations, dates, methods, and computational techniques, as well as the equipment are not changed. The evaluation of the population structure over a period of years provides an adequate measure to describe the site specific reproduction success. It is important to recognize that there are strong fluctuations in the annual juvenile fish population of many fish species, which then require a multi-year sampling regime for adequate assessment. Using a single annual fish stock sampling schedule in October makes it impossible to determine the exact reasons (flooding - flushing events) behind the fluctuating juvenile fish populations (cp. Larvae sampling). Only through a direct comparison of the results of the fish stock sampling with the larvae sampling can the direct impacts be determined.

It is recommended, especially in sensitive cases that a combination of methods be applied. Based on experience, an investigation regime combining annual larvae sampling with semi-annual fish stock sampling is particularly effective. With comparatively little effort the event causing damages for individual years in detail as well as information about long-term impacts could be provided.

With the periodic larvae sampling method used in the case study taken over the course of the year, a separation of the effects of natural flooding events and those from flushing events was obtained. This distinction can be made particularly for years in which sampling is undertaken when both flushing events and flood events have taken place. To the knowledge of the authors of the specific study this is the only method which allows for such a distinction to be made. The results of the larvae sampling for the given case study show that the impact on the larvae population can be expected to be the greatest when flushing/ flooding events take place shortly after hatching takes place. Another important observation is the sensitivity of the spawning season as it relates to flushing events. As found in the case study, the flushing event in 2006 did not result in a detrimental loss of grayling larvae. In fact, the larvae population was found to be higher in 2006 than in 2005, most likely due to the large variability in natural conditions such as the water temperature which also have a strong impact on reproductive success. This result counters the common assumption that flushing during the spawning season necessarily causes high damages. It is important to point out, that this does not mean that the observed results can simply be transferred to similar cases for which no other information exists. In the author’s opinion, larval sampling should be widely practiced in order to aid in the monitoring of flushing events. Such sampling methods are relatively simple and offer highly valuable information.
By *benthic fauna* investigations the effects of the changed substrate conditions due to impoundments in free-flowing reaches downstream could be documented comprehensively. Particularly when comparable analyses were made with the results of the substrate investigations, (esp. freeze core) interdependent conditions could be found. Bed armouring in the downstream reach at Bodendorf and changes in the living conditions reflect in changed population densities and different formation of benthic fauna. The direct damage to benthic fauna from a flushing event can be measured best by biomass. The most efficient method at the Bodendorf pilot action was shown to be the Surber Sampler. Since previous sampling data using this method existed, in the Bodendorf case study it was obvious to refrain from this kind of sampling.

Impacts due to the change of substrate conditions of the surface layers can be well assessed using the Multi Habitat Sampling method. This method is approved as the standardized method in Austria to assess the ecological condition per water framework directive.

The assessment of changes in the deeper substrate layers can be best carried out using the freeze core method. This requires, however a much larger amount of effort. The recommended dates of investigation are characteristic to those periods with low flow. For the Bodendorf case study it was attempted to carry out the investigations before the higher spring flow rates due to the snowmelt, but after the melting ice cover. For investigation periods which last over a series of years, the sampling time should not be changed to get comparable data. In the case that the substrate conditions are evaluated using the freeze core sampling method, assessment of the benthic fauna is also recommended. To minimize total investigation costs the assessment can be limited to higher taxonomic units. To statistically safeguard the results, it is recommended to take a minimum of four freeze core samples per site. The other methods used in this study have established norms which dictate the number of samples to be used.

*Habitat simulations* provide a useful tool for analysis in considering the deficits and effects of mitigation measures for surface waters. They allow for a more in-depth understanding of the effects of changing river conditions, as can be shown in the River Mur at Bodendorf which resulted in a severe disruption of the bed load transport processes. Prognoses for the effects of mitigation measures can be carried out and reviewed in terms of effectiveness of structural modifications, especially considering proposed changes which are designed for ecological improvement. In order to model the disruption of the sediment balance, additional parameters are required to characterize the river bed structure. In particular, attention should be paid to the use of colmation as model parameter, as was carried out in this study using the CASiMiR-based investigations. The incorporation of colmation can have considerable impact on the simulation results. The River Mur simulation results provided an example showing that using only the parameters of water depth, flow velocity, and dominant substrate size many acceptable spawning areas could be found, but on account of the high degree of colmation were no longer deemed suitable. The pilot study also showed that the coupling of morphodynamic models (in this study, MIKE 21C) with habitat simulations can aid in investigating deficits and mitigation measures for surface waters. The coupling can also be used to assess changes in long-term development. This means that the changes in the surface water morphology, for example the effects induced by the mitigation measures can be assessed in terms of their impact on the preservation or replenishment of endangered habitat areas such as gravel bed spawning areas. Additionally, the effects of flood events using a variety of recurrence intervals on the river structure can be studied.

More detailed information is provided in chapter 2 of *Volume 5 - Pilot Actions and Database* as well as through *Volume 6 - Impact Analysis and Recommendations* of the ALPRESERV Publication Series.
10  

Pilot action Centro di Cadore: Adapted multi-year sediment removal strategy with partially contaminated material

The Centro Cadore lake is an artificial reservoir, constructed by raising an arch-shaped dam in the Centro Cadore area during the period 1946-1949 in the Belluno province spanning the Lozzo, Domegge, Calalzo and Pieve di Cadore municipal area. More precisely, the dam is located in “Pian delle Ere” at a height of 90 m. The receiving body downstream of the dam consists of a stretch of the Piave river which receives water and sediments from the lake above. Under the maximum storage capacity conditions, the lake reaches 9.3 km in length and a level of 680 metres above the sea. At the time the artificial reservoir was constructed, it had a total storage capacity amounting to 64,000,000 m³ and a usable storage capacity of 60,000,000 m³. On average the lake covers a surface area of 2.35 km², for a length of 6.60 km; the maximum and minimum adjustment levels, on the other hand, reach respectively 680 and 625 m a.s.l. The catchment basin from where the water collected by the Centro Cadore lake arrives has a surface area of 818.5 km², plus a glacial area of 1.63 km². The main tributary is the Piave river with the Cridola and Talagona on the hydrographic left and the Molinà stream on the hydrographic right. Further small contributions also come from the water streams Anela (hydrographic left) and Galghena (hydrographic right).

10.1  

Sedimentation of the reservoir

The estimate of the volumes is a result of the comparison between two bathymetries provided by Enel Produzione (the first from 1946 and the second from May 2005) commissioned by the Belluno Provincial Government and of subsequent processing work. Apart from the bathymetries a series of deep and superficial surveys were carried out to define the material characteristics, which then underwent granulometry and chemical analyses. Finally, combining the survey data with those of the relevant sections, the various stratigographies were obtained (Fig. 10.1-1).

Fig. 10.1-1: Conceptual model of the Centro Cadore lake which shows the sediment stratigraphy along the reservoir (gravel (red), sand (yellow), silt-clay (purple) and silt-sand (green))

Based on the results of the analyses carried out, the sediments have been classified into four main types (Fig. 10.1.-1): gravel (red), sand (yellow), silt-clay (purple) and silt-sand (green).

The lake was thus conventionally divided into four different areas, each of which is homogenous in terms of the main type of materials to be extracted: lake inlet and Cridola stream, lake centre, Val Molinà or Val d’Oten confluence, and the area near the dam (this name refers more or less to the stretch which goes from the dam to the island).
The analyses show that the overall volume of sediments is about 17,300,000 m³, of which 13,400,000 m³ reduce the usable volume of the reservoir. Tab. 10.1-1 shows the location and division by type of materials to be removed to restore the original usable reservoir capacity. The most significant conclusion to be drawn is that the material for commercial use from this viewpoint would account for 52% of the overall volumes to be removed (gravel 42% and sand 9.9%).

Tab. 10.1-1: Sediment volumes to be removed in order to restore the usable reservoir capacity - Volumes on site - May 2005 (Source: reprocessing by Public Works Department - Belluno Provincial government using Enel Produzione data)

<table>
<thead>
<tr>
<th></th>
<th>From lake inlet/Cridola</th>
<th>Lake centre</th>
<th>Val d'Oten</th>
<th>Near dam-island</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>2,043,600</td>
<td>2,415,673</td>
<td>974,032</td>
<td>233,191</td>
<td>5,666,496</td>
</tr>
<tr>
<td></td>
<td>81.6%</td>
<td>51.8%</td>
<td>100.0%</td>
<td>4.4%</td>
<td>42.1%</td>
</tr>
<tr>
<td>Sand</td>
<td>0</td>
<td>1,270,807</td>
<td>0</td>
<td>66,885</td>
<td>1,337,692</td>
</tr>
<tr>
<td></td>
<td>0.0%</td>
<td>27.3%</td>
<td>0.0%</td>
<td>1.3%</td>
<td>9.9%</td>
</tr>
<tr>
<td>Silt – Clay</td>
<td>199,650</td>
<td>787,351</td>
<td>0</td>
<td>3,635,691</td>
<td>4,622,692</td>
</tr>
<tr>
<td></td>
<td>8.0%</td>
<td>16.9%</td>
<td>0.0%</td>
<td>68.2%</td>
<td>34.3%</td>
</tr>
<tr>
<td>Silt – Sand</td>
<td>260,676</td>
<td>188,836</td>
<td>0</td>
<td>1,396,858</td>
<td>1,846,370</td>
</tr>
<tr>
<td></td>
<td>10.4%</td>
<td>4.0%</td>
<td>0.0%</td>
<td>26.2%</td>
<td>13.7%</td>
</tr>
<tr>
<td>Totals per area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100.0%</td>
</tr>
<tr>
<td></td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>Totals per area</td>
<td>2,503,926</td>
<td>4,662,667</td>
<td>974,032</td>
<td>5,332,625</td>
<td>13,473,250</td>
</tr>
<tr>
<td></td>
<td>18.6%</td>
<td>34.6%</td>
<td>7.2%</td>
<td>39.6%</td>
<td>100.0%</td>
</tr>
</tbody>
</table>

The granulometry classification of sediments alone, however, is not sufficient to determine which techniques can be used to transport the latter. As a consequence, both chemical-physical analyses of water and sediments and a survey on the benthos at the bottom were performed, in order to determine any contamination and biological quality level of the lake and its receptors.

10.2 Chemical-physical as well as benthos analysis

In 2006 ARPAV carried out a series of chemical surveys aimed at assessing the contamination state of sediments in the Centro Cadore lake. More specifically, 9 core boring sediment samples were taken and the total chemical concentrations measured for 13 co-kinds of PCB, 10 IPA, total hydrocarbons and 16 metals both in the surface (0-1 metres) and deep sub-samples (7-8 metres).

To sum up, all organic compounds considered are present in the sediment of the Centro Cadore lake at total chemical concentrations below the limit measurable with instruments. The same is true for the metals Cr, VI, Se and Sn; on the contrary, for As, Cd, Pb, Tl, Zn the total chemical concentrations were higher than the table limits set out by current standards as regards contaminated sites. It should be noted that the metal contamination was mainly measured in deep sub-samples characterised by fine granulometry.
As regards the contamination state of waters, metal accumulation in the water, in the bio-accumulation in fish and sediment was measured, in addition to the genotoxicity level for the fish themselves. The water was analysed at three stations, measuring the total levels of Arsenic, Cadmium, Mercury, Nickel, Lead, Copper, Zinc and Chromium. In all stations the metals which appeared to be in quantities higher than the limits were Arsenic, Copper and Zinc. In the light of the data collected it is possible to say that the sediments from the Centro Cadore lake are not affected by specific forms of heavy metal contamination exceeding critical concentrations. The release tests, according to the E.P.A. and UNI EN ISO specification, showed that Zinc and Iron are released. The metal with the highest release value proved to be Zinc, which is also a natural lithologic constituent. In the past, until 15 years ago, in the area of Salafossa, there was in fact a mining reservoir used for zinc mineral extraction activities. It is also more than likely that the mineral extraction activities and the natural washing away of the soil itself have led to significant re-distribution of zinc and its minerals along the Piave, its tributaries and to their accumulation in the Centro Cadore lake.

The Centro Cadore lake was the subject of two sampling campaigns, carried out in August 2005 and April 2006 respectively, in order to single out and classify the macro-benthos community at the bottom of the lake. More specifically, the purpose of the study was to carry out multi-discipline surveys on the different matrices (surface Water, Sediments, Biota) in order to obtain useful information for risk assessment purposes, subsequent to the handling of sediment, through floating and/or dredging, on the river downstream of the reservoir and on the lake itself. As for the macrobenthos, the average density during both monitoring periods on the Cadore lake appears to be much lower that in the other lakes in the region, the only exception being spring data from the Mis lake which falls within the range of the Cadore. It should be noted that the Mis lake is in what to be a mining area and its sediments are characterised by the presence of heavy metals, especially mercury. The microscopic analyses of erythrocytes slides showed the absence of significant genotoxic effects (formation of micro-nuclei) on the fish. The absence of apparent genotoxic effect is understandable considering the low concentration of metals in surface waters. This, however, provides an indispensable point of reference for the future because any handling operation on deep sediments, unless it is suitably controlled, may lead to toxic and genotoxic effects on the fish. This is due to the possible, as well as probable, release of high metal concentrations in the water, possibly helped also by the changing sediment oxidation conditions.

To conclude, also in this case it has been confirmed that the physical, chemical and biological conditions measured in water, sediments and fish population in the lake highlighted the non-significant presence of toxic elements. The situation, however, seems stable, without apparent genotoxic effect for fish populations and the potentially toxic substances are for the moment relegated in deep sediments; considering the current hydrology trends in the lake, the risk of heavy metal contamination seems fairly remote.

The handling and washing of the sediment for its removal, however, unless it is controlled, would lead to a high increase in turbidity and chemical contamination of the water, surface sediments and fish populations in the lake itself. The floating downstream of the finer sediments with no control, moreover, would not only have a physical impact due to the filling of the gaps in the river substratum downstream of the reservoir, but it would also amplify the problem of metal diffusion in the sediment because there would be a shift from a situation which is controllable and basically stable to a situation where the trend of sediments downstream of the river and of the sediments they contain would get totally out of control; this would have a serious impact on macro-benthos and fish populations with very high reclamation costs.
10.3 Different alternatives for sediment removal and their related costs

The quantification of materials to be removed, their location and quality characterisation was the starting point which led to designing a general framework of techniques which could be used for their removal. There are several strategies and techniques which can be applied for the sustainable management of water reservoirs, but the best results are often achieved by combining a variety of action methods.

Generally speaking, the following extraction methods were singled out based on the type of material: removal of material which could be commercially used, found in the areas lake inlet-Cridola stream and Val d’Oten, possibly to be done with mechanical means; on the other hand, the commercial material deposited in the central lake area can be removed using dredgers or rope buckets; as for the removal of the silt material found in the area close to the dam, the alternatives considered are floating, traditional and controlled, and dredging, with subsequent transport and landfilling. The cost estimate, apart from considering the extraction costs themselves, is strongly affected by transport costs; in this respect, as regards the material with possible commercial use, the assumption was that its outlet would be the local market, whose annual absorption capacity, according to the professionals interviewed, amounts to about 500,000-600,000 m³ of aggregate material per year.

The overall assessment of interventions is divided into differentiated evaluations by individual areas and by applicable techniques based on the different objectives pursued with each analysis:

- as regards the removal of silt material without possible commercial use, the main objective is, after ascertaining the sediment contamination levels, to decide whether it is possible or not to start floating and/or dredging with landfilling, with respect to both the cost of the work and to the environmental risk;
- in the case of materials with possible commercial use, the objective is to ascertain, based on information provide by local professionals, if the conditions are suitable for the economical extraction and use of aggregate material, subsequently defining the conditions for the application of extraction methods.

Tab. 10.3-1 shows the volumes and variables considered when assessing the different possibilities.

<table>
<thead>
<tr>
<th>REMOVAL AREA</th>
<th>Lake inlet/Cridola</th>
<th>Lake centre</th>
<th>Val D’Oten</th>
<th>Near dam-island</th>
</tr>
</thead>
<tbody>
<tr>
<td>REMOVAL TECHNIQUE</td>
<td>Mechanical means</td>
<td>Dredger</td>
<td>Mechanical means</td>
<td>Floating/Dredging and landfilling</td>
</tr>
<tr>
<td>VOLUMES ON SITE (m³)</td>
<td>2,503,926</td>
<td>4,662,667</td>
<td>974,032</td>
<td>9,232,625</td>
</tr>
</tbody>
</table>

Tab. 10.3-2 sums up the material volumes affected, the duration and the unit cost of removal operations in the case of sediments suitable for commercial use. As can be noted, given the volumes affected, this appears to be a significantly long period of time; in fact it ranges between a minimum of 3.2 years for the Val d’Oten area, to a maximum of 20.1 years for the Lake Centre section assuming a dredger is used. Reducing the duration entails an increase in daily production with an immediate impact as regards heavy vehicle traffic. In this respect, Tab. 10.3-3 shows the number of trips per day which are necessary to transport the material depending on the different annual and daily production levels and depending on the different capacity of the means of transport used (14 or 19 m³).
Tab. 10.3-2: Quantity, duration and costs of removal operations as regards material which is suitable for commercial use

<table>
<thead>
<tr>
<th>Area</th>
<th>Removal technique</th>
<th>Volumes on site (m³)</th>
<th>Material dissolved in heap volumes (m³)</th>
<th>Annual extractable quantity (m³)</th>
<th>Operation duration (years)</th>
<th>Total cost of operating (£/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Inlet – Cridola stream</td>
<td>Mechanical means</td>
<td>2,503,926</td>
<td>3,004,712</td>
<td>360,000</td>
<td>8.3</td>
<td>13.96</td>
</tr>
<tr>
<td>Val d’Oten</td>
<td>Mechanical means</td>
<td>974,032</td>
<td>1,168,838</td>
<td>360,000</td>
<td>3.2</td>
<td>12.13</td>
</tr>
<tr>
<td>Lake Centre</td>
<td>Dredger</td>
<td>4,662,667</td>
<td>5,595,201</td>
<td>278,000</td>
<td>20.1</td>
<td>10.23</td>
</tr>
<tr>
<td></td>
<td>Rope bucket</td>
<td></td>
<td></td>
<td>320,000</td>
<td>15.3</td>
<td>17.81</td>
</tr>
</tbody>
</table>

\*a The total cost includes road restoring operations, extraction itself and transport.

Tab. 10.3-3: Number of trips per day depending on the amounts of material removed

<table>
<thead>
<tr>
<th>Annual production (m³)</th>
<th>Daily production (m³)</th>
<th>Number of trips/day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4-axle truck (Capacity 14 m³)</td>
<td>Road bascule (Capacity 19 m³)</td>
</tr>
<tr>
<td>180,000</td>
<td>1,000</td>
<td>71</td>
</tr>
<tr>
<td>270,000</td>
<td>1,500</td>
<td>107</td>
</tr>
<tr>
<td>360,000</td>
<td>2,000</td>
<td>143</td>
</tr>
<tr>
<td>450,000</td>
<td>2,500</td>
<td>179</td>
</tr>
<tr>
<td>540,000</td>
<td>3,000</td>
<td>214</td>
</tr>
<tr>
<td>630,000</td>
<td>3,500</td>
<td>250</td>
</tr>
</tbody>
</table>

Tab. 8.3-3 shows the results of the risk analysis carried out for the fine material removal operations, their duration and unit cost in the two cases considered: case 1, which involves restoring the original reservoir conditions (9,232,625 m³); case 2 which, on the contrary, involves lower volumes related only to restoring the usable reservoir capacity (5,332,625 m³).

The analysis of the results obtained leads first of all to discarding the idea of traditional floating; in spite of the limited duration of operations, the latter, with an outgoing concentration of 9.8 g/l, generates a high physical risk as regards the deposit of floated material, a high chemical risk because of sediment contamination, as well as the risk of anoxia. The first mainly consists in a damage to the typical habitats of the benthonic community, combined with the presence of chronic risk for transport in the subsequent periods of material downstream. The second is essentially related to the concentrations of As, Cd, Cu and Zn present in the lake sediments. Finally, the risk of anoxia is related in particular to the persistence of sediments for a prolonged period and for the high entity of sedimentation. On the other hand, there is a smaller risk related to the contamination of water, classified as low and related especially to the presence of Cd and Zn.

The technique of controlled floating seems to have a smaller impact, even though it would be advisable to carry out further tests as regards controlled release for a period of 1-3 days. The risk of substantial deposits is negligible, thanks to the smaller concentration of sediments released; as regards suspended solids, on the other hand, the risk level is strongly affected by the outgoing released concentration. A concentration level of 6 mg/l, in fact, involves a high risk, while in the case of a 200 mg/l concentration, the risk is low. The chemical risk level as
Best Practice Examples

regards water contamination is low and is related to the presence of Cd and Zn, while the anoxia risk is negligible. In view of the small amounts of material that can be released with controlled floating it was assumed to use this extraction technique for the whole duration of the concession (33 years).

Finally, the dredging of fine material involves a low risk of sediment re-suspension; the risk of water contamination is low and still related to the presence of Cd and Zn, while the risk of anoxia is negligible.

**Tab. 10.3-4: Analysis of risk, duration and cost of fine material removal operations**

<table>
<thead>
<tr>
<th>Extraction technique</th>
<th>Physical risk</th>
<th>Chemical risk</th>
<th>Operation duration (years)</th>
<th>Operation total cost (€/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional floating</td>
<td>Deposits</td>
<td>Sediment</td>
<td>High</td>
<td>Case 1: 9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water</td>
<td>Low</td>
<td>Case 2: 4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anoxia</td>
<td>High</td>
<td>11.36</td>
</tr>
<tr>
<td>Controlled floating</td>
<td>Deposits</td>
<td>Sediment</td>
<td>Negligible</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suspended solids</td>
<td>Water</td>
<td>Low</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Anoxia</td>
<td>7.28</td>
</tr>
<tr>
<td>Dredging and landfilling</td>
<td>Re-</td>
<td>Water</td>
<td>Low</td>
<td>Case 1: 12.7</td>
</tr>
<tr>
<td></td>
<td>suspension</td>
<td>Anoxia</td>
<td>Negligible</td>
<td>Case 2: 7.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low</td>
<td>Negligible</td>
<td>Case 1: 23.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anoxia</td>
<td>Negligible</td>
<td>Case 2: 29.9</td>
</tr>
</tbody>
</table>

To conclude, the suggested analysis - that was carried out thanks to the data concerning quantities (with regard to volumes per type and location) and some economic assessment parameters (timing and costs) - may support the Public Administration in the choice of the most convenient intervention for the removal of the Centro Cadore Lake sediments. The simulations regarding sediments’ volumes to be extracted and transported for the Centro Cadore Lake - also taking into account the presence of sediments of other Belluno lakes - highlight that the problem can be solved through a regional and provincial management that plans the operations for all involved lakes, identifies the market area for materials suitable for commercial use and finds solutions that reduce the impact on traffic.
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