WP6 Report

Interactions with structures

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Executive Summary

Work package 6 (WP6) focuses on the interaction between structures and sediments. Since the structures in rivers and torrents are designed to perform different functions, the work in WP6 was divided in four main research topics. Four main expected outputs of the WP6 are provided. These include one report on improved concepts of responses and three guidelines: Guideline on effective planning and design of torrent structures with low impact on sediment continuity, Guideline on improved planning of hydropower plants to improve sediment continuity between torrential headwaters and downstream river reaches and Guideline on planning and designing of effective flood protection systems, river training and restoration projects with low impact on sediment continuity. Each output provides specific recommendations for Policy makers, Practitioners and Researchers.

The first report deals with improving flood control management in European Union and flood control and sediment management in the context of integrated flood risk management. Modern protection concepts with transverse structures in torrents and erosion control in Alpine torrential catchments are presented and the importance of the prevailing sediment transport process in the torrent is pointed out. Besides the theoretical research, the results of the real case scenario research about effectiveness of barriers during flood events are analyzed. Lab experiment was applied to analyze the influence of check dams on sediment transport. Two case study concepts of protection and control system are analyzed and presented.

Different approaches (design frameworks) for planning and designing of efficient torrent control structures with low impact on sediment continuity are presented. The importance and role of various input data and analysis is emphasized and the possibility of different knowledge approaches in different problem solving phases is analyzed. New procedures for improved planning are developed including analysis of various design criteria for designing sediment traps, review of construction, functionality and management of retention basins of torrent structures is prepared. Further, the methodology for torrent check dam failure hazard ranking is presented. Physical scale model is applied to refine the process comprehension and torrent control structure design. Within examples of good practice, new methods and approaches are presented.

Hydropower plants have various impacts on the environment. Overview and problem description of the impacts is prepared with emphasis on the sediment transport which is affected in the upstream and the downstream reach. Procedures for improved planning including mechanical removal and flushing operations are presented and described together with positive and negative influences of the procedure. Management plans optimizations are proposed: removing of coarse sediment and re-introduction of sediments in the downstream channel reach and application of MCA (Multi Criteria Analysis) method.

Anthropogenic changes in the environment caused ecological, economical and technical problems, including flood hazard and interruption of sediment continuity. Detailed description with theoretical background of sediment related problems is prepared. Proposed procedures for improved planning include counter measures for bed degradation, tools for river bed widening, river bed implementations and consideration of sediment transport in flood risk management. Two practice examples are described with all the implemented measures and actions.

Introduction

1.1 Overview about the WP6

Sediment transport in running waters with its multitude of practical consequences is among the phenomena that still defy reliable prediction despite substantial progress having been made in fundamental research and the development of numerical methods. Further intensive study will be needed to acquire the capability to provide safe information that will stand the test of practice in the fields of morphological stream development, reservoir sedimentation, sediment deposition in floodplains, breach of dams, etc. There are many reasons for this unsatisfactory situation, and measurement results are among them.

Intensive soil erosion and sediment transport process can worsen the agricultural conditions in endangered areas; high sediment concentrations in rivers can present threat to aquatic organisms and influence the water quality; turbine abrasion and sedimentation in the hydropower plant reservoirs can cause significant economic damage. Therefore, sediment transport monitoring is one of the pre-required steps to improve the knowledge about erosion and sediment process in catchments. New knowledge can be applied during the planning/design of different structures and also for the integrated sediment management, which is composed of several important steps. Identification and quantification of sediment sources is one of the first steps. This information is then used with addition to the sediment connectivity study to estimate the sediment yields which are transported to the river network (basin-scaled sediment dynamics and sediment transport monitoring are included in WP4 and WP5) Then, a bed load and suspended load monitoring system is designed based on the information gathered from the previously mentioned steps. High-frequency sediment transport data with the addition of the historical information are the inputs of the sediment management. Various man-made structures like hydropower plants, water supply reservoirs, check dams, and other torrent/flood control structures have an enormous impact on sediment transport (alterations of flow behaviour due to dam constructions lead to transformations in the fluvial process where deposition of solid particles transported by the flow can be cited); therefore a detailed analysis has to be conducted to assess the influence of these structures on the natural habitat and biota. Furthermore, as a consequence of the urbanization natural afforestation is present in some European countries, which means that erosion processes are generally less intensive, but the abandoned woods can be a prominent source of the woody debris, which also has to be considered during the planning/design of structures. Likewise, large mass movements, like debris flows, shallow landslides or deep-seated landslides, can also have a significant influence on sediment yields at the basin scale.

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.

Reservoir geometry is another important factor influencing the sedimentation process, in particular its morphology. In a long, narrow backwater reach (above a river barrage) and under idealized 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 widening 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.

When designing river structures the sediment transport process must be considered as one of the most important natural processes in river dynamics. Different types of structures influence the sediment transport process differently. Besides, flood protection and hydropower production structures must be designed in a way to not affect the sediment transport in a negative way. Riverbed erosion, riverbank erosion, natural habitats degradation, etc., – all these influences must be investigated and evaluated. New standards for designing torrent structures, flood protection systems, hydropower plants must be determined to meet not only the requirements for flood protection and economical purposes but also to preserve the good ecological status of rivers and torrents.

1.2 Legal boundary conditions concerning sediment continuity

1.2.1 EU Water Framework Directive

1.2.1.1 General introduction

The introduction of the EU Water Framework Directive has been a decisive step towards the harmonisation of water legislation in the European Union. The Directive (2000/60/CE), which came into force in 2000, brought a wide-ranging revision of the European water policy, followed by a complete reorientation of the water and water bodies protection policy in Europe.

The purpose of this Directive is to establish a framework for the protection of inland surface waters, transitional waters, coastal waters, and groundwater which:

- prevents further deterioration and protects and enhances the status of aquatic ecosystems;
- promotes sustainable water use based on a long-term protection of available water resources;
- aims at enhanced protection and improvement of the aquatic environment;
- ensures the progressive reduction of pollution of groundwater and prevents its further pollution, and
- contributes to mitigating the effects of floods and droughts.

The “good status” should be achieved by the year 2015 for all European water bodies. Member States shall identify the individual river basins lying within their national territory and, for the purposes of this Directive, shall assign them to individual river basin districts. Small river basins may be combined with larger river basins or joined with neighbouring small basins to form individual river basin districts where appropriate. Member States shall ensure the establishment of a register or registers of all areas lying within each river basin district which have been designated as requiring special protection. The European Parliament and the Council shall adopt specific measures against pollution of water by individual pollutants or groups of pollutants presenting a significant risk to or via the aquatic environment, including such risks to waters used for the abstraction of drinking water. Annex I regards the information that the Member States shall provide to all competent authorities within each of their river basin districts as well as the portion of any international river basin district lying within their territory, Annex II concerns surface and groundwater, Annex III the economic analysis, Annex IV protected areas, Annex V surface and groundwater status, Annex VI the list of measures to be taken, Annex VII river basin management plans, Annex VIII the list of main pollutants, Annex IX the "limit values" and "quality objectives", Annex X priority substances, and Annex XI ecoregions for rivers and lakes (25 Articles and 11 Annexes).

The EU Water Framework Directive (EU WFD, 2000) was developed as a tool for harmonising the previously fragmented water legislation in the European Union, and has been responsible for decisive changes and reorientation in the water policy of many of its Member States.

The Water Framework Directive is an ecological directive with far-reaching targets and clear deadlines. It has created a new organisational framework at the European level for the protection of rivers and lakes, coastal beaches, and groundwater.

Among the **core elements of the Water Framework Directive** is the obligation of the Member States to

- lay down environmental objectives for surface waters, coastal waters, and groundwaters;
- extensively analyze the river basins;
- produce river basin-based management plans, with public participation, in order to achieve the set targets by the year 2015.

The **tasks** to be implemented as part of the Water Framework Directive cover three essential areas:

- **analysis** of the characteristics of the water bodies within the river basin district from the water policy, ecological, and economic points of view, including monitoring and assessment of their status;
- clear definition of the **targets to be met** with regard to the status of the water bodies;
- determination of **measures** and/or **programmes of measures** to be implemented in order to meet these objectives.

Less stringent environmental objectives apply to **heavily modified water bodies** which only need to be protected and improved in order to achieve good ecologic potential and good chemical status by the year 2015.

According to Article 2, item 9 EU WFD (2000), the notion heavily modified water bodies refers to surface waters which, as a result of physical alteration by human activity, have been substantially altered in character. They are classified in accordance with the provisions of Appendix II of the EU WFD.

According to Article 2 item 23 EU WFD (2000), **good ecological potential** means the status of an artificial or heavily modified water body so classified according to the provisions of Appendix V.

The documents to be compiled under the Water Framework Directive describing the status of the river basin districts, the measures required to monitor their status, and the measures necessary to achieve the required good status of the river basins include (EU WFD, 2000):

- analysis of characteristics;
- monitoring programme;
- programme of measures;

- management plan.

The **analysis of characteristics**, according to Article 5 EU WFD (2000), describes the initial status of the relevant river basin district, i.e. by describing the types of surface water bodies it comprises.
The **monitoring programme** as defined by Article 6 EU WFD (2000) compiles the measuring programmes according to which the different key figures of the area under review are to be measured and changes are to be surveyed.
The **programme of measures** comprises those measures which, after assessment of the river basin district in question, are to be taken to achieve the good status required (EU WFD, 2000).
According to Article 4 EU WFD (2000) essential **environmental objectives of the programme of measures** include:

- implementation of all necessary measures to prevent deterioration of the status of all surface water bodies;
- achievement of good ecological and chemical status for all surface water bodies and of good quantitative and chemical status for groundwater bodies;
- achievement of good ecological potential and good chemical status for artificial and heavily modified surface water bodies.

Article 13 EU WFD (2000) stipulates the production of **management plans** at river basin level for the planning of water policies, including:

- a **general description** of the river basin district;
- a summary of all significant **pressures** and **impact** of human activity on water bodies, a list of **protected areas**, as well as maps of the **monitoring network** for surface waters, groundwaters and protected areas;
- a list of **environmental objectives** for the water bodies;
- a summary of the **economic analysis** of water use;
- a summary of all **measures** and **programmes of measures**;
- a list of the **competent authorities**, and
- a summary of **public information and consultation measures**.

The management plan is to cover the entire river basin and is to be updated on a regular basis (every six years at the latest) (EU WFD, 2000).
Unlike other directives, the implementation of the Water Framework Directive is being followed-up by the Commission of the EU in the form of detailed guidelines and guidance documents and/or extensive reporting obligations and periodic updating of the management plans.

Waters are differentiated according to types: first they are derived from abiotic conditions, such as geomorphology, geographical situation, hydromechanics, etc. And in the second step, the typology is to be verified by ecological findings. Thereby framework conditions specific to a certain water body are defined as measurable parameters, such as current velocity and water depth, substratum composition and shape of river bed, background nutrient status and thermal regime. This enables the assessment of interventions and measures carried out on the water body, and their impact on its ecologic or chemical status by evaluating in what way the type-specific reference conditions for a certain habitat have been modified or deteriorated (DWA, 2006).

The aim is to achieve active **public participation** in implementing the Directive, especially in the production, assessment, and updating of management plans. All interested and concerned circles, such as agriculture, nature preservation, as well as municipalities and cities, are to be actively involved in the planning process.

1.2.1.2 Surface water status

1.2.1.2.1 Surface water categories

According to Annex II of the Water Framework Directive (2000/60/EC) the surface water bodies within the river basin district shall be identified as falling within either one of the following surface water categories:

- rivers,
- lakes,
- transitional waters,
- coastal waters, or
- artificial surface water bodies or heavily modified surface water bodies.

For each surface water body category, the relevant surface water bodies within the river basin district shall be differentiated according to type. These types are those defined using either 'system A' or 'system B', presented below.

Only rivers will be presented below.

1.2.1.2.2 Ecoregions and surface water body (rivers) types

System A

Fixed typology	Descriptors
Ecoregion	Ecoregions shown on map A in Annex XI
Type	Altitude typology - high: >800 m - mid-altitude: 200 to 800 m - lowland: <200 m Size typology based on catchment area - small: 10 to 100 km2 - medium: >100 to 1 000 km2 - large: >1 000 to 10 000 km2 - very large: >10 000 km2 Geology - calcareous - siliceous - organic

System B

Alternative characterisation	Physical and chemical factors that determine the characteristics of the river or part of the river and hence the biological population structure and composition
Obligatory factors	altitude latitude longitude geology size
Optional factors	distance from river source energy of flow (function of flow and slope) mean water width mean water depth mean water slope form and shape of main river bed river discharge (flow) category valley shape transport of solids acid neutralising capacity mean substratum composition chloride air temperature range mean air temperature precipitation

1.2.1.2.3 Establishment of type-specific reference conditions for surface water body types

For each surface water body type characterized above, type-specific hydromorphological and physico-chemical conditions shall be established representing the values of the hydromorphological and physico-chemical quality elements specified in point 1.1 in Annex V for that surface water body type at high ecological status as defined in the relevant table in point 1.2 in Annex V. Type-specific biological reference conditions shall be established, representing the values of the biological quality elements specified in point 1.1 in Annex V for that surface water body type at high ecological status as defined in the relevant table in section 1.2 in Annex V.

In applying the procedures set out in this section to heavily modified or artificial surface water bodies references to high ecological status shall be construed as references to maximum ecological potential as defined in Table 1.2.5 of Annex V. The values for maximum ecological potential for a water body shall be reviewed every six years.

1.2.1.2.4 Quality elements for the classification of ecological status (point 1.1 Annex V)

The classification of ecological status of surface waters (rivers) is made by the following **quality elements**:

- Biological elements
  - Composition and abundance of aquatic flora
  - Composition and abundance of benthic invertebrate fauna
  - Composition, abundance and age structure of fish fauna
- Hydromorphological elements supporting the biological elements
  - Hydrological regime
    - quantity and dynamics of water flow
    - connection to groundwater bodies
  - River continuity
  - Morphological conditions
    - river depth and width variation
    - structure and substrate of the river bed
    - structure of the riparian zone
- Chemical and physico-chemical elements supporting the biological elements
- General
  - Thermal conditions
  - Oxygenation conditions
  - Salinity
  - Acidification status
  - Nutrient conditions
- Specific pollutants
  - Pollution by all priority substances identified as being discharged into the body of water
  - Pollution by other substances identified as being discharged in significant quantities into the body of water

1.2.1.2.5 Normative definitions of ecological status classifications (point 1.2 Annex V)

The following text provides a general definition of ecological quality. For the purposes of classification the WFD gives the values for the quality elements of ecological status for each surface water category in tables, but below only the values for the quality elements of ecological status for rivers are given.

Table 1: General definition for rivers, lakes, transitional waters and coastal waters

Element	High status	Good status	Moderate status
General	There are no, or only very minor, anthropogenic alterations to the values of the physico-chemical and hydromorphological quality elements for the surface water body type from those normally associated with that type under undisturbed conditions. The values of the biological quality elements for the surface water body reflect those normally associated with that type under undisturbed conditions, and show no, or only very minor, evidence of distortion. These are the type-specific conditions and communities.	The values of the biological quality elements for the surface water body type show low levels of distortion resulting from human activity, but deviate only slightly from those normally associated with the surface water body type under undisturbed conditions.	The values of the biological quality elements for the surface water body type deviate moderately from those normally associated with the surface water body type under undisturbed conditions. The values show moderate signs of distortion resulting from human activity and are significantly more disturbed than under conditions of good status.

Waters achieving a status below moderate shall be classified as poor or bad.

Waters showing evidence of major alterations to the values of the biological quality elements for the surface water body type and in which the relevant biological communities deviate substantially from those normally associated with the surface water body type under undisturbed conditions, shall be classified as poor.

Waters showing evidence of severe alterations to the values of the biological quality elements for the surface water body type and in which large portions of the relevant biological communities normally associated with the surface water body type under undisturbed conditions are absent, shall be classified as bad.

1.2.1.2.6 Definitions for high, good and moderate ecological status in rivers

Biological quality elements

Element	High status	Good status	Moderate status
Phytoplankton	The taxonomic composition and abundance of phytoplankton correspond totally or	There are slight changes in the composition and abundance of planktonic taxa compared to the type-specific communities.	The composition and abundance of planktonic taxa differ moderately from the type-specific

	nearly totally to undisturbed conditions. The average phytoplankton biomass is consistent with the type-specific physico-chemical conditions and is not such as to significantly alter the type-specific transparency conditions. Planktonic blooms occur at a frequency and intensity which is consistent with the type specific physico-chemical conditions.	Such changes do not indicate any accelerated growth of algae resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water or sediment. A slight increase in the frequency and intensity of the type specific planktonic blooms may occur.	communities. Biomass is moderately disturbed and may be such as to produce a significant undesirable disturbance in the condition of other biological quality elements and the physico-chemical quality of the water or sediment. A moderate increase in the frequency and intensity of planktonic blooms may occur. Persistent blooms may occur during summer months.
Macrophytes and phytobenthos	The taxonomic composition corresponds totally or nearly totally to undisturbed conditions. There are no detectable changes in the average macrophytic and the average phytobenthic abundance.	There are slight changes in the composition and abundance of macrophytic and phytobenthic taxa compared to the type-specific communities. Such changes do not indicate any accelerated growth of phytobenthos or higher forms of plant life resulting in undesirable disturbance to the balance of organisms present in the water body or to the physico-chemical quality of the water. The phytobenthic community is not adversely affected by bacterial tufts and coats present due to anthropogenic activity.	The composition of macrophytic and phytobenthic taxa differ moderately from the type-specific communities and are significantly more distorted than those observed at good quality. Moderate changes in the average macrophytic and the average phytobenthic abundance are evident. The phytobenthic community may be interfered with, and, in some areas, displaced by bacterial tufts and coats present as a result of anthropogenic activities.
Benthic invertebrate fauna	The taxonomic composition and abundance correspond totally or nearly totally	There are slight changes in the composition and abundance of invertebrate taxa compared to the	The composition and abundance of invertebrate taxa differ moderately from the

	to the undisturbed conditions. The ratio of disturbance sensitive taxa to insensitive taxa shows no signs of alteration from undisturbed levels. The level of diversity of invertebrate taxa shows no sign of alteration from undisturbed levels.	type-specific communities. The ratio of disturbance sensitive taxa to insensitive taxa shows slight signs of alteration from type-specific levels. The level of diversity of invertebrate taxa shows slight signs of alteration from type-specific levels.	type-specific conditions. Major taxonomic groups of the type-specific community are absent. The ratio of disturbance sensitive to insensitive taxa, and the level of diversity, are substantially lower than the type-specific level and significantly lower than for good status.
Fish fauna	Species composition and abundance correspond totally or nearly totally to undisturbed conditions. All the type-specific sensitive species are present. The age structures of the fish communities show little sign of anthropogenic disturbance and are not indicative of a failure in the reproduction or development of a particular species.	There are slight changes in species composition and abundance from the type-specific communities attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements. The age structures of the fish communities show signs of disturbance attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements, and, in a few instances, are indicative of a failure in the reproduction or development of a particular species, to the extent that some age classes may be missing.	The composition and abundance of fish species differ moderately from the type-specific communities attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements. The age structure of the fish communities shows major signs of disturbance, attributable to anthropogenic impacts on physico-chemical or hydromorphological quality elements, to the extent that a moderate proportion of the type specific species are absent or of very low abundance.

Hydromorphological quality elements

Element	High status	Good status	Moderate status
Hydrological regime	The quantity and dynamics of flow, and the resultant connection to groundwaters, reflect totally, or nearly totally, undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
River continuity	The continuity of the river is not disturbed by anthropogenic activities and allows undisturbed migration of aquatic organisms and sediment transport.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Morphological conditions	Channel patterns, width and depth variations, flow velocities, substrate conditions and both the structure and condition of the riparian zones correspond totally or nearly totally to undisturbed conditions.	Conditions consistent with the achievement of the values specified above for the biological quality elements.	Conditions consistent with the achievement of the values specified above for the biological quality elements.

Physico-chemical quality elements [(1)]

Element	High status	Good status	Moderate status
General conditions	The values of the physico-chemical elements correspond totally or nearly totally to undisturbed conditions. Nutrient concentrations remain within the range normally associated with undisturbed conditions. Levels of salinity, pH, oxygen balance, acid neutralising capacity and temperature do not show signs of anthropogenic disturbance and remain within the range normally	Temperature, oxygen balance, pH, acid neutralising capacity and salinity do not reach levels outside the range established so as to ensure the functioning of the type specific ecosystem and the achievement of the values specified above for the biological quality elements. Nutrient concentrations do not exceed the levels established so as to ensure the functioning of the ecosystem and	Conditions consistent with the achievement of the values specified above for the biological quality elements.

	associated with undisturbed conditions.	the achievement of the values specified above for the biological quality elements.	
Specific synthetic pollutants	Concentrations close to zero and at least below the limits of detection of the most advanced analytical techniques in general use.	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS)	Conditions consistent with the achievement of the values specified above for the biological quality elements.
Specific non-synthetic pollutants	Concentrations remain within the range normally associated with undisturbed conditions (background levels = bgl).	Concentrations not in excess of the standards set in accordance with the procedure detailed in section 1.2.6 (2) without prejudice to Directive 91/414/EC and Directive 98/8/EC. (<EQS).	Conditions consistent with the achievement of the values specified above for the biological quality elements.

(1) The following abbreviations are used: bgl = background level, EQS = environmental quality standard.

(2) Application of the standards derived under this protocol shall not require reduction of pollutant concentrations below background levels: (EQS >bgl).

1.2.1.2.7 Monitoring of ecological status and chemical status for surface waters

The surface water monitoring network shall be established in accordance with the requirements of Article 8. The monitoring network shall be designed so as to provide a coherent and comprehensive overview of ecological and chemical status within each river basin and shall permit classification of water bodies into five classes consistent with the normative definitions in the section above. Member States shall provide a map or maps showing the surface water monitoring network in the river basin management plan.

On the basis of the characterisation and impact assessment carried out in accordance with Article 5 and Annex II, Member States shall for each period to which a river basin management plan applies, establish a surveillance monitoring programme and an operational monitoring programme. Member States may also need in some cases to establish programmes of investigative monitoring.

Member States shall monitor parameters which are indicative of the status of each relevant quality element. In selecting parameters for biological quality elements Member States shall identify the appropriate taxonomic level required to achieve adequate confidence and precision in the classification of the quality elements. Estimates of the level of confidence and precision of the results provided by the monitoring programmes shall be given in the plan.

Annex V also presents the design of surveillance monitoring, the design of operational monitoring, the design of investigative monitoring, the frequency of monitoring, additional monitoring requirements for protected areas and standards for monitoring of quality elements.

1.2.1.3 The EU Water Framework Directive and desedimentation measures

Desedimentation first of all requires assessment of the type of surface water body concerned. In addition, it is to be examined if this concerns an artificial or heavily modified water body, which will be frequently the case for units connected in cascade, reservoirs or diversion-type power stations.

This categorisation makes it possible to clearly specify the kind of impact, the degree of impact, and the impact radius of a desedimentation measure and thus enables quantification.

For artificial and heavily modified water bodies, the notion of **ecologic potential** is decisive. It describes the best achievable biological conditions under the given conditions of use.

In case there is a risk that restoration will lead to a decisive impairment of certain uses, such as power generation, navigation, flood protection, then it is not the ecological status in terms of the EU Water Framework Directive which is to be achieved but rather the good ecologic potential, which is to be determined based on the tables in Appendix V to this Directive.

In addition, modifications caused by future measures are taken into account in the assessment process, also considering alternative environmental options.

A number of examples show the effect and impact that desedimentation measures may have on a body of water (DWA, 2006).

Types of impact of desedimentation measures

- modification of the chemical properties of the water due to the remobilisation of nutrients, heavy metals etc.;
- modification of the physical properties, regarding turbidity, transport of suspended matter, change in pH-value;
- destruction of habitats at sediment removal sites;
- impairment of habitats at re-insertion locations (under water) or around a landfill site.

The Water Framework Directive (EU WFD, 2000) includes the following **departure points** for desedimentation measures:

- effects of desedimentation as part of heavy modification, as under Appendix V;
- regular desedimentation as permanent impairment, as under Article 4, paragraph 5;
- rare desedimentation as temporary deterioration, as under Article 4, paragraph 6.

Article 4, paragraph 5 lays down the conditions for less stringent environmental objectives compared to those required in paragraph 1. This applies if [the bodies of water] are so affected by human activity or their natural condition is such that the achievement of these objectives would be infeasible or disproportionately expensive. However, Member States must ensure efforts to achieve the highest ecologic and chemical status and to safeguard that no further deterioration in the status of water bodies occurs.

Article 4, paragraph 6 lays down the conditions for a temporary deterioration of status due to natural origins or force majeure, which are exceptional or could not reasonably have been foreseen (EU WFD, 2000).

Although the Water Framework Directive rarely includes indications for specific interventions, clear indications are given in Article 4, which are further specified in Annexes II and V, laying the basis for the assessment of individual measures to be taken in and around a body of water.

Materials in suspension and sediments are referred to only in Article 2 of the Water Framework Directive (EU WFD, 2000), where the definition of "good chemical status" states that the concentration of pollutants in surface waters should not exceed the environmental quality standards established in Annex IX.

In addition, Annex VIII mentions the term "materials in suspension" in the Indicative List of the Main Pollutants.

Guidelines and guidance documents emerging at national and European levels give additional concrete recommendations for implementing the guidelines of the Water Framework Directive (DWA, 2006).

1.2.1.4 Implementation of the WFD

The latest common implementation strategy for the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC) is laid down in Work Programme 2013-2015 "Strengthening the implementation of EU water policy through the second river basin management plans".

The agreement to start a Common Implementation Strategy (CIS) for the Water Framework Directive (WFD) in 2001 was seen as a milestone in working together towards successful implementation of the core water law at EU level. Over the past years, the impressive outputs, the added value and the cooperative spirit of the exercise have been widely recognized. Furthermore, implementation of the Floods, Environmental Quality Standards (EQS) and Groundwater Directives is now closely tied in with that of the WFD, and coordination with the implementation of other water-related Directives (Urban Waste Water, Drinking Water, Bathing Water, Nitrates, Marine Strategy Framework and Nature Directives) has improved. The Water Blueprint published by the Commission in November 2012 together with the 3rd implementation report of the WFD have identified serious implementation gaps and delays as well as actions that need to be taken to speed up the achievement of the WFD "good water status" objective. Building on the successful co-operation of the past decade and on the basis of the Blueprint proposals and the Council Conclusions adopted on 17 December 20123, a CIS Work Programme (WP) for the period 2013-2015 is presented in this document.

(http://ec.europa.eu/environment/water/water-framework/objectives/pdf/Work%20Programme%202013-2015.pdf)

1.2.2 Flood directive

1.2.2.1 General introduction

Directive 2007/60/EC on the assessment and management of flood risks entered into force on 26 November 2007. The purpose of this Directive is to establish a framework for the assessment and management of flood risks, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community.

The Directive shall be carried out in coordination with the Water Framework Directive, notably by flood risk management plans and river basin management plans being coordinated, and through coordination of the public participation procedures in the preparation of these plans. (http://ec.europa.eu/environment/water/flood_risk/)

1.2.2.2 Flood directive

According to chapter II of the Directive all Member States shall, for each river basin district, or unit of management referred to in Article 3(2)(b), or the portion of an international river basin district lying within their territory, undertake a preliminary flood risk assessment in accordance with paragraph 2 of Article 4 to provide an assessment of potential risks. Depending on the specific needs of Member States, the assessment shall include an assessment of the potential adverse consequences of future floods for human health, the environment, cultural heritage and economic activity, taking into account as far as possible issues such as the topography, the position of watercourses and their general hydrological and geo-morphological characteristics, including floodplains as natural retention areas, the effectiveness of existing man-made flood defense infrastructures, the position of populated areas, areas of economic activity and long-term developments including impacts of climate change on the occurrence of floods.

The preliminary flood risk assessment should have been completed by 22 December 2011.

Chapter III of the Floods Directive covers the field of flood hazard maps and flood risk maps. As defined by Article 6 Member States shall, at the level of the river basin district, or unit of management referred to in Article 3(2)(b), prepare flood hazard maps and flood risk maps, at the most appropriate scale for the areas identified under Article 5(1). Flood hazard maps shall cover the geographical areas which could be flooded according to the following scenarios:

(a) floods with a low probability, or extreme event scenarios;
(b) floods with a medium probability (likely return period ≥ 100 years);
(c) floods with a high probability, where appropriate.

For each of the above mentioned scenarios the flood extent, water depths or water level and where appropriate, the flow velocity or the relevant water flow shall be shown.

Flood risk maps shall show the potential adverse consequences associated with flood scenarios referred to above and expressed in terms of the following:

(a) the indicative number of inhabitants potentially affected;
(b) type of economic activity of the area potentially affected;
(c) installations concerning integrated pollution prevention and control which might cause accidental pollution in case of flooding and potentially affected protected areas identified in Annex IV(1)(i), (iii) and (v) to Directive 2000/60/EC;
(d) other information which the Member State considers useful such as the indication of areas where floods with a high content of transported sediments and debris floods can occur and information on other significant sources of pollution.

Member States shall ensure that the flood hazard maps and flood risk maps are completed by 22 December 2013.

Flood risk management plans are presented in the scope of chapter IV. According to Article 7, paragraph 2, Member States shall establish appropriate objectives for the management of flood risks for the areas identified under Article 5(1) and the areas covered by Article 13(1)(b), focusing on the reduction of potential adverse consequences of flooding for human health, the environment, cultural heritage and economic activity, and, if considered appropriate, on non-structural initiatives and/or on the reduction of the likelihood of flooding. Flood risk management plans shall include measures for achieving these objectives.

Flood risk management plans shall take into account relevant aspects such as costs and benefits, flood extent and flood conveyance routes and areas which have the potential to retain flood water, such as natural floodplains, the environmental objectives of Article 4 of Directive 2000/60/EC, soil and water management, spatial planning, land use, nature conservation, navigation and port infrastructure.

Paragraph 4 of Article 7 states that in the interests of solidarity, flood risk management plans established in one Member State shall not include measures which, by their extent and impact, significantly increase flood risks upstream or downstream of other countries in the same river basin or sub-basin, unless these measures have been coordinated and an agreed solution has been found among the Member States concerned in the framework of Article 8.

Member States shall ensure that flood risk management plans are completed and published by 22 December 2015.

1.2.2.3 Implementation of the Floods Directive

Directive 2007/60/EC on the assessment and management of flood risks sets out clear deadlines for each of the requirements and should be carefully coordinated with the Directive 2000/60/EC. The Directive has entered into force in November 2007 and by the year 2021 the 1st flood risk management cycle should end and 2nd Flood Risk Management Plans, specific requirement on climate change, and 3rd Water Framework Directive River Basin Management Plans should be accomplished.

1.2.3 RES directive

1.2.3.1 General introduction

This Directive sets out a common framework for the promotion of energy from renewable sources, which include wind, solar, aero thermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases. In particular, these provisions establish mandatory national targets for the overall share of energy from renewable sources in gross final consumption of energy (reaching 20% of the EU’s energy consumption through renewable energy sources by 2020) and for the share of energy from renewable sources in transport (10% RES in transport for each Member State) by 2020.

1.2.3.2 RES directive

For the benefit of rapid deployment of energy from renewable sources and in view of their overall high sustainable and environmental beneficial quality, Member States should, with respect to pollution reduction, take into account the contribution of renewable energy sources towards meeting environmental and climate change objectives, in particular when compared to non-renewable energy installations. The coherence between the objectives of this Directive and the Community’s other environmental legislation should be ensured.

Where appropriate, the Commission should take due account of the Millennium Ecosystem Assessment which contains useful data for the conservation of at least those areas that provide basic ecosystem services in critical situations such as watershed protection and erosion control.

According to article 13 Member States shall, in particular, take the appropriate steps to ensure that subject to differences between Member States, their administrative structures and organization are clearly coordinated and defined, with transparent timetables for determining planning and building applications and simplified and less burdensome authorization procedures, including through simple notification if allowed by the applicable regulatory framework, established for smaller projects and for decentralized devices for producing energy from renewable sources, where appropriate.

Member States shall clearly define any technical specifications which must be met by renewable energy equipment and systems in order to benefit from support schemes.

Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive by 5 December 2010.

1.2.3.3 Implementation of RES Directive

Member States had to submit to the European Commission by 30th June 2010 their National Renewable Energy Action Plans (NREAP), which set out how each Member State aims to achieve its national targets in the three sectors (electricity, heating and cooling, transport).

In order to carry out the requirements of the RES Directive, a number of documents are subsequently to be issued between 2010 and 2021, either by the European Commission or by the Member States themselves.

1.2.4 Habitats directive

1.2.4.1 General introduction

In order to ensure the survival of Europe's most endangered and vulnerable species, EU governments adopted the Habitats Directive in 1992 (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora). Together with the Birds Directive, it sets the standard for nature conservation across the EU and enables all 27 Member States to work together within the same strong legislative framework in order to protect the most vulnerable species and habitat types across their entire natural range within the EU.

Member States must take all the necessary measures to guarantee the conservation of habitats in special areas of conservation, and to avoid their deterioration and the significant disturbance of species. The Directive provides for co-financing of conservation measures by the Community.

Every six years, Member States must report on the measures they have taken pursuant to the Directive. The Commission must draw up a summary report on the basis thereof.

1.2.4.2 Habitats directive

Article 6, paragraph 1 states that for special areas of conservation, Member States shall establish the necessary conservation measures involving, if need be, appropriate management plans specifically designed for the sites or integrated into other development plans, and appropriate statutory, administrative or contractual measures which correspond to the ecological requirements of the natural habitat types in Annex I and the species in Annex II present on the sites.

According to paragraph 2 in Article 6 Member States shall take appropriate steps to avoid, in the special areas of conservation, the deterioration of natural habitats and the habitats of species as well as disturbance of the species for which the areas have been designated, in so far as such disturbance could be significant in relation to the objectives of this Directive. Paragraph 4 states that if, in spite of a negative assessment of the implications for the site and in the absence of alternative solutions, a plan or project must nevertheless be carried out for imperative reasons of overriding public interest, including those of a social or economic nature, the Member State shall take all compensatory measures necessary to ensure that the overall coherence of Natura 2000 is protected. In agreement with each of the Member States concerned, the Commission shall identify, for sites of Community importance for which co-financing is sought, those measures essential for the maintenance or re-establishment at a favourable conservation status of the priority natural habitat types and priority species on the sites concerned, as well as the total costs arising from those measures, as defined in paragraph 2 of Article 8.

Member States shall bring into force the laws, regulations and administrative provisions necessary to comply with this Directive within two years of its notification.

1.2.5 Environmental Quality Standards Directive

The 2008/105/EC Directive lays down environmental quality standards (EQS) for priority substances and certain other pollutants as provided for in Article 16 of Directive 2000/60/EC, with the aim of achieving good surface water chemical status and in accordance with the provisions and objectives of Article 4 of that Directive.

It notes that Member States should improve the knowledge and data available on sources of priority substances and ways in which pollution occurs in order to identify targeted and effective control options. Member States should, inter alia, monitor sediment and biota, as appropriate, at an adequate frequency to provide sufficient data for a reliable long-term trend analysis of those priority substances that tend to accumulate in sediment and/or biota. The results of the monitoring, including monitoring of sediment and biota, should, as far as required by Article 3 of Decision No 2455/2001/EC of the European Parliament and of the Council of 20 November 2001 establishing the list of priority substances in the field of water policy (5), be made available in order to inform future Commission proposals under Article 16(4) and (8) of Directive 2000/60/EC.

2 Aims

Sediment management in diverse Alpine torrential watersheds and river basins must be based on a detailed analysis of the interactions between existing and planned man-made structures (i.e. torrent control works, hydropower plants, river restoration schemes) and sediment dynamics including large wood as an important habitat element. WP6 is dedicated to these interactions and will provide several guidelines in the field of river/torrent structure design and integrated sediment management.

The aims of the WP6 are to:

- identify the assessment of mutual interactions between river/torrent structures, torrential and river sediments, and large wood,

- evaluate the effects of hydropower dams on sediment continuity for design and planning purposes,

- evaluate river hydro-morphological alterations due to longitudinal sediment continuity disruption and performance analysis of river restoration measures,

- carry out a performance analysis and definition of optimal planning and design of torrent control works to reduce their impact on longitudinal sediment continuity,

- provide guidelines for planning torrent structures, hydropower plants and flood protection systems.

In order to achieve the work package aims, detailed field measurements and analyses of mutual interactions between torrent and river control structures, torrent and river sediments, and (large) wood have been performed in several Alpine study sites (in the Dolomites, in the Maira River Basin in Piemont, Italy, in the Gradaščica River Basin, Upper Sava valley, and the Bistričica River, Slovenia, and in the Drau River Basin). Different techniques and tools to develop improved concepts of responses of such structures to floods and debris flows, and to gain a large database for the proposed guidelines (Guidelines for planning/designing of efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches) have been used.

The next step was to study the interaction of different hydropower dams and sediment transfer (Drau, Urslau, Ill) where basic physical and numerical modeling of hydropower dams have assisted to optimize sediment transfer and continuity, developed common strategies to sustain reservoir capacity and sediment continuity and came up with the proposed guidelines (Guidelines for improved planning of hydropower plants aimed to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches).

Afterwards the evaluation of river hydro-morphological alterations due to longitudinal sediment continuity disruption and river restoration measures, focusing on downstream river bed degradation, loss of dynamic gravel bars and bank erosion, analysis of the effects produced by dams and other types of transversal structures on sediment continuity, river restoration possibilities and man-made structures and their failure mechanisms, and development of common strategies to sustain reservoir capacity and sediment continuity was carried out. The results are presented in the proposed guidelines (Guidelines for planning and designing of effective flood protection systems, river training and restoration projects that have lower impact on sediment continuity).

Finally, using the database from the detailed field measurements and analysis performed in the first step, a critical and refined performance analysis of different types of torrential control structures (e.g. check dams, retention basins) when impacted by flash floods and debris flows was conducted with respect to their efficiency and optimal design, and the proposed guidelines (output 6.2) were prepared.

Actions within WP6:

- Assessment of mutual interactions between control structures, torrential and river sediments, and large wood
- Evaluation of the effects of hydropower dams on sediment continuity for design and planning purposes
- Evaluation of river hydro-morphological alterations due to longitudinal sediment-continuity disruption and performance analysis of river restoration measures
- Performance analysis and definition of optimal planning and design of torrent control works to reduce their impact on longitudinal sediment continuity

Targeted outputs of WP6:

- Output 6.1: Improved concepts of responses of torrent/river control structures to floods and debris flow impacts (including wood)
- Output 6.2: Guidelines for planning/designing of efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches
- Output 6.3: Guidelines for improved planning of hydropower plants aimed to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches
- Output 6.4: Guidelines for planning and designing of effective flood protection systems, river training and restoration projects that have lower impact on sediment continuity

3 Chapters – WP6 Outputs

3.1 Report on improved concepts of responses of torrent/river control structures to floods and debris flow impacts (including wood)

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3.1.1 Introduction – up-to date insight on the main driving forces for improving flood control management in the European Union and Alpine Space context

A critical reflection about the effectiveness of implemented natural hazard management concepts – e.g. responses of torrent/river control structures to floods and debris flow impacts (including wood) –, should be a constant part of water management process, land use planning and the system of protection from natural hazards. Thus, like natural (hazards) disasters are a permanent part of the natural systems evolution, the development and adjustments of protection concepts is strongly linked with social evolution.

In other words, by the respective critical judgment of current protection concepts at a particular point in time and, a specific geographical area, and a country's boundary conditions, it is also necessary to gain insight into a longer historical period. Before making a simplified critique of the existing state, we should consider objective natural and human factors which led us to the existing state and the implemented protection concept. In the context of flood-protection regulations, we should not overlook the effects of certain political decisions, legislations and other more or less democratic processes which can in certain time periods strongly, indirectly and directly, affect the "expert" solutions. Namely, it is obvious that in many cases the priority is to use land for settlements, agriculture, infrastructure and energy generation – instead of a more long-term, sustained approach by avoiding flood risk areas and the preservation of natural environment specifics. This kind of "hard" decisions can require major reconfigurations of the environment, i.e. to provide the desired land uses or exploitation of hydropower. Consequently, as a subordinate decision process of water regulation, flood protection possibilities are limited. This kind of insight into history can reveal many impacts and demands, restriction/boundary conditions, which were in the historical period concerned the only acceptable and feasible "expert solution" for reducing flood risk.

With this perspective, nowadays when we still deal (or even more so) with the great flood damage and identified deficiency about the good status of the water environment along many European streams it would be too easy to say that in the past we made many professional mistakes or that our concepts of flood protection were misguided, and that today we need revolutionary changes. This kind of judgement cannot succumb only to the unilateral assessment of the purely nature-centric, or purely anthropocentric perspective. The human society is part of nature. The extremely rapid evolutionary development in all society domains of the last century, particularly the dynamic development of municipalities in Alpine areas due to tourism and economic growth (also in the areas endangered by natural hazards), and the detected considerable changes of natural factors (also as negative effects of mostly generally accepted consequences of climate change) should be considered as a challenge to permanent adaptation, upgrading and improving the existing concepts for reducing natural hazards threats. The activities and results of the SedAlp project clearly confirmed that this challenges are well recognized and that all SedAlp partner countries already implemented the intensive checking and upgrading of existing concepts of flood protection and sediment management.

Nevertheless, today's natural and society framework of planning conditions is very demanding. An enormous increase in damage potential in hazard-prone areas has taken place over the last decades. The demand for space from different sectors is constantly increasing (settlements, agriculture, infrastructure, industry, tourism, leisure, natural conservation, etc.). However, the space for permanent settlement in Alpine areas is very restricted (12–15% of the available land surface). Land is cultivated mostly in valleys, i.e., lowlands in floodplains important for flood retention and establishment of natural rivers dynamics.

It is in great interest of all Alpine Space countries to combine their effort and to help each other in terms of natural hazard management because of similar natural circumstances and social systems' arrangements. This is especially important because natural disasters are not limited by country borders. Nevertheless, this will not lead to the harmonization of all approaches and management because national and regional levels of development are not the same; they all have their own unique histories and traditions regarding torrential and lowland water management. Nevertheless, this is a great opportunity for each participant to make important development steps (as to their abilities), departing from the present situation into the direction that was, after a joint analysis and discussion, recognized as the most sustainable and optimized, with minimum negative consequences for natural areas and future generations.

The reflections about water management concept correctness in the Alpine region, and the natural disaster protection strategies in a European-wide context are today particularly relevant because of the accepted EU directives (WFD, FD, RES), presenting the common European framework for future activities in this field. From the point of view of floods, the Floods Directive is particularly important as it exposes the importance of integral flood risk management – thus not focusing on structural measures only (Fig.1)

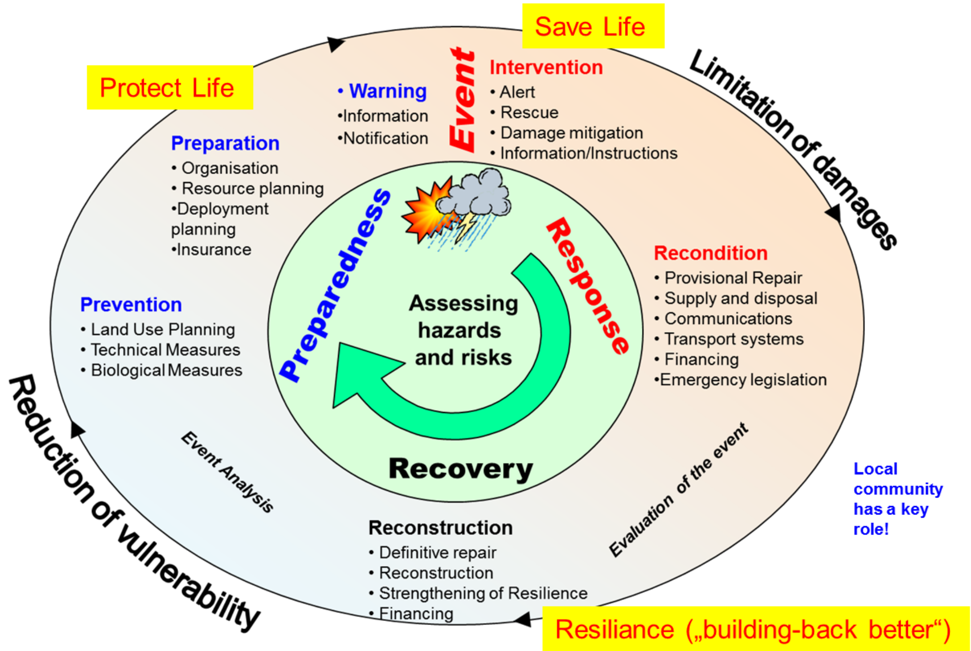


Figure 1: Integral Flood Risk Management / Cycle (Source: PLANALP, adapted by J. Papež)

This means that it is necessary to improve and coordinate all the options regarding prevention, preparedness, response, and recovery. Equally, structural (bed load retention dams, drift wood racks, etc.) and non-structural measures (land use planning, forest protection management, etc.), public awareness raising and self-protective actions should be considered.

Flood Risk Management Plans – FRMP (22 Dec. 2015) are the crucial document to be produced by all countries at the end of the first phase of the Floods Directive implementation. The FRM plans, with regard to the specific circumstances in alpine regions, are a crucial basis for the security and future development of alpine living spaces. These plans are to include measures to reduce the probability of floods and their consequences. They will address all the phases of the flood risk management cycle but focus particularly on prevention, protection and preparedness. Objectives according to EU-FD:

- reduction of the likelihood of flooding
- flood forecasts and early warning systems
- sustainable land use practices
- no measures that (significantly) increase floods in other MS (e.g. downstream in the river basin)
- focus on non structural initiatives (measures)

One of the main parts of FRMP's is the Catalogue of Measures, where the measures will be structured in groups for each 4 phases of the integral flood risk management cycle (Fig.1).

It is clear that in the future active protection measures would be still needed, although in the hierarchy of flood prevention options passive flood prevention measures are favoured (expropriation of frequently flooded sites and buildings; building ban in flooding zones; preservation of natural floodplains and creation of new ones; adaptation of land use in the areas along river courses, etc.) as compared to active flood prevention measures (artificial retention through flood retention basins; water maintenance; straightening and regulation; etc.).

Moreover, because of coordination with the Water Frame Directive objectives (good status of waters) even more effort will be directed at close-to nature flood protection measures

(near-natural water engineering), and the preservation of the natural river dynamics and improvement of ecological conditions.
All of this leads to the main topic of the SedAlp project – how can we improve our concepts of sediment management that we will at the same time meet the requirements of the society for reliable and persistence flood protection and, in parallel, maintain or even enhance sediment continuity which is in many cases the precondition for good status of water and the environment. Sediment transport processes are not only a threat during extreme events but also the crucial factor for maintaining a good ecological status of rivers (as required by the EU WFD).

3.1.2 Flood control and sediment management in the context of integral flood risk management – SedAlp recommendation on an improved planning approach

Article 2 of FD 2007/60/EC: contains the definition of a "flood", i.e. "the temporary covering by water of land not normally covered by water. This shall include floods from rivers, mountain torrents, etc".

In Alpine areas, discharge processes are usually affected by sediments and bed load material, which not only cause great damage but also problems with clean-up efforts due to the huge amounts of rubble and debris mass. Huge amounts of driftwood carried along aggravate the flood situation. Log jams lead to uncontrolled discharge and, consequently, to great damage in residential areas.

When producing the catalogue of measures for flood risk management plans, structural measures (e.g. bed load retention dams, drift wood racks) as well as grove tending strategies and maintenance procedures are to be provided. Sediment management and suitable non-structural measures as well are of particular importance. In many areas, on the alluvial fans and in downstream populated valleys with transport infrastructure, there is a critical imbalance between the existing man-made facilities and the morphological spatial demand of rivers. This means that the rivers have to be provided with an appropriate space for flood discharge. In addition to this safety aspect, in case of floods there the improvement of the morphological situation of the stream is possible (synergy effect with the Directive 2000/60/EC), (Hornich, 2014).

The SedAlp project recognizes the enormous challenge posed by the today's changing world and conflicting requirements for increased safety against natural hazards whilst improving the state of the natural environment as a development opportunity. This is an opportunity to turn the adjustment and optimization of both the existing flood protection measures and future concepts and regulation of torrential areas and lowland streams in the Alps towards a more sustainable and rational arrangement with the focus on optimizing sediment continuity.

With this intention 3 guidelines were prepared in the scope of WP 6 (Interaction with Structures) which in great part consider the process of planning, design and maintenance of the existing and future planned flood mitigation measures and energy resource facilities:

1. Guideline for planning/designing of efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches

2. Guideline for improved planning of hydropower plants aimed to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches

3. Guideline for planning and designing of effective flood protection systems, river training and restoration projects that have lower impact on sediment continuity

In the next chapter, this report presents the modern protection concepts with various cross-sectional structures used in torrent and erosion control field, which could be used in the planning process proposed in the guidelines. The knowledge of the functionality and effectiveness of various measures is the basis for designing an efficient strategy in the context of flood management.

It is impossible to propose a general prescription (recipe), but rather a set of existing structures; the developed three-step decision-making process allows the torrential and water management experts to adjust the appropriate solutions to most situations in the Alpine region.

It has to be stressed that torrent control measures are especially important in the cases of major and less frequent floods, especially devastating debris floods and debris flows that have to withstand extremely high natural forces, and also overload situations. The maintenance of torrent control works built in recent decades is of major importance to ensure their effectiveness in controlling hazards on alluvial fans. The long time elapsed from the early extensive implementation of torrent regulation works in the Alps has necessitated the production of studies aimed at evaluating their efficiency, and the need for maintenance.

3.1.3 Modern protection concepts with cross-sectional structures in torrent and erosion control in Alpine torrent catchments

3.1.3.1 Historical development/evolution of technical protection measures and state of the art of today's protection concepts in torrent control (LP)

Since the beginning of systematic torrent control in Austria 130 years ago barriers have been constructed for protection purposes. Until the end of the 1960s, solid barriers were built at the exits of depositional areas to prevent dangerous debris flows from reaching high consequence areas. The development of solid barriers with large slots or slits to regulate sediment transport began with the use of reinforced concrete during the 1970s (Rudolf-Miklau, Suda 2011). In order to dissipate the energy of debris flows, debris flow breakers have been designed since the 1980s. By slowing and depositing the surge front of the debris flow, the downstream reaches of the stream channel and settlement areas should be exposed to a considerably lower dynamic impact.

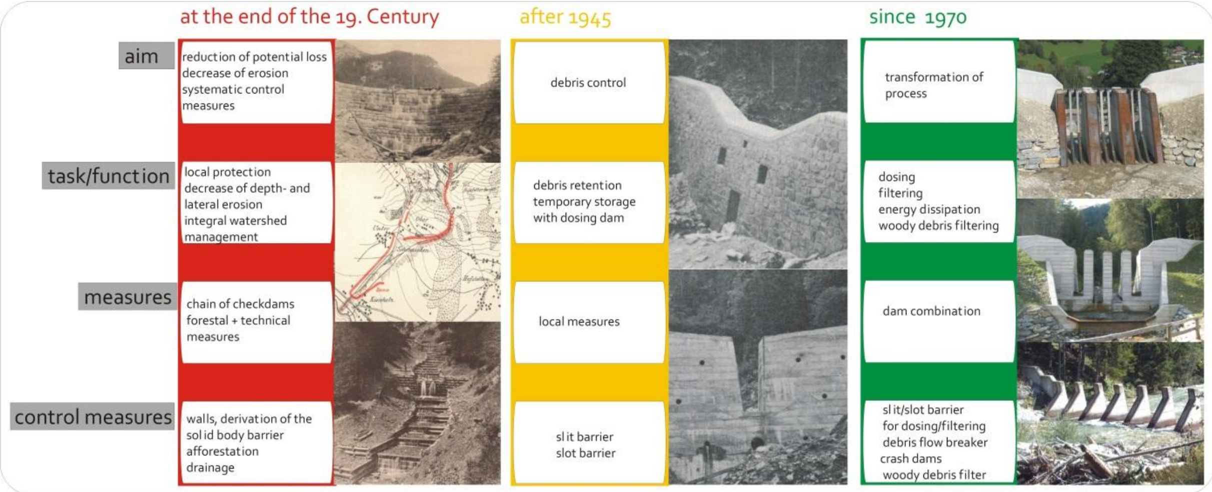


Figure 2: Historical development/evolution of technical protection measures (Moser, 2014)

In the past, the technological development of these constructions was only steered by the experiences of the engineering practice while an institutionalized process of standardization comparable to other engineering branches was not existent. In future, all structures have to be designed and dimensioned according to the EUROCODE standards. This was the reason to establish an interdisciplinary working group (ON-K 256) at the Austrian Standards Institute (ASI), which has managed to developed comprehensive new technical standards for torrent control engineering, including load models, design, dimensioning and life cycle assessment of torrent control works (technical standard ONR 24800 – series).

Debris flow dams and breakers count among the torrent control works. According to the "classical" principles of torrent control (Aulitzky, 1980; Kettl, 1984), these structures have to be situated as close to the source of hazard as possible and should be designed for the predominant displacement process in order to gain the maximum efficiency (Rudolf-Miklau, Suda 2001). Torrents are per definition perennially or intermittently running water courses with steep slope, rapidly changing discharge and massive solid transport (debris, bedload, drift wood) at times. Extreme torrential events comprise four definable displacement processes (Iverson, 1997; Hübl, 2006; Marc o, 2007):

- floods;
- fluvial solid transport;
- hyper-concentrated solid transport (debris floods), and
- debris flow (stony debris flow or mud-earth flow).

According to Mazzorana et al. (2009) the sequence of a torrent event corresponds to a process chain that is triggered by heavy rain or snow thaw, inducing intensive surface runoff, accretive erosion and slope failures in the headwater area of the torrent catchment, transforming into displacement processes downstream and leading to the deposition of debris and drift wood on alluvial fans, flood plains or gravel bars. This paper is focused on the processes of debris floods and debris flow as well as the corresponding protection structures.

As a rule the design of torrential barriers has to follow their functions (Kettl, 1984). According to ONR 24800:2008 the functions of torrential barriers can be divided in the following functional types:

- stabilisation and consolidation;
- retention;
- dosing and filtering;

- energy dissipation.

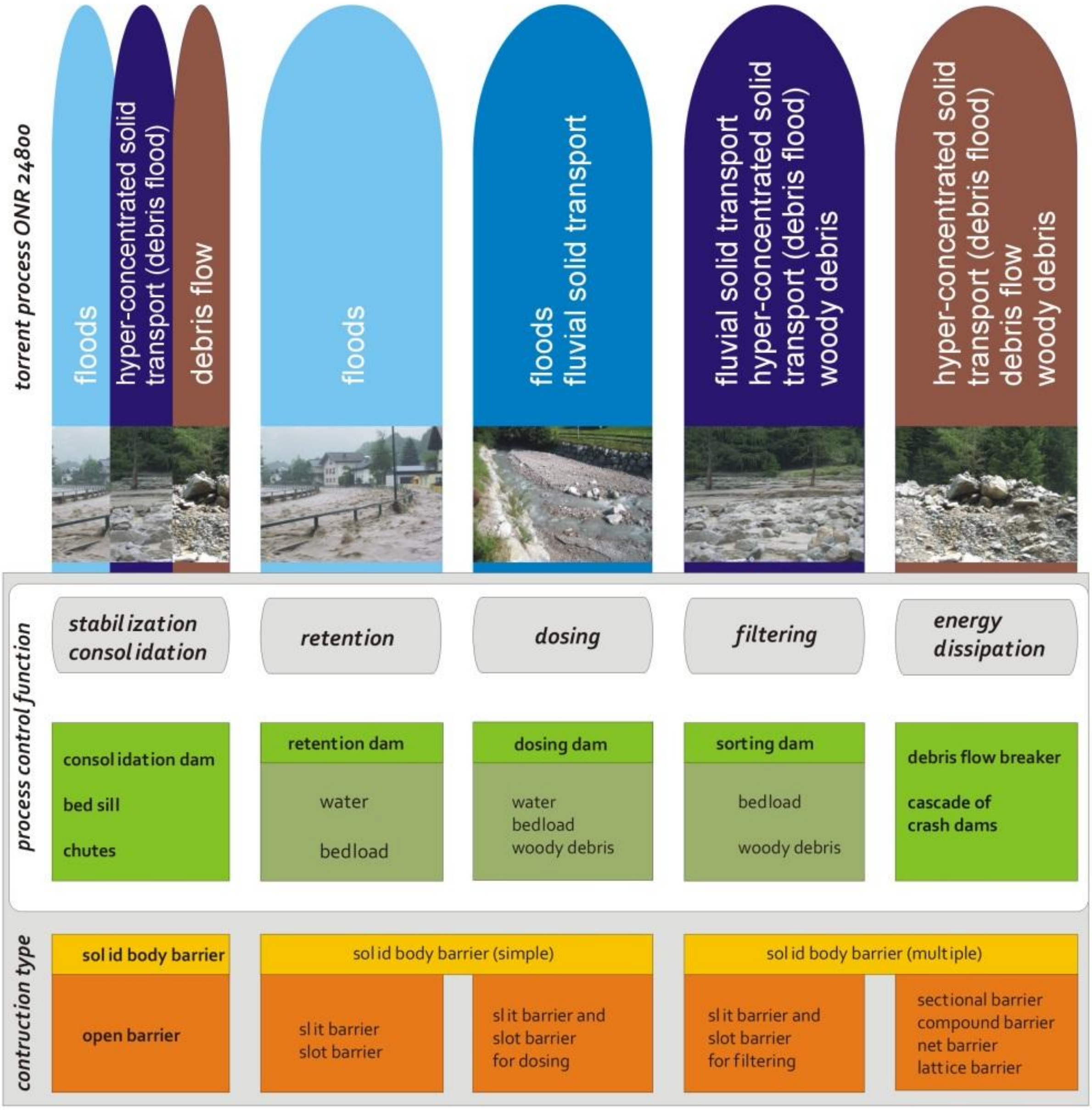


Figure 3: Torrent processes related to process control function and construction type (Moser, 2014)

Modern protection concepts in torrent control are scenario-oriented and try to optimize different functions in a chain of protections structures (function chain). For torrential displacement processes with high concentration of solids the following types of structures are applied (Suda & Rudolf-Miklau, 2010):

- barrier types for retention
- barrier types for dosing and filtering
- barrier types for energy dissipation

3.1.3.2 <u>Decision-making process of defining the protection concepts in torrent control</u>

One result from the WP 4 is the **definition of displacement processes for each torrent section**. This is more or less the first step to designing the optimal construction type. The criteria for each process (floods, fluvial solid transport, hyper-concentrated solid transport – debris flood, debris flow and woody debris) are defined in the technical standard ONR 24800 – series in Austria. According to ONR 24800 the functions of torrential barriers can be divided into **process control functional types** (stabilization/consolidation, retention; dosing and filtering; energy dissipation). Torrent control works include by definition all kinds of structures, which are realized in a torrent's catchment or stream bed, in order to stabilize the bed and adjacent slopes, to regulate the discharge of floods, to dose runoff and solid transport, to filter large components (blocks, drift wood), to dissipate the energy of debris flow or to deviate (by-pass) hazardous flow processes from objects or areas at risk (Bergmeister et al., 2009).

The last step is the **designing of the construction type**. Nevertheless, it has to be stressed that the final decision about torrent control measures must be consistent with respect to integral water management in the broader basin, a part of which is addressed in torrential catchments. This is especially important from the point of view of integral sediment management, realizing all the possibilities for sediment continuity option – if is it "desired".

The described decision-making process is transparently shown in the following 4 flow charts. From the perspective of following the 3 Guidelines (Chapters 4.2, 4.3, 4.4), particularly 4.2, this decision-making process is subordinate to the wider planning/design considerations described in Chapter 4.2. On the other hand, it presents the state of the art of managing possibilities, i.e. it is an essential tool for professional realization of professionally correct scenarios of flood protection regimes available today.

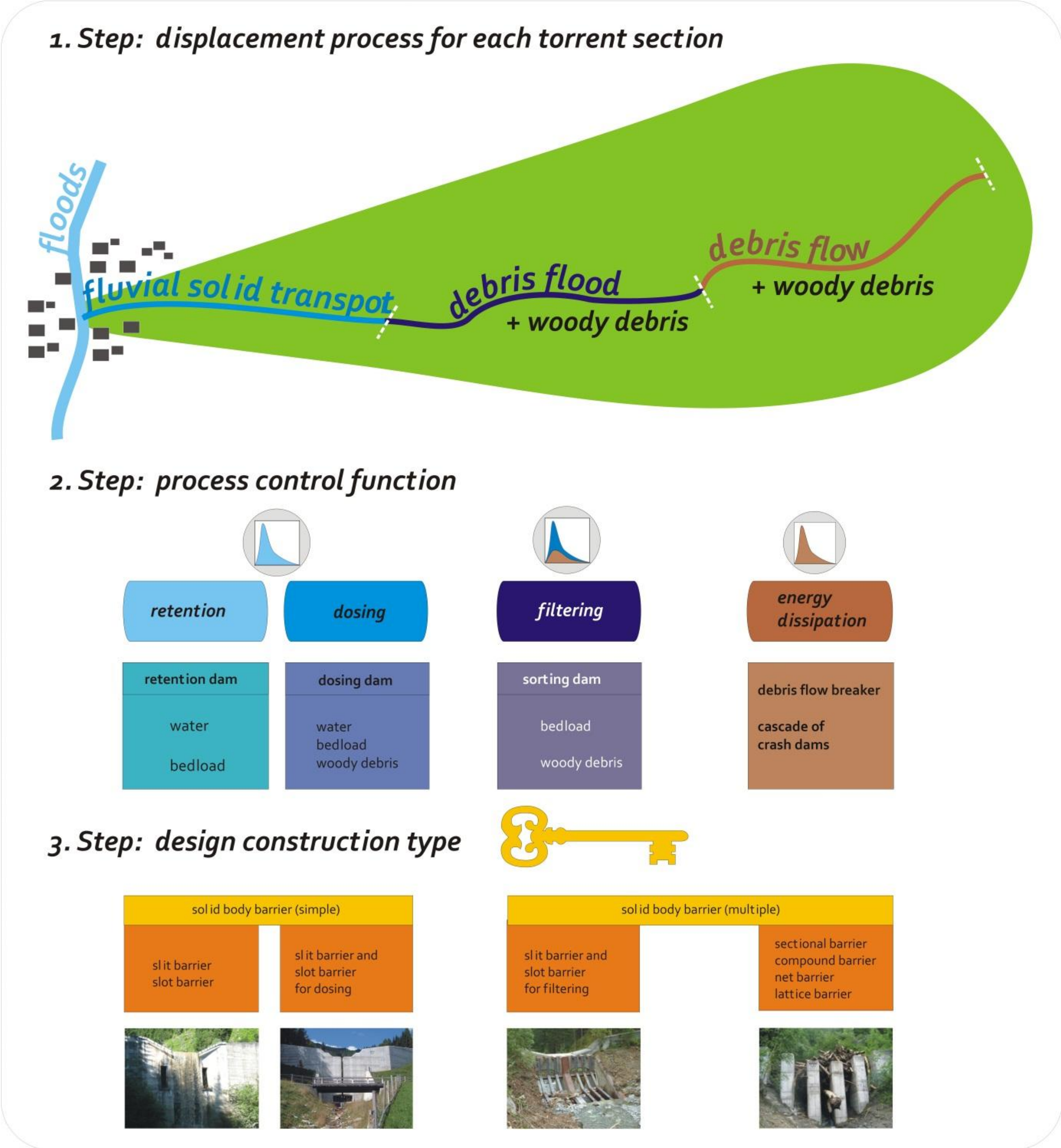


Figure 4: Three steps in designing the optimal construction type (Moser, 2014)

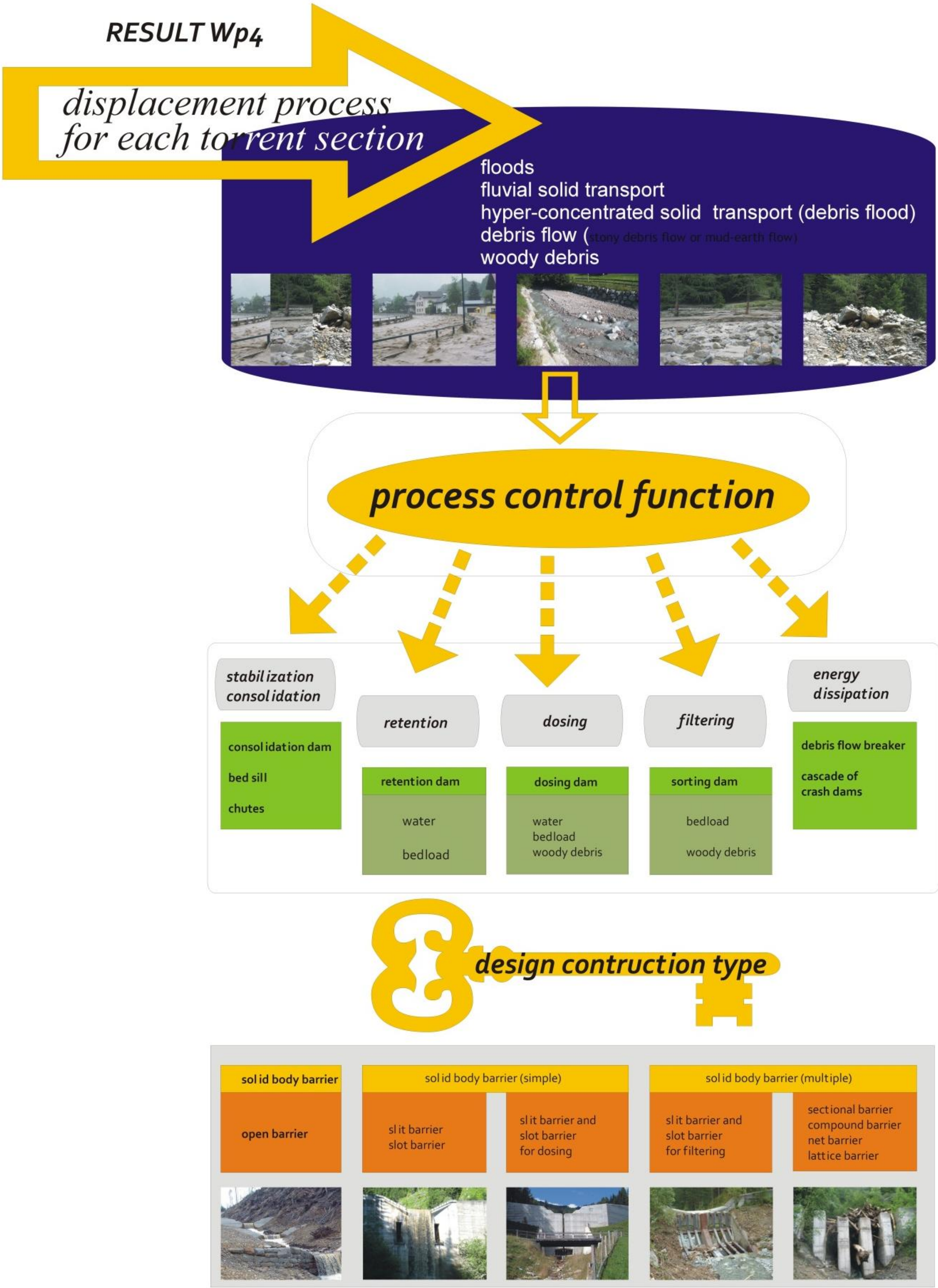


Figure 5: Displacement processes, established for each torrent section, are the basis for defining the needed process control functions, which present one of the main foundations for decision-making about the set/chain of adequate protection structures according to water and risk management goals (Moser, 2014)

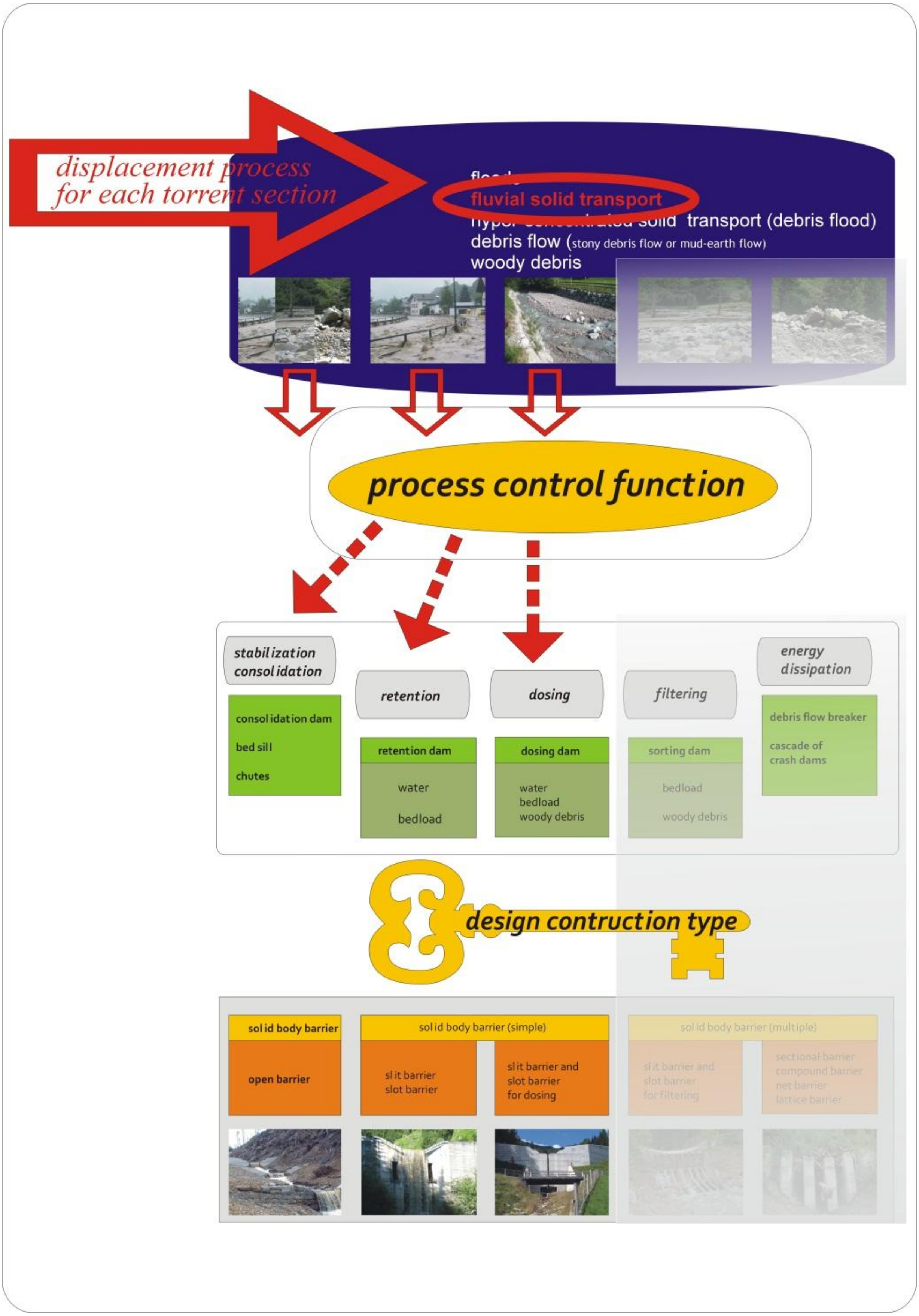


Figure 6: The appropriate process control functions for the torrent section with dominant fluvial solid transport are stabilisation/consolidation, retention and dosing (Moser, 2014)

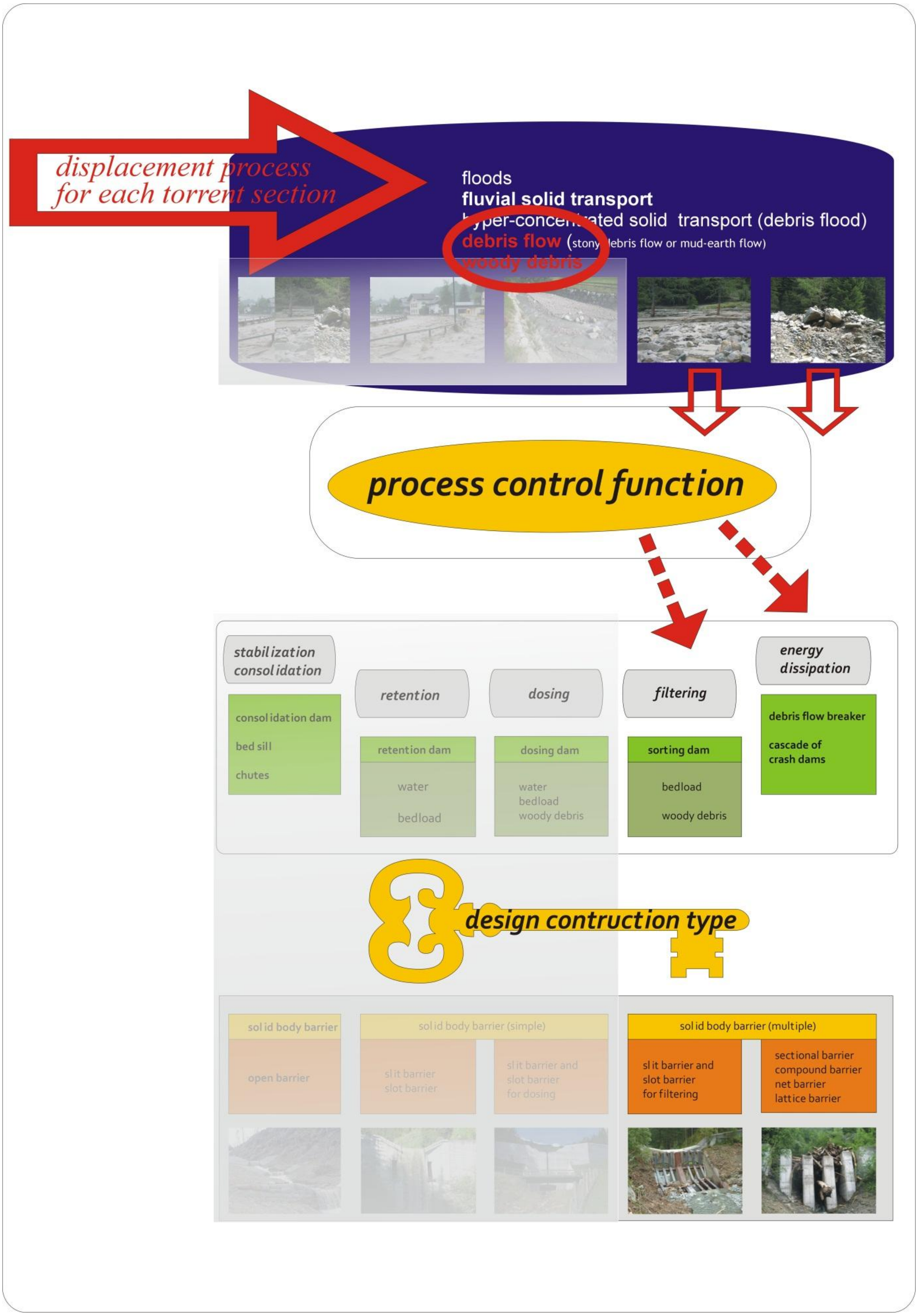
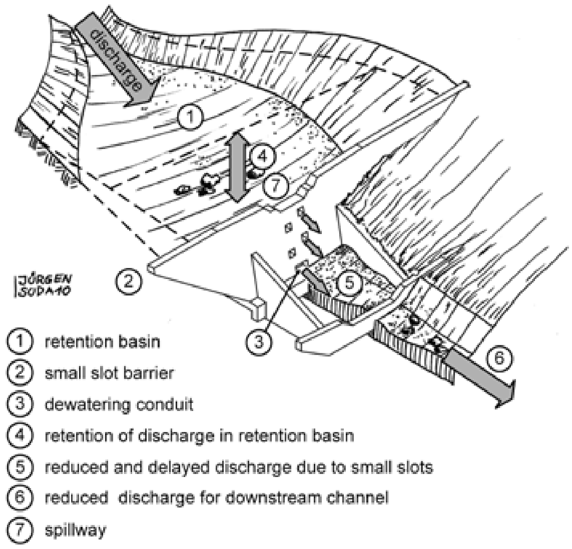


Figure 7: The appopriate process control functions for the torrent section with dominant debris flow and/or woody debris are filtering and energy dissipation (Moser, 2014)

3.1.3.3 Types of structures for torrential displacement processes with high concentration of solids

3.1.3.3.1 Barrier Types for Retention

The retention includes barriers that support the tailback of debris in natural or artificial reservoirs. The retention of debris is the storage of solids behind dams or in artificial basins. For retention small slot barriers are used. Retention of solids leads to a more or less permanent deposition of sediments. Regularly, the retained debris has to be excavated or spilled from the reservoir in order to keep the function effective. This concept is mainly applied if the torrent downstream has no sufficient transport capacity. This type of barrier function is inefficient if directly exposed to debris flow.



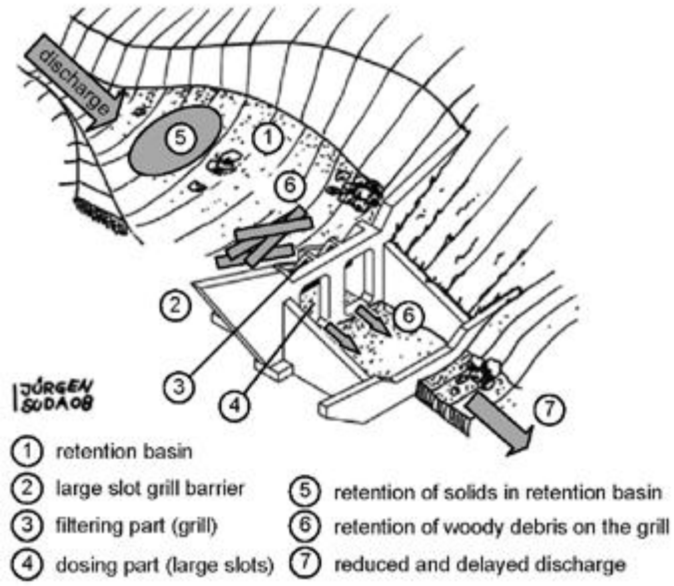
Schematic view of a small slot barrier for debris retention (Rudolf-Miklau, Suda 2011)

Slot barrier (Karthäusengraben, Salzburg, Austria)

Figure 8: Barrier types for retention (Moser, 2014)

3.1.3.3.2 Barrier Types for Dosing and Filtering

The dosing of debris means the temporary retention of coarse bedload during flood peak and the controlled spilling of sediments with descending flood discharge. The intermediate storage of the accumulated material is designed to balance hazard mitigation and a healthy riverine environment. The filtering includes all kind of barriers that serve the selective retention of coarse solid components like boulders or drift wood from the flow process. Filtering structures have to be designed in a way that fine grained bedload can drift through without being retained. The filtering should be limited to those solids that cause the clocking of bridges and narrows in the lower reach. As dosing/filtering barriers large slot grill barriers are used. This type of barriers controls the transport and deposition processes of sediment, boulders and woody debris.



Schematic view of a large slot grill barrier for dosing and filtering (Rudolf-Miklau, Suda 2011)

Large slot grill barrier for filtering (Leisnitzbach, Salzburg-Austria)

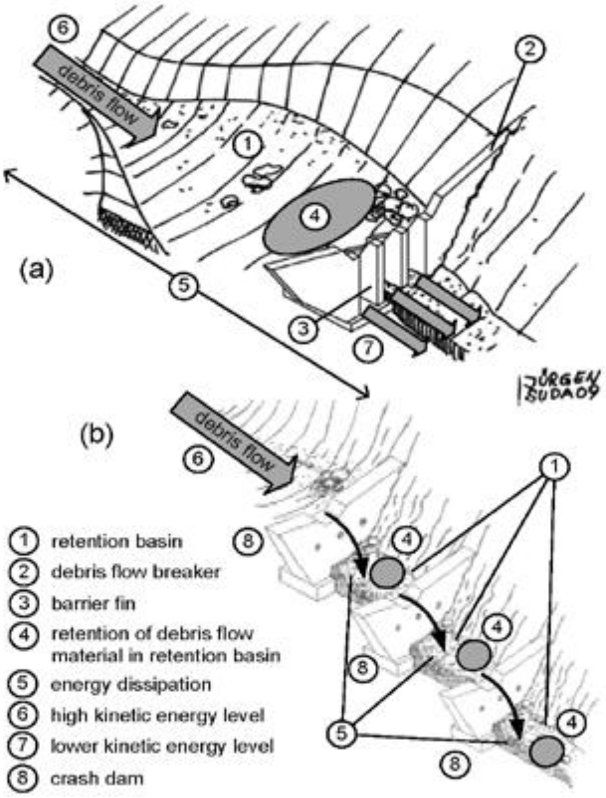
Figure 9: Barrier types for dosing and filtering (Moser, 2014)

3.1.3.3.3 Barrier Types for Energy Dissipation

Measures with energy dissipation are designed to reduce debris flow energy of debris flows (Kettl, 1984; Jenni & Reiterer, 2002). By slowing and depositing the surge front of the debris flow, downstream reaches of the stream channel and settlement areas are exposed to a considerably lower dynamic impact. The function of dissipation of debris flow energy can either be reached by retarding the flow process (breaking the surge front) or transforming the displacement process. The purpose is reached either by massive constructions that directly impact the debris flow process (“debris breaker”) or by dams that cause a fall and energy dissipation in the spilling pool (“crash dam”).

The function of debris breaker is reached in combination with a retention basin. The debris flow enters the retention basin and interacts with the dissipation structure. A part of the debris flow is deposited in the basin. Due to the lower inclination of the basin level and the flow resistance of the breaker the kinetic energy of the process will be reduced. Debris flow breakers are built with reinforced concrete and situated as an uppermost structure in a function chain. A combination of “debris breaker” with other function at the same barrier should be avoided. If one structure is not sufficient the function may be distributed among several consecutive debris breakers.

Crash dams are as a rule situated on the alluvial fan. If the function of process transformation cannot be reached by one dam only, a sequence of dams (cascade) may be carried out.



Schematic view of a large slot grill barrier for dosing and filtering (Rudolf-Miklau, Suda 2011)

debris flow breaker – Sectional barriers with fins (Kreuzgraben, Salzburg)

crash dams - compound barrier (Klemmgraben, Salzburg, Austria)

Figure 10: Barrier types for dosing and filtering (Moser, 2014)

3.1.4 Effectiveness of checkdams

In the context of an examination in Austria, 131 structures for bed load control were investigated in detail in geometry, function and mode of operation. The degree of function fulfilment is acquired by "debit – is" scenarios by means of analysis of debris input, deposition at the structure as well as debris output of every single barrier. The debit initial setting arises from the assumed design event with a return period of 100 to 150 years. The documented impacts of the last 20–30 years are compared to this to be able to show the possible differences in the function fulfilment. The function fulfilment degree is judged both with regard to quality (correlation of assumed transport process to the actual one) and quantity (correlation of mobilized and deposited debris volume). The analysis of data showed that function fulfilment was reached completely at 59%, partly at 36% and not at 5% of all taken events and structures, without consideration of the function type. Reasons for insufficient function fulfilment – considering self-acting emptying of retention basins, too – are found in one for the structures unsuitable function, in the woody debris difficulties, in the geological qualities of the debris as well as in an inadequate discharge. At increasing fine substance quota or increasing cohesion, the trend to rooms by mean discharges decreases rapidly. The indispensable consequence is machine clearing to maintain the protection effect of the barrier.

Given that due to the lack of experience, a self-acting emptying was just started for older buildings, the necessary driveways for artificial cleaning are no longer available. If the expensive opening is not possible, the function of the torrential barrier will be reduced to retention. Projects at the level of the technique stand out due to a permanent driveway possibility. This driveway should be passable also during an event, to remove possible woody debris jams as quickly as possible, to be able to maintain drifts of bedload through the barrier further on.

An emptying without support already is not practicable at numerous torrential barriers, because middle discharges, which are normally available, have a too low tractive force to erode a filler. This primarily occurs in dolomite creeks.

3.1.5 Effectiveness of barriers documented during events in Austria

3.1.5.1 Debris event on 29 July 2008

The flood event at the torrent Karthäusenbach/Salzburg on 29 July 2008 proves the effective reduction of the kinetic energy of the debris process by a combination of crash dams and water, and bedload storage in a retention basin downstream the crash dams (Moser 2008). A part of the debris flow was deposited in the basin. These crash dams are in combination with a slot barrier downstream.

Figure 11: Stored bedload and energy dissipation by a combination of crash dams (Moser, 2014)

Figure 12: Water and bedload storage in the retention basin downstream the crash dams (Moser, 2014)

3.1.5.2 Bedload event on 9 August 2014 (Moser et al. 2014)

The flood event at the torrent Leisnitzbach/Salzburg on 9 August 2014 shows the functionality of a self-acting emptying of a sectional inclined rake barrier. This event with drift wood generated a temporary storage of bedload behind the structure. The inclined structure remained free on the left side, so the bedload could pass the structure during the flatter flood hydrograph.

Figure 13: Sectional inclined rake barrier after the event with self-acting emptying (left), and machine cleared (right) (Moser, 2014)

3.1.5.3 Debris flow event on 1 August 2014

An example for declining the high energy level of a debris flow to a lower level (dissipation) by a combination of sectional barriers with fins is the debris flow event with drift wood at the torrent Klemmgraben/Salzburg on 1 August 2014. Here, the upper barriers declined the high energy level of a debris flow to a lower level whereas the lower sectional barrier filtrated the woody debris during the event.

Figure 14: Sectional barriers with fins – debris flow dissipation and filtration of woody debris during the event (Moser, 2014)

3.1.6 Check dams influence on sediment transport in steep slope stream

3.1.6.1 General context

Urbanized areas and facilities have increased a great deal during the last decades in the European mountains. Numerous villages and infrastructures are situated in valley bottom and on fans. These areas are regularly threatened and flooded by torrents. Torrent related hazard mitigation has been developed and theorized for more than a century (Fabre, 1797; Gras, 1850; Surel, 1870; Thiéry, 1891; Demontzey, 1894).

Grade control structures (check dams and bed sills) belong to the various technics used by engineers in torrent control works, in addition to plantations, bank protections, dykes, sediment traps, etc. (Van Effenterre, 1982).

Substantial research has been carried out on design criteria and a large literature exists on subject like toe scouring, civil engineering design and equilibrium slope [e.g. Porto and Gessler, 1999; Gaudio et al., 2000; Lenzi et al., 2003a, 2003b; Osanai et al., 2010; Rudolf-Miklau and Suda, 2013).

On the other hand, hydraulics and sediment transport in steep slope streams are still active fields of research (e.g. Comiti et al., 2007; Rickenmann and Recking, 2011; Nitsche et al., 2012; Yager et al., 2012; Heyman et al., 2013).

However, despite a long field experience of practitioners and structures existing for more than a century, it is not yet clear how grade control structures affect sediment transport at different time scale (from instantaneous to long term). To study this point, small scale flume tests were undertaken at the Grenoble IRSTEA Laboratory. Here we present some preliminary results.

3.1.6.2 Experimental SETUP

A 4.8-m-long, 0.107-m-wide, 0.4-m-deep and 12%-steep tilting flume was used. The sediment mixture consisted in natural poorly sorted sediments. Water and sediment discharges were set constant to feed the flume with a solid concentration of about 4%. The bed slopes S_i and the outlet solid discharge Qs were regularly measured (as illustrated on Figure 15).

Three different setups were tested: a reference test without grade control structure and two tests with one and three grade control structures. More details can be found in (Piton and Recking, 2014a, 2014b, 2014c).

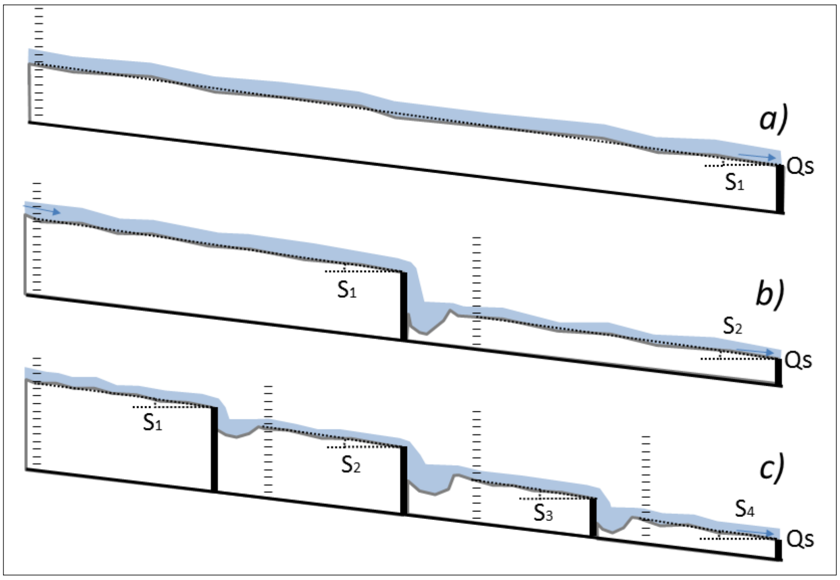


Figure 15: Sketches of the different setup: a) Ref Test; b) 1GCS Test; c) 3 GCS Test

3.1.6.3 <u>RESULTS</u>

As both feeding rates did not present variation, changes in outlet solid discharge were assumed to be due to bed variations in the bed storage. These phenomena are mainly controlled by grain size sorting. We observed strong fluctuations of solid flux and slope in each reaches of all runs between: (i) steep aggradating armoured bed and (ii) milder and finer bed releasing bedload sheets during erosion events and inducing bedload pulses. Bed states are illustrated in Figures 16 a) & b). Fields observations let us think that similar strong grain size sorting effects are observed in active torrents as illustrated in Figure 16) c) & d).

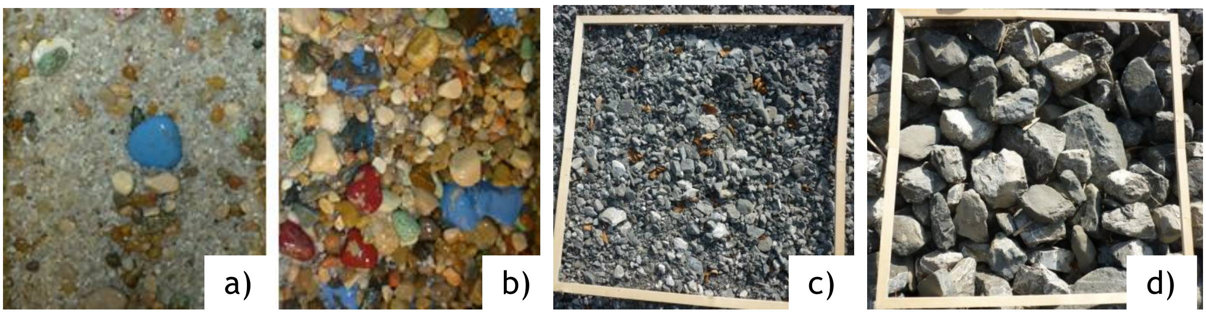


Figure 16: Extreme bed state, in the flume : a) fine bed in erosion, b) coarse armoured bed in aggradation; in the field : c) Manival Torrent (French Alps): fine bed on a gravel sheet, d) coarser bed on a reach in aggradation

This dynamic equilibrium with constant aggradation and erosion events is considered to induce a temporal storage of sediment in the stream bed. This concept was presented by (Jaeggi, 1992) as illustrated in Figure 17.

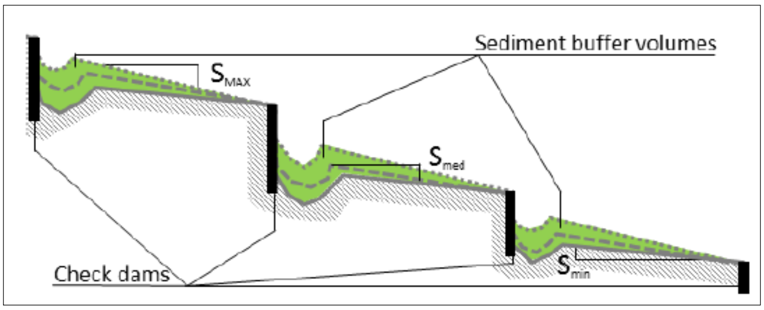


Figure 17: Illustration of the buffer volumes induced by check dams construction and reaching slope dynamic equilibrium (adapted from (Jaeggi, 1992) in (Piton and Recking, 2014b))

These fluctuations of the slope and temporal sediment storage are reported to happen in the field by numerous practitioners in France. They were also observed during the SedAlp project by IRSTEA in the WP5 (see Figure 18).

Figure 18: Field observation of temporal sediment storage upstream check dam (upstream dam highlighted in yellow): left – eroded reach; right – reach in aggradation storing sediment (photo from Coraline BEL – PP7 IRSTEA)

In the flume, these fluctuations occur with and without check dams. However all experiments showed consistent results: **transported volume** associated with erosion events **decreased with the length between two subsequent check dams**. Solid transversal structures shorten the backward propagation of the erosion and prevent downstream change in the bed level at the check dam crest (creation of fixed point in the stream bed level). As long as they are not buried by too strong aggradation, check dams allow a "bed level independence" between reaches.

In our experiment, check dam do not influence sediment supply. The structures are considered to be built in the transfer channel downstream sediment production areas. In these reaches, on the long term, as the total inlet flux is kept constant, a decrease in transported volumes induces an increase in the erosion event frequency: sediment releases are more frequent but littler. As proposed by (Poncet, 1995), check dams participate efficiently in hazard mitigation **because "*they release in retail what torrents would too abruptly delivered wholesale*".**

Further research on hydrology influences has to be undertaken to confirm the possible extrapolation of our results, especially to study effects of high floods inducing equal mobility and variation of water and sediment supplies.

3.1.7 Analysis of the protection work system on the Maira river

3.1.7.1 Introduction

The analysed stretch of the Maira River that goes from the sources in the municipality of Acceglio to Dronero has no continuous protection structures, unless in well situated areas.

Taking a general overview of the mountain basin, there are no particularly artificialized stretches, except for the town of Acceglio and Chiappera.

Therefore, excluding Acceglio and Chiappera and regarding longitudinal structures, there are no dikes except for some sporadic areas in Prazzo. Anti-erosion structures are rare and are often bridges and diversion works. These are mainly dry rock barriers from several decades ago.

Wires in the mountain basin are practically all for hydroelectric purposes. There are three of them that draw water by using very important transverse structures:

- in Acceglio in the small town of Granpianusso, serving the ENEL power station. It is a dam with two 4 m high sluice gates, which close directly on the visible bed paving downstream. Also upstream, the dam is 4 m high;
- at Ponte Marmora in the town of Marmora, serving the ENEL reservoir that also collects turbined water from the power station on the right bank at the confluence with Rio Marmora;
- in Dronero, immediately downstream of the bridge for the Tetti hamlet. The structure is no longer in use, therefore the water is not diverted;
- also in Dronero, immediately upstream of the town, there is a large dam that diverts the water for farming and hydroelectrical purposes.

Two dams are present in Acceglio and in San Damiano Macra. One other dam is present in the Combamala valley, but is not used now.

There are many transverse structures on the Maira, upstream of Acceglio. They are check dams with the purpose of stabilising the bottom of the left slope, affected by landslide movement.

Numerous other check dams with the purpose of stabilising the slopes and containing the transported liquid material have been built on the tributaries, particularly on the Rio Mollasco and the Rio Marmora.

Overall, the works present on the mountain basin of the Maira may be schematically summarised as follows:

Table 2: Protection works on the mountain basin of the Maira

bank protection (walls, rock barriers, gabions)	7000 m
dikes	1200 m
check dams	58
sills	40
groynes	25
bed paving	373 m
bridges	67

Following is a description of the defence works with the division into homogeneous stretches resulting from geomorphological analysis carried out to assess the Morphological Quality Index (MQI) according to the method proposed by ISPRA.

Detailed description of each stretch

3.1.7.2 Stretches Maurin and T0

The top stretch of the Maira currently has a sluice that conveys the diverted water to the recent underground unit located on the right slope of the valley. Apart from the crossings, there are no other important structures. The first we come across are in Chiappera, where the Maurin flows through the town: there are three crossings and walls to protect the continuous banks. The section is completely artificialized. A short rock barrier near to where the hydroelectric power station discharges downstream from Chiappera is the only works apart from the bridges before the Saretto dam.

The dam is defined by an earth barrier covered in clay on the reservoir side, which is covered with a protective layer of Reno mattresses and bituminous conglomerate.

From where the dam discharges in Saretto (beginning of T0 strech), the Maurin changes its name into Maira and changes its behaviour, as its flow is regulated by the dam and it has no significant tributaries.

The Maira flows freely without any structures except for the main road crossings, to the town of Ponte Maira. Anti-erosion walls have been built here on the left and right slopes downstream of the bridge and also some concrete sills to stop the riverbed bottom from sinking.

A little further downstream there are 4 important stabilising check dams. They were built to ensure, due to the slope change and the formation of sediment beds, the stability of the left slope affected by landslide movement. All of the check dams are in good condition and their construction goes back to the late sixties.

Figure 19: Maria River – stabilising check dams

Some bank protections on the left and right of the Maira, concerning the river near to the confluence with the Rio Mollasco. They are old non-continuous concrete walls.

3.1.7.3 Stretch 1

In this stretch, there are works in the concentric of Acceglio. They are continuous longitudinal structures, protected by a rather dense series of sills (20 elements).

The structures are mainly walls, but there are also two quarried rock barriers filled with concrete.

The water flow of the Maira to Acceglio is therefore completely artificialized and the works make up a single protection system.

The erosion tendency of the Maira is highlighted by the protection structure on the left bank at Gran Pianusso, which protects the main road. It is a rock barrier followed by a wall, which is further protected from erosion by a series of gabion groynes. They are not recent structures.

There are sporadic structures on both banks as far as the dam of the power station in Acceglio, situated further upstream from the municipal border of Prazzo. The diversion is for hydroelectric purposes. The dam does not have a fish ladder for the ichyofauna and can divert a yearly average capacity of 0.65 m3/s with a maximum of 1150 m3/s.

From the presence of sediment both up and downstream (including dead wood), it is deduced that the sluice gates are raised periodically and the sediment is drained.

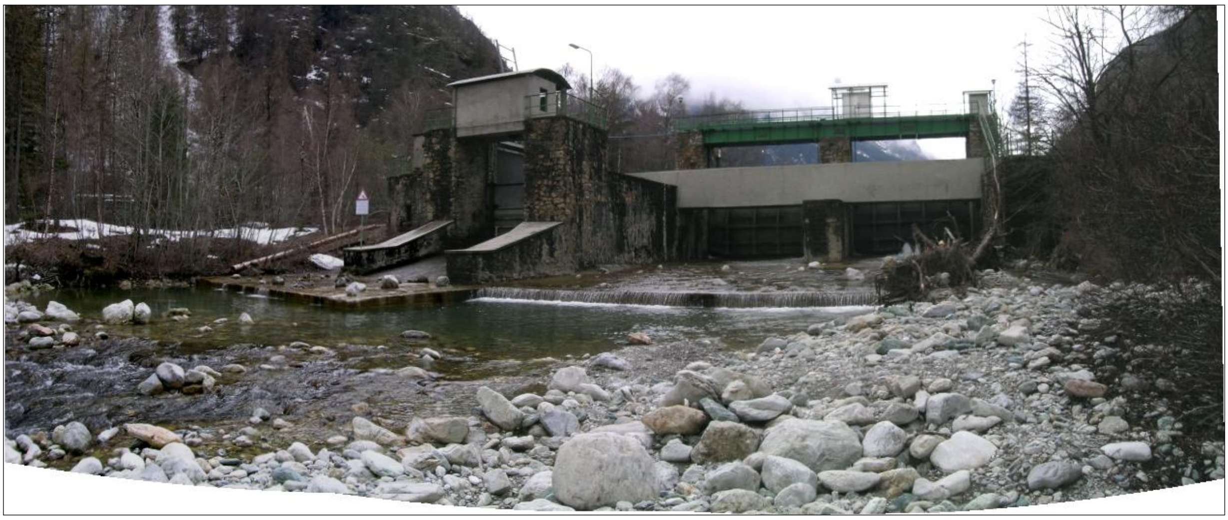


Figure 20: Maria River – dam of the power station in Acceglio

3.1.7.4 Stretch 2

Between Maddalena and Prazzo, the Maira flows in a section contained between the two sides. Two check dams are present at the beginning of the stretch, characterised by a consistent height, each one having a counter dam (for the SICOD survey there are 4 check dams). They are concrete retaining dams whose height varies from 6 to 12 m. The counter dam of the downstream check dam is completely siphoned. The larger check dams are filled with sediment.

Figure 21: Maria River – check dam

There is a large quantity of sediment upstream from the hamlet of Maddalena di Prazzo. The Maira flows, bordered by the road and the right slope, with a minimum width of approximately 15 m. As in the previous stretch, there is a vegetated strip covered with young birch trees.

Other works present are sporadic protection structures of bridges and isolated stretches of dikes on the left bank below Prazzo.

There is a higher level of works at Ponte Marmora, where the Rio Marmora flows into the Maira. Here are the traces of two old crossings and a series of gabion groynes, still connected to the river but no longer efficient, as well as several bank protections on both the right and left.

The flow of the Rio Marmora into the Maira is partially artificialized by the presence of paving to serve the discharge of the hydroelectric power station, located to the right. No consistent signs of sediment from the Rio Marmora are recorded.

There is a reservoir immediately downstream of the confluence with the Rio Marmora on the right side of the Maira, which feeds through a weir accompanied by a structure that houses mechanical diversion apparatus. The reservoir also collects the turbines water from

the power station.

Figure 22: Maria River - the weir

At this point, the Maira has a width of 25 m. The weir is a reinforced concrete structure that creates a drop of 2 m downstream and a small dam upstream of just 50 cm. Sediment can transit during ordinary floods over the structure as is well demonstrated by the bed on the left bank downstream and by the consistent presence of sediment in the following stretch. Metric-sized boulders can be seen.

Figure 23: Maria River – eroded gabions

Downstream from the dam are defence works of the conduit that conveys water from the reservoir toward San Damiano: they are eroding.

3.1.7.5 Stretch 3

After Ponte Marmora, the Maira proceeds its flow embedded between the left and right slopes. No works are present except for small protection structures behind the bridges, all with a single span that connects the main road to the other slope of the valley, towards isolated small villages perched on the river terrace.

Figure 24: Maria River – eroded gabions

Only one bridge has a stabilising sill downstream, which leads to the hamlet of Villette just before Macra. The stream of Celle flows into this stretch, which does not give any significant contributions to solid transport.

Figure 25: San Damiano Macra

Defence works can be found and several isolated dikes at San Damiano Macra, where there is a dam with mechanical parts for hydroelectric purposes.

The dam has a slide covered with stone blocks on which four mechanical sluice gates are positioned at a total height of approximately 12 m. The dam closes a 40 m section, while the lake upstream reaches a width of 60 m.

A partly eroded bed paving is present downstream from the dam with bank protections that cover the riverbed bottom for 47 m.

Throughout this long route the Maira moves sinuously between sediment beds and dead wood that are still present from the avalanches of the 2008/2009 winter. The pebbles get smaller in size as you get closer to the dam.

Figure 26: Maria River – damaged bridge

There are nine bridges, all with a single span. The bridge that connects the hamlet of Bassura di Stroppo with the right bank has two spans; it has, however, structural damage.

The bridge for the hamlet of Garino was also damaged after the flood of 2008 but has been replaced by a new single span structure.

3.1.7.6 Stretch 4

The dike wall must be noted on the left bank to protect the homes alongside the river, in Cartignano, just downstream of the bridge.

There are no other structures. The artefact that accesses the right bank, therefore at the concentric of Cartignano, has an eroded central part.

Here the Maira flows still quite embedded, even if the section starts to widen.

At the hamlet of Tetti di Dronero, an arched bridge that is very high over the river, connects the two banks and allows the weir, which is immediately downstream, to be reached. Going down towards the weir it is possible to see the conglomerate walls on the right.

Figure 27: Maria River – the weir

The weir is currently not in use but its structure is still fully functional. It is the structure destined to supply the Marchisa canal, which is now supplied by turbined water from the power station in Dronero.

3.1.7.7 Stretch 5

This stretch starts immediately upstream from the concentric of Dronero, at an important weir.

The length of the body of the weir, transversal to the current, is 20 m, with a height downstream of 4 m. The step created upstream is around 2 m. Sediment with a particle size that does not exceed 50 cm can pass through the weir. The structure diverts water for both hydroelectricity and farming for a total of average yearly-diverted capacity of nearly 4 m3/s.

Figure 28: Maria River – weir

Figure 29: Maria River – Dronero

The concentric of Dronero has few bank protections that are not continuous and are limited to crossings and a series of small intake and outlet works along the right bank.

On the same bank, there are several recently restored concrete groynes. The erosive action on the rigid structures had, in fact, caused the body of the groynes to collapse.

3.1.8 Concept of torrent control in the Bistričica torrent (Slovenia)

In the Slovenian SedAlp test bed, the Bistričica torrent catchment, detailed field measurements and analysis of interactions between torrent control structures and torrential sediments were performed with the intention to confirm, or develop, improved concepts of responses of such structures to floods and debris flows. The main activities were:

- Assessment of functioning, effectiveness and eventual shortcomings of comprehensive torrent control works, implemented after the 1990 catastrophic event
- Assessment and improvement of the supervision process and maintenance measures
- Expert justification of eventually needed upgrading of the existing torrential control measures' concept

The main input was a process-oriented functional analysis of the torrent catchment with regard to slope and channel processes in WP4, the results of historical analyses of catchment's response to several flood events, the changing natural conditions in the last 75 years in WP4, and the established set of data of sediment transport gained during the work in WP5 (monitoring of the retention basin of the key barrier).

3.1.8.1 Bistričica torrent catchment

The Bistričica river originates in the Kamnik-Savinja Alps, more specifically, in the south-eastern slope of Krvavec, under the Križišče (1658 m). From its source the river flows along the valley of the same name to Stahovica (430 m) where it flows as a right tributary into the torrential Kamniška Bistrica river. According to the type of the stream it is a typical torrent. The catchment area is mostly steep and morphologically highly diverse. Most of the catchment area is oriented towards the south, southeast and southwest. In this latter direction the left slope is oriented, covering 3/4 of the total catchment area. The catchment (11.5 km2) has an elongated shape, approximately 5.75 km long and about 2 km wide with Q100 =51.22 m3/s. The average channel inclination of the upper part is within a range of 14% to 23%, in the middle part 6.3–8.9%, and in the lower part 5.3–6.8%. According to the terrain slope, the area is considered as highlands. The surrounding areas consist of forest (about 1/2 of the surface), meadows, fields and pastures (1/2 surface). The share of settlement (water-impermeable) surfaces is marginal, but they are largely located (as also road) directly near the torrential bed. In the Bistričica valley, there is characteristic alpine climate vegetation. Beech, hornbeam, spruce and pine (Fagus, Carpinus, Picea and Pinus silvestris, respectively) prevail, mixed with other tree species, of which the most frequent are: fir (Abies), sporadic larch (Larix), junipers (iuniperus, communis), mountain ash (Fraxinus excelsior), Acer platanoides (Acer platanoides) and oak (Quercus).

The bottom of the approximately 400-m wide main valley of the Bistričica is covered with a thick layer of glacial and partly slope, alluvial gravel and gravel. The layer thickness is 5 to 6 m in the lower and middle parts, and 50 m in the upper part. The layer of the main watercourse with its tributaries is greatly eroded and corroded, and is therefore a major source of sediment, which the Bistričica eroded and transported downstream along the riverbed.

This is demonstrated by a cross-section of the channel above Slatna with river terraces, which testify to the subsidence layers of gravel. The silting and sliding of the valley floor in the bed of Bistričica is supported by many springs percolating at the foot of the steep rocky slopes on the left, in the gravel, which flow into the main channel. We assume that there is groundwater on the clay layer. Strong erosion of the stream is shown in the upper part of the channel, from Klemenčevo or Slatna upstream, where approximately 1 km2 of landslide slopes are located. Based on the cross-section of the main valleys we assumed that the thickness of the gravel layer is from 20 to 30 m (or more). According to the length, the amount of instable incoherent material is estimated at least 20 million m3. The gravel layer that covers the bottom of the Bistričica valley and, as such, does not offer resistance to erosive and corrosive functioning of the watercourse, and is also a source of sediment, is one among the factors adversely affecting the catchment area, especially the steep rocky slopes of dolomite and limestone surrounding the valley.

The torrential area has a distinctly alpine climate with hot summers and cold, harsh winters. South winds prevail, indirectly causing abundant, orographic rainfall and strong thunderstorms, often with hail. The average annual rainfall for the Bistričica was estimated at about 1850 mm. It is determined on the basis of data recording raingauges Cerklje, Kamnik, and Krvavec. Since it is exposed to the south, southeast and southwest, it is exposed to intense solar radiation alternating with cold, causing intensive decomposition and weathering of dolomite and limestone rocks.

3.1.8.2 Torrent control regulation after the catastrophic event in November 1990

In the territory of the Bistričica torrent catchment in the past there were two catastrophic events (debris flow), i.e. in 1933 and 1990. After the 1990 debris flow event the torrential channel from the Klemenčevo hamlet to Županje fields was completely devastated in approx. 70% of its length, as well as roads, electricity and water supply. Four bridges were destroyed, residential and agricultural structures were damaged and partly buried by sediment, large areas of agricultural land were carried away or buried. In the hinterland of the Blatnica and some tributaries, several landslips, and major or minor landslides were triggered, one of which was particularly large. The small number of existing torrential facilities generally worked effectively (especially the main old retention barrier from 1940, whose retention basin was buried to the top and largely stopped the massive sediment transport). Most of check dams and bank protections were damaged or swept away as well as the greater part of the natural vegetation from the banks.

After the event in 1990, many additional protection structures were built: 1425 m of longitudinal structures (the situation before 1990 – 518 m), 50 sills (before 1990 – 12 sills) and 3 dams (before 1990 – 5 dams). The designed measures were planned to maximize the ecological acceptability. Indeed, today's appearance of the series of consolidation check dams (sills), because of their rustic performance, irregular toppings and pools, is completely natural looking and for the uninformed observer it is hard to recognize them as man-made structures.

In 2011 five additional larger consolidation protection check dams were built in the upper part above the retention dam to support the landslide-prone area under the local road.

Figure 30: Devastating consequences after the catastrophic event in November 1990

	before 1990	after 1990
Longitudinal structures [m]	518	2043
Sills (Nr.)	12	67
Dams (Nr.)	5	8

Figure 31: Extensive regulatory torrential works were carried out during 1991–1993

The current status of the torrential control system was critically assessed based on the event documentation from the last 10 years (events in 2007, 2010, 2012) analysed by a team of experts (including experts with long experience of monitoring the situation and planning, and implementation of measures in this catchment area). The inputs were: reports elaborated by river supervisors, historical photos, design and documentation about maintenance, intervention and restoration works.

The lower and medium parts:

- Extensive restoration and consolidation of the lower and medium parts after the extreme 1990 event seem appropriate – 50 additional sills and longitudinal protection

structures properly stabilize the grade level of stream as well as river embankments and the stream itself. Practically no vertical erosion is possible.
- In the case of the Bistričica torrent there are no known negative influences on the recipient river (Kamniška Bistrica) regarding minimizing sediment transport in the last 25 years to the mouth of the torrent (which does not have a typical torrential alluvial fan). The influx of sediments from the upper part of Kamniška Bistrica is larger than its sediment transport potential, which leads to regular removal of sediments from the sediment bar upstream of the confluence with the Bistričica.

Upper part:

- During normal conditions, the main sediment retention dam functions properly (with positive effects on flood safety downstream).
- The retention of sediments does not have negative impacts on the stream, because of systematic stabilization of the torrential bed and many small "erosion-prone areas" along the channel.
- It is necessary to take into consideration the situation in 2007 (long lasting events with large sediment transport). It is possible that this scenario repeats -> full sediment retention basin caused the transporting of a large amount of bedload downstream -> critical consequences for the settled areas -> the main critical points are bridges and stream sections with lower inclination – an additional system of 5 check dams mitigated this gap.
- 5 additional consolidation check dams, built in 2011, at the beginning of the upper part successfully prevent land sliding and vertical erosion – it functions properly.


Figure 32: One of the critical locations – No. 3; left: usual state, right: during the 2007 event (full of sediment; the retention basin of the upper main retention barrier was full)

3.1.8.3 Scenario-oriented assessment of torrent protection concepts

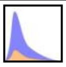
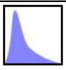
Based on the results of the analyses in WP4 and WP5 – extensive hazard potential in head waters (large potential for releasing a huge amount of sediment during one event); intensification and occurrence of different adverse erosion phenomena in the upper part of torrent could cause a "chain reaction" with the final, most destructive torrential outbreak – debris flow; this could cause a similar event like the one in 1990 – the current protection structures could mitigate the potentially devastating consequences, but the existing damage potential is very high. Suggestions for maintenance and improvements:

- Preparation of a draft concept of refurbishment of the existing sediment storage dam (greater volume of reservoir basin – managing bigger events)
- Preparation of a draft concept of setting selective debris flow protection barrier(s) under the extensively eroded and unstable upper part (as protection in the case of the aforementioned extreme event); under normal conditions this energy dissipation and filtering must have only limited influence on sediment transport. They have to allow for transport of fine dolomite sediments which will be also in the future deposited in

the main retention basin provided that the maintenance condition are excellent; normally deposited sediments are also useful for building purposes, flood and erosion protection works, or for the needs of the local community and individuals.

Table 3: Scenario-oriented assessment of torrent protection concepts in the Bistričica torrent

	Situation before the torrent control measures in 1990 Scenario 0 ("extreme" events)			
	displacement processes	process control functional types	construction type and design: status	construction type and design: *remarks*
Upper part	debris flow + woody debris	energy dissipation filtering	☹	*only one solid retention dam (6,000 m3)*
Middle part	debris flood* + woody debris	energy dissipation filtering, retention	☹	*only few consolidation check dams and bank protection*
Lower part	fluvial solid transport	stabilisation, consolidation	😐	
	Situation after the implemented torrent control measures in 1993: Scenario 1 ("normal" events + no additional protection structures)			
	displacement processes	process control functional types	construction type and design: status	construction type and design: *remarks*
Upper part	debris flood + woody debris	energy dissip. filtering	😐	*existing cascade of crash dams and the retention dam have a limited functionality in the case of long lasting events (retention volume)*
Middle part	debris flood* fluvial solid transport	Consolid. retention, dosing	😐	
Lower part	fluvial solid transport floods	stabilisation, consolidation	☺	
	Situation after the implemented torrent control measures in 1993: Scenario 2 ("extreme" events + no additional protection structures)			
	displacement processes	process control functional types	construction type and design: status	construction type and design: *remarks*
Upper part	debris flow, debris flow + woody debris	energy dissipation filtering	☹	*existing cascade of crash dams and the retention dam have a limited functionality in the case of long lasting events (retention volume) no filtering objects*
Middle part	debris flood* + wood fluvial solid transport	consolidation retention, dosing	😐	
Lower part	fluvial solid transport floods	stabilisation, consolidation	😐	
	Situation after the torrent control measures in 1993: Scenario 3 ("extreme" events + additional protection structures)			
	displacement processes	process control functional types	construction type and design: Status **	construction type and design: design & implemented construction types
Upper part	Debris flow + woody debris	energy dissipation	☺	debris flow breakers ***, cascade of

		filtering		crash dams
Middle part	Debris flood* Fluvial solid transport 	consolidation retention, dosing	☺	consolidation dosing or filtering dam
Lower part	Fluvial solid transport Floods 	stabilisation, consolidation	☺	consolidation dam

* hyper-concentrated solid transport; ** some level of residual risk will always remain!; *** the alternative is a very extensive regulation of the channel and erosion-prone areas in the headwater area using the systems of consolidation check dams, landslide stabilisation and anti-erosion soil bioengineering measures.

3.1.9 Maintenance of torrent protection structures

3.1.9.1 Importance of regular maintenance

Integrated water management begins in torrent catchments. Bedload transport control is successfully carried out by correctly positioned and designed consolidation and retention structures. These structures are generally integrated in a system and, therefore, their functions are interactively supplementing. Damaged structures and structures that are not maintained regularly do not protect, but offer a deceptive impression of security. In case of their destruction, the consequences may be even worse than if there were no protective structures at all. It is therefore essential that they are well and regularly maintained.

The state of water infrastructure is estimated based on the findings of river control and planning services (method: expert assessment, product: the report about the status quo with a proposal for maintenance or reconstructions works), which conduct regular field patrols and operate water infrastructure facilities.

In accordance with the findings of internal databases on the current situation and the degree of regulating of analysing the hydro system and catchment areas, which are managed/regulated by each concessionaire and the central government databases, each year ARSO and the concessionaire prepare an annual plan of minor maintenance work; in accordance with the established priority (expert assessment) and the available resources the annual plan includes the protection structures and watercourse sections planned for maintenance. Based on the available funds for major (i.e. investment) maintenance, the concessionaires have to prepare design documentation for major maintenance work.

For minor maintenance work the available resources are shared based on a predefined key (based on integrated data on the number of facilities, diversification of the hydrographic network, etc.) between the 8 administrative areas. This key has not changed in recent 30 years. For major maintenance works, the available resources are shared equally by the region and by additional interventional needs (for example: the observed damages on a large flood/accumulation dam). The funds provided for the rehabilitation/reconstruction work are divided into percentages of identified damage in individual areas.

3.1.9.2 Annual technical maintenance documentation – Removal of bed load deposits from sediment retention dams

Cleaning or emptying of facilities is carried out based on programs to clean sediment, which are based on geodetic measurements of the retention space. The programs specify the range and depth of extraction, the admissible amount of collected material, restrictions and conditions of performance, and the conditions for removal and deposit of the material. The main characteristic of the annual technical maintenance documentation Removal of Bed Load Deposits from Sediment Retention Dams are the following:

- It is produced in accordance with paragraph 3 of Article 72 of the Waters Act
- It is based on field surveys and the register of sediment retention dams
- The main goal of sediment abstraction from a retention area is to maintain the full functionality of retention dams and prevention of flood hazards
- It consists of general pages, a technical report, the recapitulation, and the general maps of each concerned retention dam
- If restoration works have to be done, technical documentation with drawings is attached

The improved 2014 version already includes the findings developed under the SedAlp project:

- A new version of the register of sediment retention dams (additional attribute data)
- A new methodology of a more optimal definition of priorities for maintenance (because of the lack of maintenance funds it is not possible to execute all the needed maintenance works each year)

The retention structures are classified into classes A, B, C and D. The description of the classes is given in the table below.

Table 4: The ranking of the importance of retention barriers in four classes (Klabus, 2013)

A	IMPORTANT KEY retention structure that must have a continuously available capacity of retention space – retention space must be emptied as soon as possible after its storage capacity exceeds 40%
B	IMPORTANT retention structure whose retention space must be emptied as soon as possible after its storage capacity exceeds 80% (if possible as well as before)
C	LESS IMPORTANT retention structure which can be emptied if necessary, or when the retention storage capacity exceeds 90%, or as part of maintenance or intervention action in the catchment area
D	LESS IMPORTANT retention or retention/stabilization structure which is scheduled for emptying because its function is stabilizing, or it is located in a less accessible location and its emptying would be irrational or even impossible

Regular maintenance of the retention barrier does not mean only emptying of the retention basin, but also the timely rehabilitation of damage caused by high water, erosion, changed circumstances, or age. On dams the most common damages occur in the cascade base area (damage of bottom and riparian vegetation, undermining the final check dams, etc.) and overflow (abrasion or the torn parts of the crown, etc.). Serious damage to dams is more rare, but their condition deteriorates with age. Much depends on the quality of the embedded material (concrete, decomposition, cracks, weathering of wood, etc.). After a certain time they need comprehensive renovation, additional stone incorporated in front of the old building (in extreme cases), as well as reconstruction.

3.1.9.3 <u>Manual for operating and maintaining sediment retention dams</u>

In the framework of the SedAlp activities, the "Internal General Procedure Manual for Operating and Maintaining Sediment Retention Dams" (Slovenia) was revised.

The Manual consist of I. **General part**

- The Procedure manual defines the methods of maintaining sediment retention dams, with the goal of ensuring their safety and purpose
- Retention dams are water management structures owned by the Republic of Slovenia, the Environmental Agency of the Ministry of Environment and Spatial planning
- According to the Concession Contract between the Agency as the awarding authority and the concessionaire, the Agency must ensure financial resources for the maintenance works carried out by a concessionaire

II. **General description of individual sediment retention dams**

III. **Description of concessionaire tasks**

In case of normal conditions:

- annual field survey and elaboration of technical documentation for "Removal of bed-load deposits from sediment retention dams", including the way of restorating potential damages.

In case of emergency:

- if bad weather conditions or high waters occur in the catchment area, the river supervisors have to carry out a detailed field survey to assess the overall condition of each retention dam. If a particular retention area is full, or the dam is damaged, the awarding authority must be conctacted and the maintenance actions proposed.

IV. **Instructions for sediment abstraction – additional sections**

- Recording/inventory of the excavated amount of sediments
- Recording the grade of excavated sediments

3.1.10 Conclusions and recommendations

In the European Alps, channel processes are mostly triggered by rainfall events and associated runoff processes. Apart from the possible flood hazards during an intense rainstorm event, major damage is often caused by fine and coarse sediment which is entrained either in form of fluvial bedload transport or debris flow. Typically, the damage increases with the total amount of sediment transported to the fan during an event, particularly if the water and the sediments leave the channel on the fan (Rickenmann, 2014). For most torrents sediment transport during a high waters event is more or less problematic. The basic principle in regulating such torrent catchments is sediment retention within the slope areas of headwaters, possibly already at the top, or at least in mid sections, i.e. in addition to the reduction of the direct damages caused by sediment transport in the following sections of torrents, thereby preventing the lifting of channel bed in recipients (i.e. rivers in the valley bottoms), which greatly reduce the number of problems caused by erosion or flooding of lowland streams.

So, an essential aspect of risk management is the planning and design of mitigation measures which reduce the existing risk to an accepted level of residual risk. Such planning and design is one of the biggest professional challenges in the regulation of torrents, because in dealing with the threat from the negative effects of sediment transport, the water and sediment regime in the whole river basin should be considered to keep the positive effects of dynamic sediment transport, e.g. sediment continuity – where necessary.

A wide variety of structural mitigation measure designs are applied in torrent control works. In selecting the best adjusted arrangement, great importance must be placed on the knowledge of all ongoing geomorphic processes and their possible interaction with the mitigation measures. This means that a multidisciplinary approach has to be applied, including specialised skills in applied geomorphology, fluid dynamics, forestry and structural engineering. Although there is a large pool of experience gained by practitioners working in this field, there are still many scientific gaps. The rare occurrence of design events obliges the engineers to derive special solutions, taking into account the functionality, efficiency, and the stability of the structure. Therefore it is most important to collect and exchange the experience of the existing mitigation measures worldwide (Miklau, 2008).

In recents decades, the concepts of responses of torrent/river control structures to floods and debris flow impacts (including wood) clearly improved. The construction types of modern torrent control works are specified according to their function. The main functions within a protection concept can be summarized as follows (FIEBIGER, 1997):

Consolidation and stabilisation:	Fixation of the longitudinal profile of a torrent bed at a distinct elevation to stop depth erosion and/or lateral slides
Retention:	Storage of water and/or deposition of bedload during an event
Sorting:	Filtration and deposition of specific bedload components during an event
Dosing:	Temporary retaining of water/sediment
Debris flow breaking:	Declining the high energy level of a debris flow to a lower level (dissipation)
Woody debris retention:	Filtration of woody debris during an event

From the structural mitigation measures in torrent control, certain types of cross-sectional objects – protection barriers and certain types of longitudinal protection structures are in use in combination with a variety of soil bioengineering measures. The barrier typology is based on the division between Solid Body Barriers and Open Barriers. Barriers featuring no functional openings in the barrier body are called Solid Body Barriers. Open Barriers include barrier types with openings to allow parts of the water and/or sediments to pass through.

The role of the construction of technical measures is that the construction of adequate facilities in torrential channels and catchments establishes as close as possible the state of compensatory elevation of the torrent bed or even, in the long-term, an equilibrium of the channel (in which the clean sediment completely unburdened water will no longer erode the riverbed). Technical measures also stabilize certain sections of the torrential channel, and protect the various structures on the torrential banks against erosion, high water and sediment, etc.

The identification of problems and adequate solutions should be addressed through the collaboration of policy makers, practitioners and researchers, taking into account the following recommendations.

Policy Makers:

- Adequate risk-based land-use planning, taking into account flood threat, has to protect the areas from water and sediments – it has to strictly control the urbanization of floodplains without losing the space for sediments
- There are few rivers and torrents in Alpine Space today that are not regulated or managed to some degree, either because of potential hazards or benefits to anthropogenic activity –it has to be stressed and taken into account that water and sediment transfer in water basins are closely connected and that, as a general rule, many types of management address both
- Protective infrastructure where necessary
- By planning flood protection measures along lower sections of rivers, or in flat valleys, we must take into consideration the existing sediment management in all sub basins upstream and the headwaters of the river concerned to avoid unpredicted structural changes to rivers and damage when building new flood protection structures (e.g. dykes). The final decision has to be supported by long-term planning and agreement about the adequate maintenance and investment concept in the whole basin
- Extreme events such as floods and related large-scale sediment transfer can result in large geomorphological changes on watercourses, which leads to necessary updating of the existing status of water/sediment regime on large scale, i.e. of the whole river basin – so, even though the sensitive natural disaster period demands quick actions (affected population, economy and environment), there should be enough time and resources for expert assessment of the overall situation in the basin
- Timely and adequate monitoring and maintenance of the existing water infrastructures/protection constructions is essential to preserve their protective function – for the necessary continuous and sufficient financing – the maintenance of the existing facilities should be given priority over the construction of new ones; damaged structures do not protect but offer a deceptive impression of security. In case of their destruction, the consequences may be even worse than if there are no protective structures at all
- It has to be expected that after some extreme events there will be no great damage to the settlements or infrastructure, but there could be major costs of intervention in the headwaters and smaller sub basins, where the amount of maintenance costs of protection structures could increase (mainly cleaning of retention) – actually these costs could be presented as benefits (less damage)
- Practically all protection structures on watercourses, designed to protect against erosion, floods and sediment-related extreme events are planned to some design event – which means that in any case some residual risk remains (in case of a bigger event or in case of e.g. structure failure) which requires the implementation of an integral risk management concept with all known additional measures of prevention (e.g. tending of protective forest), preparedness (e.g. contingency planning) and response (e.g. warning, evacuation, intervention)
- Targeted, consistent risk dialogue with all the parties involved in sediment management in the related basin in order to strengthen the prevention efforts and promote the adopted approach to optimizing sediment continuity
- According to the unquestionably comparable sediment-related problems in the whole alpine region, it is recommended to set-up systemic and long-term knowledge-experiences-sharing, and official "sediment management networks" on regional, national and international levels that, in addition to flood protection, also highlight the best practice examples regarding sediment continuity

Practitioners:

- It is recommended that for possible extreme torrential events one of four displacement processes for each torrent section are defined: floods, fluvial solid transport, hyper-concentrated solid transport (debris floods) and debris flow and woody debris (recommended expert literature ONR 24800 – series of Austrian standards)
- It is recommended that the functions of torrential barriers are divided in the following functional process control functional types: stabilization/consolidation, retention, dosing and filtering, energy dissipation
- Modern protection concepts in torrent control have to be scenario-oriented and have to optimize different functions in a chain of protection structures (function chain) with consideration of sediment continuity (if desired and feasible)
- The final decision about torrent control measures must be consistent with respect to integral water management in the broader basin, part of which is addressed in torrential catchments
- The last step is to define and design the optimal construction type (e.g. solid or open body barrier)
- Due to the increased settlement on fans and riversides on the one hand and the decreasing efficiency of check dams because of filled up deposition areas, on the other hand, it is recommended to use recently developed protection methods like temporary storage of sediments by control structures with slots and inclined rakes
- For the selective retention of coarse solid components like boulders or drift wood from the flow process filtering structures are appropriate which have to be designed in a way that fine grained bedload can drift through without being retained
- Debris flow breakers have to be built with reinforced concrete and situated as an uppermost structure in a function chain, but the combination of "debris breaker" with other functions at the same barrier should be avoided
- In the design phase of open check dam sediment trap the driftwood hazard has to be very carefully assessed, because of its great effect on check dam functioning (defining the adequate shape and type of the open check dam)
- The functional maintenance access has to be implemented during the building phase to enable the maintenance of the retention basin
- "Usual" grade control structures (check dams and bed sills) could be still designed as consolidation measures to be efficiently used in hazard mitigation
- During the maintenance phase the existing structures regarding possible overloading scenarios have to be checked where possible (considering the possible increasing frequency and intensity of events) and consequently increase their degree of protection where appropriate to adjust to new situations
- Implement robust and adaptable new protective systems, which do not suddenly collapse under excess loads (torrential extreme events!)
- Retained debris has to be regularly excavated or spilled from the reservoir/retention basin (where planned) in order to keep the function effective
- In the case of the defined debris flow process it is recommended to replace or combine the usual sediment retention protection concept with energy dissipation by debris flow breakers with additional sediment sorting and dosing barriers
- Based on the accumulated experience (manly from Austria and South Tyrol), in the case of building open barriers it is recommended to plan two or three barriers with complementary functionality in a chain, rather than only one open large barrier
- Special attention is placed on the self-cleaning functionality of open barriers, to reach one of the goals – minimizing the maintenance costs – unfortunately, there is no common, most appropriate type and spacing – it depends on each torrential catchment – but event documentation and silent witnesses are the main input

- The behaviour of open structures during the events has to be regularly monitored and documented; each such experience has to be considered in the future dimensioning

Research:

- Long-term data collection, analysis and survey of sediment retention basins has to be further implemented; also the surveying during filling and self-cleaning (self-cleaning optimization), and after disasters (focus on sediments & driftwood)
- Further research on hydrology influences on check dams systems has to be undertaken
- Further development of management of sediment connectivity
- Improvement of construction types (during events, self-cleaning function, etc.)
- Research into small-scale experiments about the interactions between water, sediments and driftwood to different type, shape and openings of open check dams

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3.2 Guideline for planning/designing of efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches

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3.2.1 Background

Preventing the release of sediments from their sources in mountain catchments, stabilizing the streambeds through the realization of grade control structures and retaining solid material volumes transported during extreme events are widespread strategies to reduce risks in mountain areas. On the contrary, it is ascertained that, without releasing sediments either from their sources or from their intermediate deposits and without maintaining sediment connectivity throughout the stream network, the reactivation of hydro-morphological and the associated ecological functionalities is physically unfeasible for supply-limited and highly altered mountain rivers. In parallel, on several debris cones and alluvial fans a clear increasing tendency of wealth moving into flood prone areas could be retraced over the last decades, leading to a possible net exacerbation of risk. Hence, concerning sediment continuity a fundamental and intentionally strongly polarized management question might be posed: Reactivating sediment supply to the main stream network and bearing the arising risk costs, or retaining sediments and bearing the costs to sustain the functionality of the system (i.e. expensive maintenance of protection systems and artificial control of sediment supply for restoration purposes)?

We argue that striving for design excellence in sediment management can greatly contribute to resolve the above outlined apparent contradiction, namely effectively reactivating the hydro-morphological and ecological system dynamics, while keeping risk well below acceptable levels and reducing cost flows over the system's life-cycle to sustainable levels.

To this aim, in this section, first, the problem spectrum is defined and then, based on that, a structured conceptual planning approach is outlined in form of guidelines for planning/designing of efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches.

Thereupon we will provide a series of good practice examples with respect to one or more phases of the structured planning approach. The chapter is concluded by key recommendations for policy makers, practitioners and researchers.

3.2.2 Problem description

Despite the amazing level of technological breakthroughs achieved at an ever accelerating rate since the start of the Industrial Revolution, we are surrounded by many technological, environmental and ultimately societal problems, where poor design contributed to pave the way for their creation (Suh, 2001). Among other relevant causes, purely empirical and trial and error based approaches are the mostly reported triggers of design failures (Zobel and Hartmann, 2009).

Designing, by means of such approaches, artefacts of any kind at the intersection between hydro-, litho- and anthroposphere to enhance a chosen set of functionalities is particularly problematic, since cause-effect chains remain, at least partially, unveiled and the impacts associated with their realization, might emerge in the long run and might exhibit non-linear responses (Mazzorana and Fuchs, 2010).

Following Mazzorana et al. (2014) we revisit here, as an instructional example, the long history of torrent control in South Tyrol, Italy.

As a strategy to stabilize mountain streams, the construction of check dams has a long tradition in many mountain regions. Following Länger (2003), in the second half of the 19th and during the early 20th century, protection against natural hazards was mainly provided by building permanent constructions in the upper part of the catchments which were targeted at decreasing both the magnitude and frequency of events and the associated sediment release, supplemented by afforestation of the valley slopes to reduce erosion and prevent the initiation of events. Due to the increasing land-use pressure (i.e. demand for residential purposes as well as agricultural and industrial development), this consolidation approach was progressively extended to a large number of streams throughout the entire European Alps. Despite the associated necessary investments into such conventional mitigation strategies, losses could not be satisfyingly prevented (Mazzorana et al., 2008) and the number of damaging torrent events still remains on a considerable level (Mazzorana and Fuchs, 2010).

The aim to reduce the hazard potential by consolidating the stream beds, and in particular by using grading structures that artificially may retain amounts of sediment, has to be judged carefully. Due to a limited technical lifetime of any constructive mitigation, in combination with the possibility of technical failure (residual hazard), the natural disposition factors gradually change. This gradual change, however, does not seem to be acknowledged by the local actors, i.e., the population affected. Continuously, land-use in the run-out areas of hazardous processes increased since the 1950s, and depending on the respective national and regional building laws, a considerable amount of values was concentrated in endangered areas (Fuchs et al., 2013).

By an analysis of available data, however, it was shown that losses due to natural hazards cannot be completely prevented, which in turn generated a higher demand for protection in those areas heavily developed in recent decades. Therefore, starting already from the 1960s, the respective agencies responsible for the protection against natural hazards continued to pursue the consolidation strategy throughout the European Alps by constructing new grade control structures, prevailingly as masonry works in a first stage and then progressively as concrete structures. Such consolidation check dams, built in staircase-like sequences and targeted at preventing bed incision and stabilising adjacent hill slopes, are widespread in Alpine streams and are still used nowadays to mitigate flood and debris flow hazards. To give an example, approximately 30,000 check dams have been constructed in the Province of South Tyrol, Italy, since 1900, and 16% of them were judged not to satisfy the required reliability and, consequently, technical efficiency requirements (Mazzorana et al., 2008).

In order to partly overcome these challenges, a large number of open, filtering check dams have been constructed since the early 1970s (Zollinger, 1984). The functional efficiency of this type of structure was gradually refined firstly by improving the mechanical sieving function and subsequently by modifying the design to obtain a cost-efficient dosing function (Armanini et al., 2000).

In many cases, however, the design of such systems was inherently weak due to (i) the erroneous assumption of full performance of the previously constructed consolidation structures and (ii) due to procedural and content related gaps in the adopted planning procedures (Mazzorana and Fuchs, 2010).

The need to carry out capillary monitoring activities as an essential requisite to both ascertain the condition and functionality of the realized constructions and to elaborate appropriate maintenance strategies was not fully recognized until recently. At the beginning of the 21st century, large, but more or less systematic and homogeneous, check dam condition survey campaigns were conducted in many alpine regions.

As a result of these efforts a maintenance planning paradox became apparent, namely that a large amount of consolidation structures would need urgent maintenance to fulfil their functional requirements, but due to the decade-long delays in both recognizing the maintenance needs (i.e. extreme decline of the performance level) and in implementing maintenance strategies, the costs to be borne were disproportionate.

At this stage a fundamental and intentionally strongly polarized management question might be posed: Reactivating sediment supply to the main stream network and bearing the arising risk costs or retaining sediments and bearing the costs to sustain the functionality of the system (i.e. expensive maintenance of protection systems and artificial control of sediment supply for restoration purposes)?

Irrefutably both pure strategies leave managers and stakeholders unsatisfied and ultimately the concerned societies at risk. The intention to optimize single functional requirements at the costs of the entire spectrum of functionalities reflecting aggregated demands has to be judged carefully from a sustainability perspective. The implementation of traditional flood risk mitigation strategies, such as preventing the release of sediments from their sources in mountain catchments, stabilizing the streambeds through the realization of grade control structures and retaining solid material volumes transported during extreme events in retention basins, accompanied by not precautionary settlement expansion policies may strongly restrict the degrees of freedom for the design process.

The resulting implications are particularly relevant for the expected quality of river restoration initiatives. Without adequate liquid and solid discharges at the upstream boundary of a restored river stretch and without the possibility for lateral mobility the conditions for dynamic evolutions pathways are unfavourable.

Given this complex problem setting we emphasize the absolute need of high quality design in integral natural hazard risk and sediment management.

We argue that striving for design excellence can greatly contribute to resolve at least locally the above outlined apparent contradiction, namely effectively reactivating the hydro-morphological and ecological system dynamics, while keeping risk well below acceptable levels and reducing cost flows over the system's life-cycle to sustainable levels.

The ultimate success in terms of hydro-morphological enhancements of down-stream river reaches depends, however, from a broader sediment management strategy, which aims at re-establishing sediment connectivity throughout the entire stream network and not at particular hotspots only.

Obtaining from a sediment control system (i.e. open check dams) an optimal performance with respect to the release of sediment fluxes given a broad variety of loading configurations is a complex design task and represents an important, though partial, contribution to such a holistic sediment management strategy.

Our aim therefore is, rather than providing ready to use recipe-like constructive solutions, to trace a comprehensive planning roadmap, to set and then dissect the sediment transport related integral risk mitigation problem through a balanced strategy of investigation. From a methodological standpoint it is largely acknowledged (compare Lange and Bezzola, 2006) that moulding recipe-like solution patterns without a rigorous quantitative verification of the functionality levels is a risky endeavour, which, compared to the large investment costs, does not seem justifiable.

As an example, Gems et al. (2014) suggest a structured strategy involving both a preliminary numerical study of envisaged solution designs for a sediment deposition outlet area and a refined experimental investigation by means of physical scale model tests for a restricted set of feasible options. So far in the field of natural hazard risk management the introduction of a comprehensive design framework (Suh, 1990), enabling a logical articulation of (i) desired (i.e. by the concerned society) and prescribed (i.e. by law and by regulations) system requirements, (ii) the corresponding set of functional requirements which have to be met by the envisaged system, (iii) the design parameters as an anticipated physical characterization of the system and (iv) the process variables as critically impacting factors, is still missing. To close this gap in the next section we will propose first a framework for design by slightly adapting the domain structure of the axiomatic design method developed and popularized by Suh (1990 and 2001) and we will discuss a rational knowledge management scheme for design.

3.2.3 Design Framework

The design in general involves an interplay between "what we want to achieve" and "how we choose to satisfy the need" and Suh (2001) systematized the design thought process involved in this interplay by introducing the concept of domains in order to delineate and demarcate four different kinds of design activities, namely: (i) the customer domain, which is characterized by the needs (or attributes) that the customer is looking for in a product or process, (ii) the functional domain, where the customer needs are specified in terms of functional requirements (FRs) and constraints (Cs), (iii) the physical domain, where design parameters (DPs) are identified to satisfy the specified FRs and (iv) the process domain, where suitable process variables (PVs) are identified to specify the product development or the process implementation.

One necessary adaptation of this framework concerns the adoption of the Sustainability vs. Stakeholders' interests' domain (i.e. the Su – St Domain, compare Figure 1). In fact, the management of mountain torrents and rivers ultimately seeks to find alternatives and prospects that represent different syntheses amongst: i) what society desires, ii) what complies with the natural evolution patterns (i.e. river styles), and iii) what is allowed by the existing legal framework.

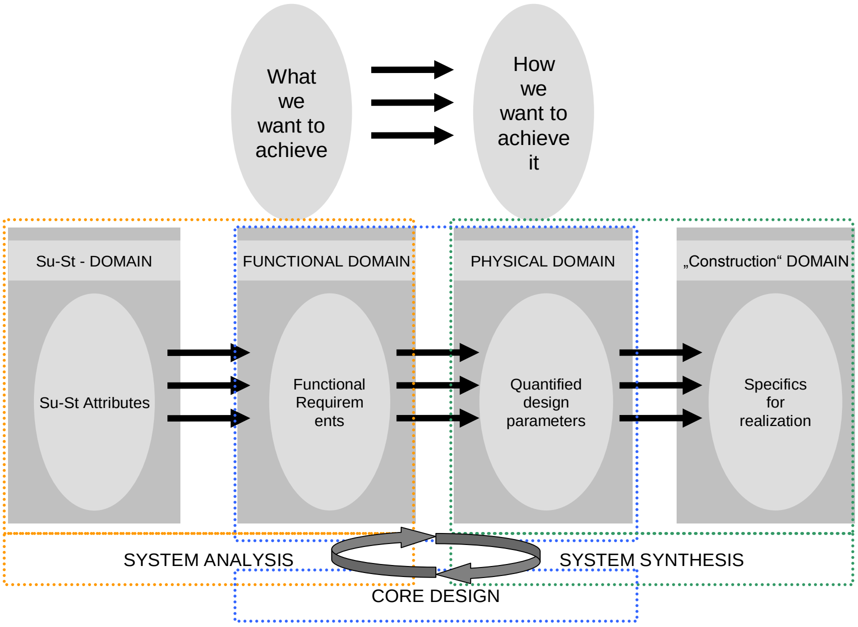

Figure 1: Conceptual planning steps – mappings in the design process (adapted from Suh, 2001)

Unlike products traded explicitly in active markets, where customers express their wants through their consumption choices, the Su – St Domain has to be analyzed through proper techniques. In Figure 2 we show a conceptual scheme of a computational architecture (CA) based on a system of key objectives to quantity the relevant attributes as a characterization of the Su-St Domain.

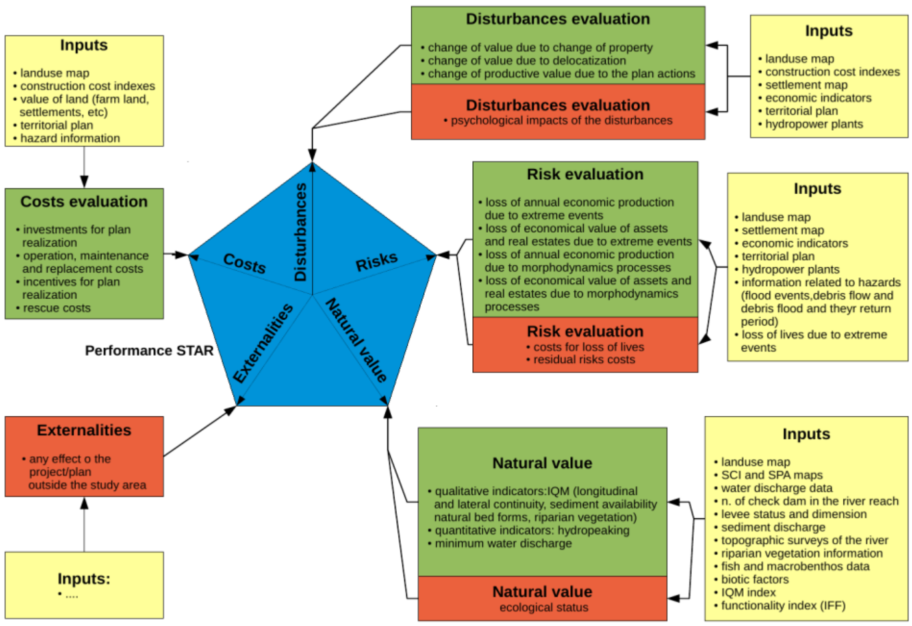

Figure 2: Conceptual scheme of a computational architecture. In the green boxes we list indicators that are commonly assessed in objective terms, whereas in the orange boxes we report decision relevant knowledge to be elicited from experts, stakeholders and decision makers

The CA is the tool developed to describe and simplify the overall mountain stream complexity, by evaluating 5 major indicators, namely disturbances, risks, costs, natural value and externalities. The indicators can be estimated provided that some input data are available. The required data are reported in the yellow boxes in Figure 2. Once the input data availability is assessed, the evaluation can be performed. Each indicator presents quantitative aspects relatively easy to be estimated, which are reported in the green boxes; typically these aspects are directly evaluated by applying simple algebraic formulae on territorial data. Therefore the use of GIS software is strongly recommended, because the input data are spatialized and distributed over the whole system domain.

The aspects reported in the red boxes represent the effects that can be hardly estimated quantitatively, because they depend not only on quantitative inputs, but also on human interpretations of phenomena and perceptions of values. As an example the estimation of the values associated to loss of lives cannot be made, except in a conventional way. The estimation of the "red" aspects requires a participative approach.

Once each indicator has been estimated, suitable utility functions can help in evaluating the five final indicators. A utility function is a useful tool for the inter-comparison of not directly comparable physical quantities by applying a normalization procedure.

As an example an approach for objective values normalization is to choose a linear utility function. This approach, shown in Figure 3, equates the maximum (or minimum) utility with the maximum (or minimum) objective values.

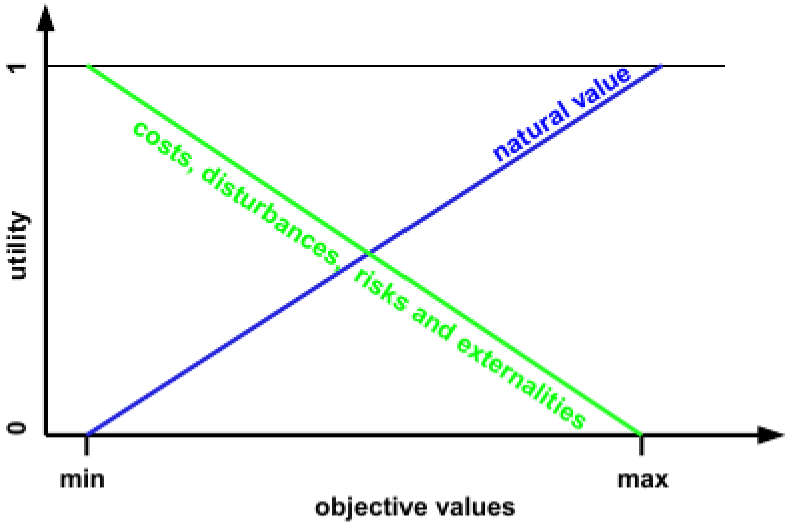

Figure 3: Linear utility function

More precisely, the maximum utility relative to the natural value corresponds to the maximum objective value, and the maximum utility perceived for costs, risks, disturbances and externalities corresponds to the minimum objective value. The methodology can be easily modified to take into account more complex non-linear utility functions that could be determined by applying a participative approach.

In a general framework the global utility of an alternative can be evaluated as:

$$G_u = w_c \cdot v(C) + w_r \cdot v(R) + w_d \cdot v(D) + w_n \cdot v(N) + w_e \cdot v(E) \quad (1)$$

where G_W denotes the global utility; C,R,D,N and E and are the total costs, the risks, the disturbances, the natural value and the externalities, respectively. $v(\cdot)$ denotes the scalar utility function and w_c, w_r, w_d, w_n and w_e are weights, such that:

$$w_c + w_r + w_d + w_n + w_e = 1 \tag{2}$$

A general approach requires that all the utility functions and all the weights are determined, by a specific interview with the stakeholders. Several technical approaches are available for the identification of utility functions and for the determination of the weight to be associated to each fundamental objective, such as the trade-off or the swings methods.

The procedure should be applied to the current state of the considered stream system and to every project alternative. A comparison between the current state and all the project alternatives can be made by comparing the final indicators values; results can be used in a participatory approach in order to point out whether the current state is satisfactory or an alternative would improve the overall functionality (objective and perceived) of the considered stream system.

As second adaptation we conceive design as an iterative process or as an envisioning-problem setting and problem solving cycle comprising the following steps (compare for details, Mazzorana and Fuchs, 2010):

1. Problem identification and description.
2. Formulation and visualization of the Ideal Final Result (IFR) to be achieved. Description of a “model” to be approximated.
3. Analysis of all possible physical, spatial and temporal resources for an optimal attainment of the IRF.
4. Definition of admissible system changes: The planning process is meant to address the removal of obstacles to the full attainment of the IFR.
5. Elaboration of solution concepts based on the IFR.
6. Evaluation of the developed solution strategies. The evaluation should clearly state for each design solution or project alternative (i) what has been enhanced, (ii) what has been worsened, (iii) what has been substituted, (iv) what remains to be done with reference to the attainment of the IFR and (v) whether the systemic and developmental contradictions could be solved.
7. Participatory selection of the optimal solution taking into proper consideration cost-benefit criteria.

Moreover adequate attention should be devoted to the system analysis and the core design process, which should assure the “translation” of the set of identified functional requirements for the planned risk mitigation system into quantified design parameters, or using the terminology of axiomatic design, provide a consistent mapping from the functional domain to the physical domain, thereby providing the basis for the ex ante verification of crucial design requirements (compare Figure 4).

Throughout the distinct problem solving phases (i.e. diagnosis or system analysis, prognosis or expected system development and synthesis or system design) the integrated use of knowledge derived (i) from event documentation or subjective sources (empirical approaches), (ii) from the application of numerical models and (iii) from the insights gained from scaled laboratory models is schematized with respect to different lead processes (i.e. Fl or floods, BT or bed-load transport, DFD or debris floods and DF or debris flows). The reader may note that, whereas the state of the art in event documentation is well established for all process types, professionally applied numerical modelling and as well laboratory experiments are fully reliable only for floods and bed-load transport process characteristics. Unequivocally, this assessment is to some extent of a subjective nature and corresponds to the author's conviction. Extensive research with a great progress has been accomplished in the last decades, both, in numerical und experimental modelling of debris floods (DFD) and debris flows (DF) (e.g. Rosatti and Begnudelli, 2013). However, reflecting the author's opinion, DFD- and DF-modelling is prevailingly addressed by abstract cases / case studies yet, mainly with a strong scientific focus and background. For practical applications, e.g. for sediment management applications or for the performance assessment and the design of specific torrential hazard mitigation measures, still more effort is required in order to provide reliable models or modelling approaches which are applicable to situations in practice and thereby fully accepted by the stakeholders (compare Figure 4).

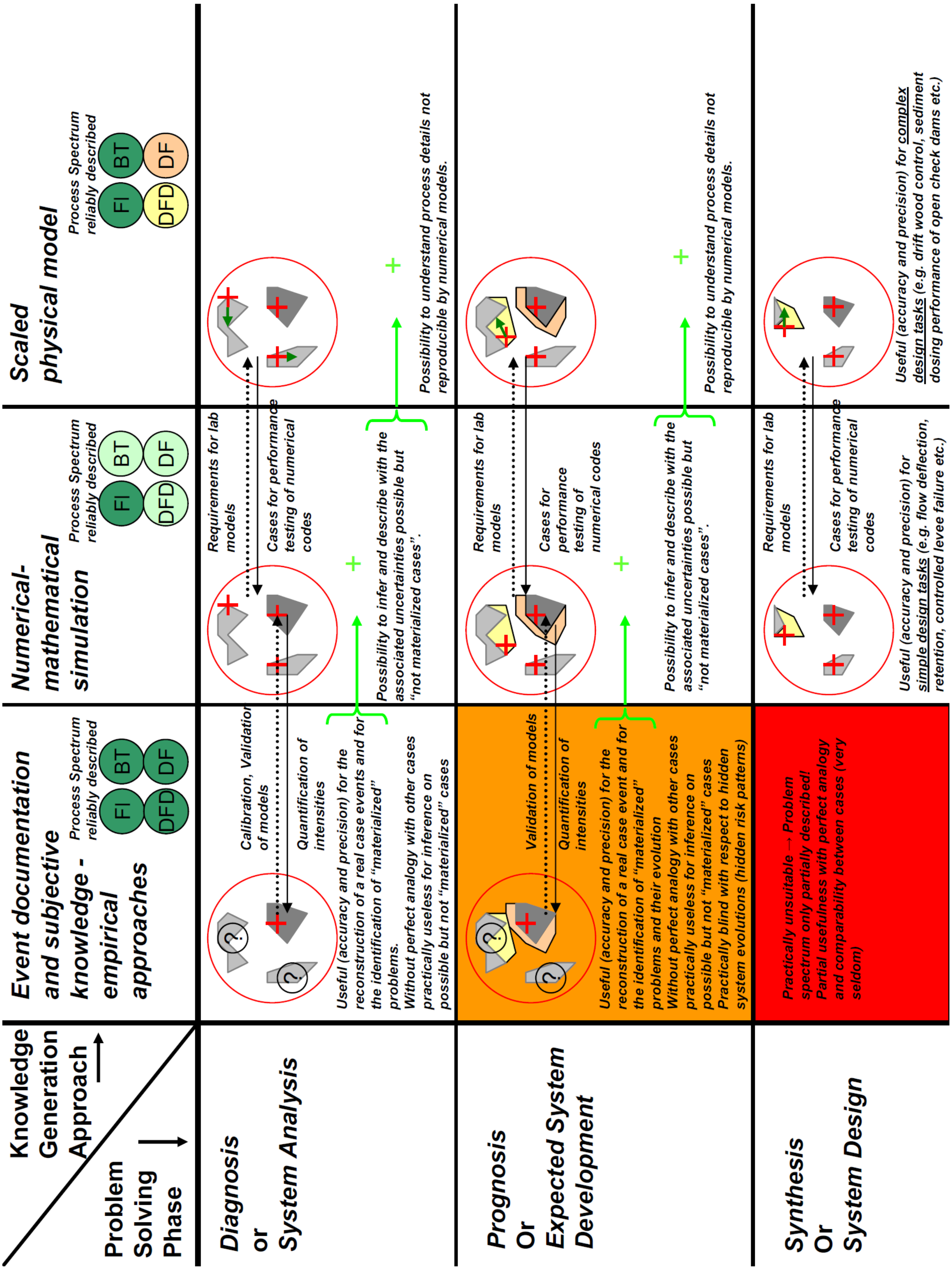

Figure 4: Proposed knowledge management navigator throughout the core design process

The illustrated limitations should, however, not discourage the application of numerical models and laboratory experiments, since, conversely, through backward oriented knowledge generation approaches alone, the interpretable problem spectrum is limited to what past events highlighted and serious difficulties may arise both in quantifying process intensities and frequencies (compare Figure 4). Moreover the pure backward oriented strategy is practically useless for inferring possible process behaviours outside the occurred range of historical hazard events. This strategy alone is suitable for a complete and verified system design if and only if perfect analogy and comparability with previously solved problems exist.

Reflecting the available approaches within the knowledge generation process illustrated in Figure 4, a considerable mutual dependence is apparent, which, in turn, emphasizes the importance of each approach within the core design process. Basically, numerical-mathematical simulations as well as laboratory experiments require the availability of data from field surveys and historical event documentations for an adequate parameter setting and for the models calibration and validation. Furthermore, regarding the zone of influence and the impact area of specific torrential hazard mitigation measures, numerical models are often applied to a larger extent. They provide process input data for the laboratory experiment, which is specifically focusing on the mitigation structure within a rather small area, but also allow for an assessment of the mitigation measure on a considerably larger scale. Accordingly, with the intention of a comprehensive core design process, the consideration of each approach and its interactions with each other appears mandatory.

3.2.4 Procedures for improved planning

Earth systems in general and mountain stream systems in particular work at some distance away from equilibrium. On removal of internal constraints, within these open systems, irreversible processes take place as drivers towards local equilibrium.

With respect to the topic of this chapter, the irreversible processes mentioned above are the sediment transport processes driven by available energy gradients in their different forms and manmade structures can be intended as part of the constraints.

The performance of these structures is in close relation with the delay (i.e. kinetics) of the irreversible evolution pattern in a given mountain stream system.

From an anthropocentric perspective wealth has moved into flood prone areas. For mountain streams this is the case essentially on alluvial fans and debris cones. Re-linking the discussion to the broader physical view one might argue that the way in which constraints apply and the timing of their removal is crucial either to minimize flood risks on endangered areas or to assure sediment feeding to the downstream river network.

Given the importance of the life-cycle performance of sediment control structures, in this sub-chapter we present first a thorough review of design criteria for sediment traps, followed by an overview of the procedures applied by local authorities to improve the planning process.

In due consideration of the importance of the life-cycle performance of sediment control structures, we elaborate on check dam failure hazard ranking.

In coherence with the proposed knowledge management navigator proposed, this subchapter is round off by the modelling aspects related to process dynamics in mountain streams. Intentionally particular emphasis is put on physical scale modelling.

3.2.4.1 <u>Review of design criteria for sediment traps</u>

3.2.4.1.1 Context and purpose of application

Why trap sediment and use open check dams?

Sediment trap is a common term used in highly different contexts. Many hydraulic systems need to be protected against sediment transport and deposition. Due to complex coupling effects between upstream torrential watersheds and downstream lowland rivers, fans naturally constitute buffering areas for sediment. However, channel shifting, stream bed aggradation and flow spreading has to be prevented to protect human facilities and villages that had been built on fans. These torrential hazard phenomena are generally related to sediment deposits on the fan part of the watercourses. In these cases, some parts of the sediment supplied by the headwaters have to be trapped for hazard mitigation purposes. For instance, in steep slope streams, this kind of facilities become crucial when debris flows and hyperconcentrated flows are likely to occur and can completely fill the channel at the flood scale. In this case, detention basins are built on alluvial and colluvial fans (e.g. Zollinger, 1983) or even upstream in the steep slope mountain channel to break energy and surges of erosive power (e.g. Mizuyama et al., 1996; Wu and Chang, 2003; Kim et al., 2012; Choi et al., 2014).

The characteristic components of these traps are illustrated in Figure .

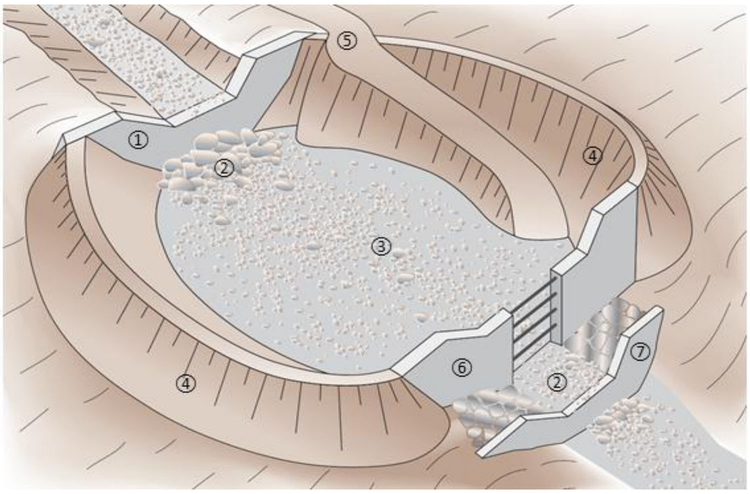

Figure 5: Open check dam sediment trap characteristic components: 1) inlet structure, 2) scour protection, 3) deposition basin, 4) lateral dykes, 5) maintaining access, 6) open check dam, 7) counter-check dam (Piton and Recking, 2015a) adapted from Zollinger, 1984

3.2.4.1.2 Historical use of sediment trap

Vischer (2003), in his presentation of the Swiss flood mitigation history, reports that the first Swiss deposition basins aiming to trap sediment were built in the 1840s. Such facilities were used only in specific cases and as the last resort due to the difficulty to dredge it by hands. Upstream bed stabilization works as check dams series or afforestation technics were thus preferred. The situation was similar in other European countries.

The number of sediment traps with open check dams increased substantially during the 1980s. Nowadays, leveling engines allow dredging the thousands of cubic meters of sediments more easily than the sediments erratically deposited by torrents. The access of engines to sediment traps remains a key point in maintenance costs (Garcìa et al., 2008). The increasing number of open check dam to design triggered a need in design criteria. Works were published concerning the presentation of this kind of structures (e.g. Van Effenterre, 1981; Johnson and McCuen, 1989) and basic design criteria for outlet openings' dimensions (e.g. Watanabe et al., 1980; Mizuyama, 1984; Senoo and Mizuyama, 1984; Ikeya, 1985, 1989) and general filling processes (e.g. Zollinger, 1983, 1984, 1985).

During the 90’, Japanese and European authors continued to stress the interest of open check dams. The research continued on design criteria definition (e.g. Armanini et al., 1991; Deymier et al., 1995; Poncet, 1995; Mizuyama et al., 1996).

Since 2000, the precise place that open check dams take in general torrent hazard mitigation plans has been highlighted (Leitgeb, 2002; Hübl and Suda, 2008). Complementary to field and small scale models, numerical models were and are still in development to better estimate erosion and deposition processes occurring in these structures (e.g. Busnelli et al., 2001; López et al., 2010; Shrestha et al., 2012; Campisano et al., 2013, 2014). Design standards were also proposed (e.g. ONR24803, 2008; Osanai et al., 2010; Rudolf-Miklau and Suda, 2013), but they mainly dealt with civil engineering aspects rather than design concerning hydraulics and sediment transport in open check dams.

In addition to problems brought by water and sediments, field and especially disaster feedbacks raise the necessity to pay a deeper attention to driftwood effects and complementary approaches dedicated to this problem have been developed (e.g. Kasai et al., 1996; D’Agostino et al., 2000; Department, 2000; Koulinski and Richard, 2008; Schmocker and Hager, 2013; Schmocker et al., 2014).

Up to now, no document gathered the state of the art on the subject of the **design of sediment traps with open check dams,** more especially concerning the geometry and shape of the opening. In mild and steep slope streams, open check dams can trap coarse bedload transport (pebbles, cobbles and occasional boulders), possible debris flows surges and Large Woody Debris depending on the shape of the opening and of the upstream deposition basin.

3.2.4.1.3 New elements learnt during SedAlp

Piton and Recking (2015a, 2015b) gathered the state of the art of open check dams design criteria in two companion papers:

- The first paper (title: DESIGN OF SEDIMENT TRAPS WITH OPEN CHECK DAMS: A REVIEW, Part I: hydraulic and deposition processes) gathered and compared the results of empirical approaches, field feedbacks and applied scientific works dealing with open check dams’ hydraulic design. The first paper exposes primarily the open check dams’ possible objectives, reports a classification aiming to fix the varied vocabulary used to describe structures and proposes a design procedure steps. In a second part, the general structures’ functioning is detailed, stressing the importance of each structural part (spillway, central openings and bottom outlet). The processes leading to sediment deposition are then described. Design criteria are reported, when existing, or scientific gaps are highlighted, when still remaining. The gathered literature generally belongs to mixed practitioners' / researchers' works (for instance INTERPRAEVENT proceeding), sometimes in French and German or, not yet gathered, in English journal papers.
- The second paper (title: DESIGN OF SEDIMENT TRAP WITH OPEN CHECK DAMS: A REVIEW, Part II: woody debris problems) is more specifically dedicated to driftwood. It proposes a bibliography review concerning, first, driftwood production in torrential watershed, their recruitment and transfer by floods. In a second part, the sensibilities to driftwood of the main different kinds of open check dams are listed. To finish, design criteria concerning driftwood and open check dam are given and the remaining scientific gaps are stressed. This companion paper is largely inspired by the detailed and exhaustive report by Lange and Bezzola (2006) of driftwood management in Switzerland. For similar aspect in larger low-land rivers, see the review of Schmocker and Weitbrecht (2013).

A better comprehension of the processes taking place in sediment traps will allow practitioners and designers to adapt sediment trap design to the relevant and adapted sediment continuity of the studied river. If numerous trap shapes tend to catch all sediments, some technics allow a partial transparency of the structure to sediments. Each torrent hazard mitigation plan has to be adapted to the local sensibilities and phenomena. These general guidelines will hopefully help structures designers to find the best adapted design to their local problems allowing the maximum reasonable sediment continuity whenever possible.

3.2.4.2 Construction, functionality and management of the retention basins of torrent control structures

3.2.4.2.1 Context of application

Numerical simulations and laboratory experiments require the availability of data and results gained from field surveys and from the analysis and considerations of historical event documentations. This is a mandatory condition for model setting, calibration and validation.

The current management criteria, policy and design guidelines of the sediment retention basins have been investigated with the aim of defining the state of the art about this topic. The obtained information should be useful to develop the studies related to the interaction with structures and for planning/designing efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches, looking also to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches.

The main objective of this section is to analyze how the retention basin of torrent control works and in particular the structures for debris flow hazard mitigation.

The aim of this topic was pursued through interviews to the two most advanced agencies for mountain basin control and hydraulic structures of the north-east of Italy, the Autonomous Province of Bolzano and the Autonomous Province of Trento.

The detailed purposes of the interviews were:

- to collect information about the hydraulic structures in the agencies areas: number of structures, typology, construction period, functions;

- to find out the policy adopted to design the hydraulic structures and to manage the sediment that accumulates in the retention basins;

- to understand how the sediment is currently managed and the adopted criteria in cases where they were not provided by regulatory instruments.

3.2.4.2.2 Methodological and procedural details

The interview was divided in four sections:

1. General information – In this section the information was collected to define the general situation about the retention basins currently present in the area under consideration: number of retention basins, types of structures, dimensions, construction period and function of the structures. The reasons that lead to construct a particular type of structures were also investigated in this section.

2. Regulatory information – The regulatory instruments, where present, adopted by the agency or the managing authority to design the structures and to manage the sediment that accumulates in the retention basins.

3. Design information – Information about the figure in charge of the design and realization of the structures; the criteria adopted to design the structures and to preserve the sediment continuity (if present). The economic criteria considered (maintenance and manage costs, cost-benefit analysis) during the design process.

4. Management information – The criteria adopted to manage the sediment that accumulates in the retention basins: when the retention basins are emptied, where the sediment is stored or transported after an emptying operation, if the reintroduction of the removed sediment is allowed. In this section, the monitoring systems adopted to verify the efficiency of the structures, the manage costs of the sediment that accumulate in the retention basins and the intention to improve the actual structures were also analyzed.

3.2.4.2.3 Results

Autonomous Province of Bolzano:

1. General information:

Since 2001, a GIS-based database has been created that records the structures built in torrents and hill slopes of the province to manage the hydrogeological risk. The main operations followed to complete the 'cadastre' are:
- detection and description of the past works, by project analysis and field surveys;
- continuous addition of the new realized and tested works.

The works are divided into:
- transversal hydraulic works: check dams, sills, open barriers for debris-flow mitigation;
- longitudinal hydraulic works: channel-lining works, artificial banks;
- soil bioengineering: greening, live cribwalls, live fascine, drainages;
- avalanche protection works.

The Province also adopt another database: the monitoring system after event (called ED30). In this database each event (floods, debris flows and landslides) is recorded thus allowing also the monitoring of the structures' efficiency.
Currently, the structures mainly used to reduce the debris-flow hazard are beam barriers and sectional barriers with fins. In recent years, some old barriers, characterized by low permeability, have been modified improving the performance of the work and allowing the passage of sediments for ordinary floods. These types of structures were built because they are considered as the most efficient for debris-flow risk mitigation. The self-emptying capability of the barrier is not considered in the management costs because the works built up to now have not given benefits from this point of view: as soon as the retention basin is filled, even partially, it is always mechanically emptied. So there is no apparent cost reduction or at least it has not been analyzed. It should be noted, however, that the use of more open filters has declined because the designers prefer not to take risk.

2. Regulatory information

The regulatory tools adopted by the province to regulate the design and management of the hydraulic works are:
- The provincial law 12th July 1975, n. 35: it defines that the design and execution of the works has to be done by the Province unless there are other administrative-technical reasons.

- The General Plan of Public Water Utilization (PGUAP): it defines the principles of the province in the field of water management; specifies the release criteria of authorizations for public water use that seek to ensure the sustainability of uses and the possibility, for future generations, to benefit from an environment still intact.

3. Design information

The design and construction of hydraulic works is carried out directly by the Province personnel and they could be committed to practitioners and private companies only in cases of special need (Provincial Law 12th July 1975, n. 35). There are no fixed criteria to design debris-flow barriers, but while the filters designed a few years ago were intended to block the sediments of the event and to allow a further emptying by ordinary floods, now the current design tends to focus on the rising curve of the debris-flow hydrograph, trying to create barriers that filter the sediment as the retention basin is filling, looking for a dynamic lamination of the debris flow.

4. Management information

Debris that accumulates in the retention basin of debris-flow barriers is always removed as soon as possible. The defense of the settlements is the criterion that leads to each operation that follows a debris-flow event. The sediment extract by the retention basins of debris-flow barriers is never reintroduced directly downstream, since the effects of this operation are difficult to predict (risk of damage for ecosystems, hydraulic problems, etc.), apart from a pilot study on streams subject to erosion. Although there are no protocols for the sediment management in the retention basin of the torrent control works, there are principles that the Province seeks to follow during the design and the operation of maintenance of the structures. These principles are:

- Do not prevent the transport and the ordinary flow of sediment
- Do not extract sediments from the river bed
- Remove the traps for sediments like closed check dams
- Improve the management of sediments, learning and progressing through experience that mature over the years. This is achieved through the continued monitoring of streams thanks to fixed sections of monitoring.

Autonomous Province of Trento

1. General information

The 'cadastre of the hydraulic works' has been kept since 1978 for the secondary streams and it was later extended to the large rivers of the valley. It is a database where each torrent control construction is described: location, geometrical characteristics, year of construction and state of conservation. The classification is not always reliable, and all the types are not easily identifiable in the 'cadastre'. However, in the Province there are 284 debris-flow open barriers, built since 1980.

2. Regulatory information

The main legislative instrument of the Province is the General Plan of Public Water Utilization (PGUAP) published in the Official Journal No. 119 (24th May 2006). It provides the general guidelines to the management of streams and hill slopes: Chapter V, Art. 22. This legislative instrument does not provide precise criteria and recommendations to manage the sediment that accumulate in the retention basins of torrent control works. There are only indications regarding the extraction of sediments from the riverbed: art. 26, PGUAP.

3. Design information

The design and construction of hydraulic works is carried out directly by the Province personnel. Calculations for the stability of structures are always committed to external practitioners. The fundamental criterion that is considered in designing is the reduction of risk; considerations on the costs of maintenance and management are secondary.

4. Management information

Debris that accumulates in the retention basin of debris-flow barriers is always removed as soon as possible. The destination of the extracted material is defined case by case. Generally the volume material is measured and it is stored in a temporary location. Occasionally, where possible, the material is reallocated downstream through lateral accumulations.

The torrent control structures are constantly monitored; the sampler has to fill a form in which the maintenance is qualitatively evaluated describing the structural damages in a scale from 1 to 4.

3.2.4.3 Torrent Check dam failure hazard ranking

Torrent check dams are key structures when considering sediment transport on torrents. Check dams on torrents are planned with different aims and sediment control (grade control and sediment retention) with flood protection being as one of the most important. Failure of check dams poses a serious threat to downstream reaches and should be dealt with seriously. The operating period of a torrent structure must be part of the planning process, and lifetime events of the structure must be considered. Various parameters influence the life expectancy of the check dam.

The methodology for check dam failure hazard ranking was developed taking into account various parameters of check dams, the watershed, the river channel and the surrounding area. The results of the study show the most critical structures of the considered area. The most critical parameters or weaknesses of each structure come forth and infrastructure manager/planner can carry out the necessary actions to improve the failure hazard rank of the selected check dam.

When planning a new check dam or a series of check dams, the proposed methodology is useful for analysing how to plan an efficient check dam with low failure hazard in the operational period.

3.2.4.3.1 Methodological and procedural details

26 check dams were investigated considering 20 parameters.

A. Basic check dam parameters
   1. Height of check dam
   2. Sediment trap volume
   3. Type of check dam
   4. Construction type

B. Torrential watershed parameters
   1. Q_{100} discharge
   2. Melton number

3. Debris flow magnitude (m3/km2)
4. Torrential watershed erosion state

C. Maintenance and management
   1. Available documentation
   2. Maintenance plans
   3. Maintenance data (historical)
   4. Data of sediment removal

D. Risks for environment
   1. Risks for settlements
   2. Risks for infrastructure
   3. Chain of check dams
   4. Ownership and management

E. Condition of check dam
   1. Degradation processes
   2. Area of influence of check dam
   3. Stilling basin condition
   4. Downstream channel condition

Description of the parameters is included in the analysis.

Height of check dam: Height from the stilling basin to the weir of the check dam

Sediment trap volume: The volume was determined based on construction plans, in the case of a lack of documentation, field measurements of the trap have to be carried out

Type of check dam: Determines if the check dam is a grade control structure or if it also retains solid material

Construction type: Concrete, stones, mix of concrete and stones, wooden cribwall

Available documentation: Construction plans, plans of executed works, plans for operations and maintenance

Maintenance data (historical): Do we have some historical data on maintenance, what kind of measures were taken, lack of maintenance (data)

Data of sediment removal: Is the sediment trap regularly cleaned, do we have data of sediment removal (periods, volumes of removed sediment), is the check dam sediment trap periodically monitored

Q_{100} discharge: Water discharge with a 100-year return period

Melton number: Melton number (Melton, 1965)

Debris flow magnitude (m^3/km^2): Debris flow volume per km^2 of the watershed area

Torrential watershed erosion state: Erosion activity in the watershed area, number and size of erosion areas, erosion hazard

Risk for settlements: Is there a hazard for downstream settlements in case of check dam collapse, density of building downstream

Risk for infrastructure: Is there a hazard for infrastructure in case of check dam collapse, importance of the infrastructure (roads, railway and other infrastructure)

Chain of check dams: Are check dams built in a series or is there only one check dam whose stability is not dependent on other check dams

Ownership and management: Is the ownership and related responsibilities (management, maintenance) clear

Degradation process: Are degradation processes present on the check dam structure (abrasion, cracks, erosion)

Area of influence of check dam: Erosion processes, active landslides near the check dam

Stilling basin condition: State of the stilling basin (no damage, damaged, completely destroyed)

Downstream channel condition: Is the downstream channel regulated, dimensioned for Q^{100} discharge, riverbed and bank erosion process

A common research form was proposed where all important data about the check dam are collected. A field survey of the structure in combination with documentation archive investigation must be carried out to ensure the correct values of each parameter. The parameters were ranked from 1 to 4 based on documentation analysis and professional judgement in the field, and the final ranking for each structure was determined.

	Basic check dam parameters	Torrential watershed parameters	Maintenance and management	Risks to the environment	Condition of check dam	Final ranking
SMALL	8 – 13	8 – 17	8 – 9	8 – 13	8 – 14	40 – 81
SMALL TO MEDIUM	14 – 15	18 – 19	10 – 11	14 – 15	15 – 23	82 – 83
MEDIUM	16 – 17	20 – 21	12 – 15	16 – 19	24 – 27	84 – 89
MEDIUM TO LARGE	18 – 21	22 – 23	16 – 22	20 – 21	28 – 29	90 – 99
LARGE	22 – 36	24 – 32	23 – 32	22 – 32	30 – 32	100 – 164

Table 1: Final values/ranks of check dam failure hazard

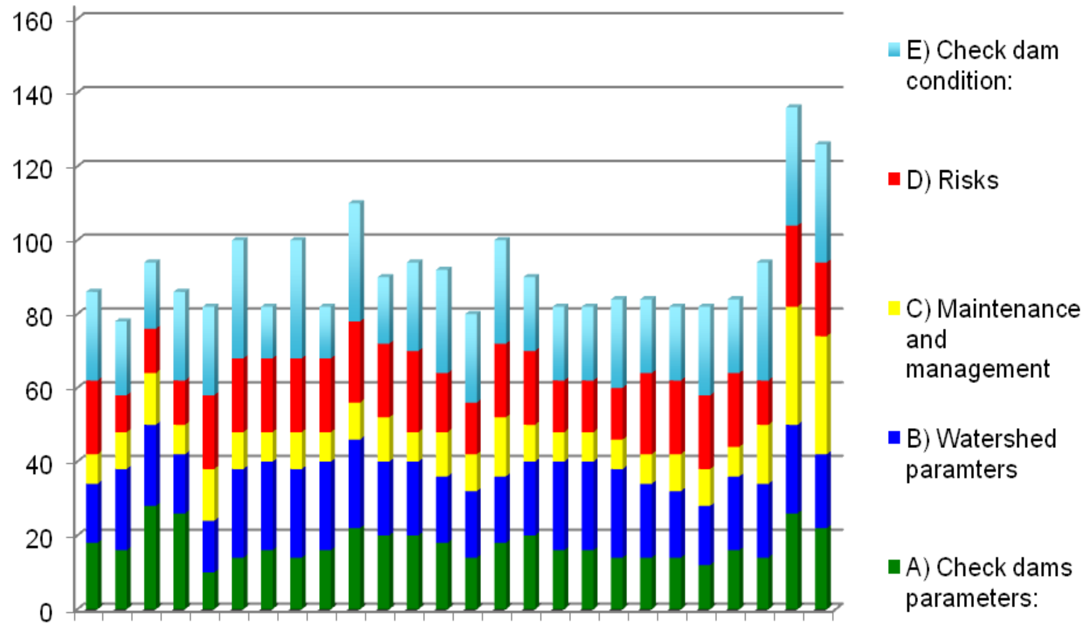

Figure 6: Final ranking of the surveyed 26 check dams

Figure 6 shows the final ranking of the surveyed check dams and presents the importance of each group of parameters (contribution to final ranks). The infrastructure manager can use this kind of presentation to plan maintenance actions in the future to efficiently reduce the failure hazard of a check dam. This method should be applied for periodical monitoring of check dams to prevent failures and its serious consequences for settlements and infrastructure, and also for the planning process to analyze the hazard in advance and prevent high failure hazard in the future.

3.2.4.4 Refining the process comprehension and torrent control structure design by physical scale modeling

Since the seventies, the Forest Technical Service of Austria has been using open bedload sorting (control) dams to control bed load and sediment transport. The reasons for insufficient function fulfilment are found in the structures' unsuitable function, in the woody debris difficulties, in the geological qualities of the sediment or bedload as well as in an inadequate discharge.

With this project the optimal design of existing bedload sorting (control) dams should be defined. This was realized with lab experiments to analyze the interactions of bedload and sediment with control structures under controlled conditions and the influence of the transport capacity downstream the bedload sorting (control) dams.

3.2.4.4.1 History of physical scale models for torrents

For this project, the available data on physical scale models were reviewed. In 1901, Wang (1901) made the first experiments to understand fan formation. Stiny (1917) gave further descriptions on the related processes. Hampel (1968) made numerous experiments to investigate the deposition behaviour of torrents and gave recommendations on the construction of retention basins. He showed the influence of the grain-size distribution and the slope on the deposition. His key findings are:

Deposition is more dependent on the sand content of a sediment mixture than on the grain-size distribution. An increase of the sand content by 7% results in an increase of the slope of the deposition by 1%. An increase of the channel slope by 10% results in an increase of the slope of the deposition by 1%. And finally, an increase of the mean grain diameter by a factor of 10 results in an increase of the slope of the deposition by 3%. Hampel (1974) investigated different types of check-dams and concluded:

1. The relation between beam distance and maximum grain-size should be bigger than 1 to favour self-emptying.
2. Horizontal beams are preferable over vertical beams.
3. The distance between the beams should not be bigger than 1.5 the width of the beam.
4. Series of check-dams with decreasing beam distance are recommended.

For Zollinger (1983) the key parameters to optimize a deposition basin are the size and form as well as the height and size of the openings of a dam. For self-emptying the following factors are most important:

1. High discharges with low sediment concentration.
2. High content of fine sediment and no presence of cohesive material.
3. Long, narrow and steep deposition basins.
4. Backwater effects reduce the sediment peaks and prefer self-emptying processes.
5. Driftwood must be removed after clocking.
6. Armour layer should be destroyed.
7. Openings of dams have to be over the whole height, but there may be beams in-between.
8. The receiving river and the torrent below the dam must be able to transport the passing sediment.
9. The deposition basin must be reached by machines.
10. Control and maintenance are essential.

Setznagel (1989) made a lot of experiments in order to test the different types of check dams for the processes of bedload transport and debris flow.

Unfortunately all of the above mentioned experiments were not Froude-scaled. That means that the results can only be regarded qualitatively, but cannot be related quantitatively with nature.

3.2.4.4.2 Methodological and procedural details

Part 1: A physical scale model to investigate torrential filter structures

For the actual project, pre-investigations were made by Hainzer (2013) and Trojer (2013) at the Institute of Mountain Risk Engineering. All experiments are Froude-scaled. The physical scale is 1:30. Hainzer (2013) investigated the deposition and self-emptying behaviour of a screw dam with vertically inclined beams. Trojer (2013) extended the experiments by adding driftwood and comparing the screw-dam with a beam dam with horizontal beams. The experiments were made in an elongated deposition basin with 5% channel slope. Therefore a scaled hydrograph and sedigraph were applied. During the falling limb of the hydrograph no sediment was added to model the self-emptying at the end of the experiments.

Part 2: Hydraulic scale model tests for the analysis of bedload transport processes in stepped torrent channels

A project goal is to generally analyse and further optimize the bedload transport characteristics in the torrent channel to the recipient. Knowing the sediment inputs from the tributaries is very important for the protection of the lower reaches. For this purpose, the existing scale hydraulic model of the Schnannerbach (Tyrol, Austria) in the hydraulic laboratory at the University of Innsbruck was used to make further investigations. In the original tests, several experiments were carried out to increase the sediment transport capacity of the Schnannerbach torrent channel and its confluence with the receiving river, the Rosanna. On the actual state of the channel and on the optimized conditions, steady-state tests as well a fully unsteady reconstruction of the 2005 flood event were performed. All tests were carried out under mobile bed conditions. Different grain size distributions, according with field survey data, were tested.

The main aim of the experiments is a qualitative assessment of the capacities in the torrent channel and the confluence zone and, further, the transport rates in the torrent channel in order to define critical sediment loadings and grain size mixtures, which lead to an overload of the torrent channel. Additional experiments within the SedAlp project should investigate the influence of different gradient changes of the torrent channel in combination with different grain size distributions of the sediment input.

3.2.5 Good practice examples

As a conclusion of the logical sequence entailing first deploying a general framework and then the “codifying procedures” for particular problem settings, in this subchapter we describe practical examples. We now focus on how constraints can be modified in order to obtain a controlled reduction of available energy gradients rather than artificially and costly maintaining gradients through pure consolidation strategies.

In this subchapter we present first a field assessment of the self-cleaning behaviour of an open check dam built in the Rudan stream in the Province of Belluno, Veneto Region, Italy. In a second step an application example carried out in Slovenia highlights the propensity to failure of poorly maintained check dams, thereby informing decision makers that there is an obvious trade-off allotment between costs for consolidation and process-frequency reduction. Without proper maintenance hidden hazards may strongly increase.

Intervening favourably in natural process dynamics by dosing solid transport during extreme events is worth being attempted. The uncertainties associated with process dynamics and the process-structure-interaction (in particular at filters) call for a detailed design. To this aim laboratory experiments proved to be useful. Good practice examples are therefore dedicated to the insights gained from the physical scale model to investigate such problems.

3.2.5.1 Field assessment of the self-cleaning behaviour of an open check dam

Mountain basins are typically characterized by steep slopes. In Europe, mountain streams are generally named “torrents”, that means rivers with bed gradient ranging from 2–3% to 60–65% (D'Agostino, 2010). Alpine torrents are typically characterized by slope values from 10% to 30%. In many cases in these basins flood events are flashy and associated to the entrainment of large amounts of sediments; the term *torrential* indicates the impulsive response of the catchment to convective storm events. Alpine torrents are dominated, for example, by the mechanism of linear erosion that affects the bank-bed system, affected by thalweg degradation in the upper parts and able to transport huge amounts of sediments during floods (D'Agostino, 2010). The mean slope of the thalweg can be defined as the driven factor of sediment transport in mountain streams. In a mountain environment it is of crucial importance to define the dominant sediment transport characteristics so to be able to design appropriate torrent control works, particularly in scenarios of possible extreme floods. It is possible to define two main groups of protection measurements against floods associated to sediment transport (D'Agostino, 2010):

- *extensive not structural actions* dealing with forestry, soil bioengineering and shallow landslide management;
- *intensive hydraulic works*, concerning transversal and/or lengthwise structures along the river networks.

On the other hand, looking to the functional types, it is possible to define two main typologies (D'Agostino, 2010):

- *Consolidation structures*: aim to stabilize the stream bed and the banks in the upper and medium part of the basin, to reduce the degradation of the channel and decrease the sediment supply to the fan areas. This typically consists in sequence of check-dams, bed sills, grade control structures or manmade artificial step pool systems (Lenzi et al., 2000).

- *Retention structures*: permit to control the transit of impulsive water-sediment flows, typically consisting of check dams of proper height (2.5–12 m), with the function to trap and partly strain the estimated amount of sediment volume in the expected form of transport.

Considering the retention structures the filtering check dams are hydraulic structures, which are widely adopted in mountain streams to partly retain debris-flows volumes. Their large use is mainly due to the function of reducing peak discharge and sediment concentration of the debris-flow surge. If their function is optimal, a progressive emptying of the storage basin occurs when more watery discharges flow after the peak or in the occasion of successive ordinary floods. Different criteria have been proposed in the literature to correctly design the filter openings, but performance analyses are scarce in the field. In this context the aim of this topic is to verify the functionality in terms of the self-cleaning capability of the multiple-slit check dam built in 2011 in the rio Rudan (Bettella and D'Agostino, 2013).

The study area is the rio Rudan basin, a small catchment located in the Province of Belluno (Veneto Region). It is characterised by a dolomitic nature: high-sloped rocky cliffs make up the upper part along with a narrow, steep valley covered with talus deposit. Fluvial deposits cover most of the lower part, with a minor percentage of morainic, alluvial and fluvio-glacial materials. The basin has a typical Alpine climate with annual precipitation ranging from 950 to 1300 mm, mainly occurring as snowfall from November to April. Runoff is usually dominated by snowmelt in May and June whilst summer and early autumn floods represent an important contribution to the flow regime. On the fan apex, a multiple-slit check dam was built in 2011 (Figure 7).

Figure 7: The debris flow barrier (on the left), and the retention basin (on the right)

The main characteristics of the structure are: spillway 11.1 m long and 3.4 m deep (able to let the design peak discharge pass – 120 m^3/s), structure 6 m height in the spillway, 4 slits 1.3 m wide, retention basin with a capacity of about 7000 m^3.

As to be able to consider and detect the functionality of the structure multiple field activity were carried out. first of all a survey using a Terrestrial Laser Scanner (TLS) was conducted to have a detailed 3D model of the empty retention basin. After some events that happened in the stream some field survey were carried out. The cross-sections were measured to detect the modifications in the stored volume present in the retention basin.

The hydrological events were monitored thanks to the installations of two rain gauges in the Rudan basin that permitted to monitor the precipitations. A rainfall-runoff model to define the peak discharge and validation through field surveys and empirical formulas (D'Agostino, 2005) and physical equations (turbulent flow or dam break hypothesis) was applied. For this issue the grain-size distribution of the sediments deposited in the retention basin was measured. Some attempts to define a correlation between grain size and associated form of sediment transport were carried out to define also how the slit check dam works.

During the time period under consideration only a small debris-flow event occurred in the rio Rudan partially filling the retention basin behind the slit-check dam. During this event there was a deposition of about 850 m^3, and the maximum height of the deposit was around 1.30 m. This debris flow occurred on July 14th, 2012 and was triggered by a rainfall of 35 mm (maximum intensity: 34.4 mm/hour in 15 min). The estimated bulked peak discharge of the event is on the average 9 m^3/s. The successive storm events did not trigger other debris flows but only weak bedload transport floods, which favoured the self-cleaning of the storage basin.

The topographic survey carried out after the debris-flow occurrence showed a gradual self-maintenance of the retention basin. The results suggest that the ratio R between size of the coarsest components of the debris flow occurred (D_{90} = 0.29 m) and the minimum cross-stream openings (1.3 m) are the key factors for the hydraulic design: $R \approx 4.5$.

Moreover, the time sequence of flood events, stream morphology, debris-flow characteristics have also a great influence on the self-emptying behaviour. So, as to the case study, a pattern of conditions facilitated the self-cleaning of the slit check dam (in particular event magnitude and the time sequence of flood events).

This fact has proved a reduction of the maintenance costs and the safeguard of the sediment continuity. Further monitoring actions are necessary to analyze the interaction between the filter and flood events of higher magnitude to better understand how this structure works in more complex conditions.

3.2.5.2 Application of the failure hazard ranking procedure on check dams in Slovenia

3.2.5.2.1 Problem setting

Many check dams in Slovenia are in a very poor condition and pose a serious threat in case of failure. One of these check dams was the check dam on the Suhelj torrent in NW Slovenia (test area). Failure hazard ranking showed that this check dam belongs to the medium to high hazard of failure.

Suhelj check dam (st. 0.92 km)

A. Basic check dam parameters: 14 points
B. Torrential watershed parameters: 24 points
C. Maintenance and management: 10 points
D. Risks to the environment: 20 points
E. Condition of check dam: 32 points

TOTAL: 100 points → medium to high hazard

3.2.5.2.2 Planning approach (by explaining its added value with respect to the problems to be solved and the traditionally applied procedures)

Considering all the evaluated parameters, the analysis shows that the condition of the check dam is the most critical one. Notably, in spring 2014 restoration measures were carried out and the deteriorating check dam was completely reconstructed, including the stilling basin.

The reconstruction of the check dam was the most efficient measure to reduce the failure risk which was carried out after price/performance analysis. If we wanted to reduce the failure hazard even more, we would have to take actions, including mitigation measures downstream to reduce the negative impact on settlements and infrastructure, restoration of erosion areas in the watershed, and a complete reconstruction of the downstream torrent channel. All these measures are more complex and costly.

Figure 8: Suhelj check dam before restoration

Figure 9: Suhelj check dam after the reconstruction (in spring 2014)

After the reconstruction, a new failure hazard evaluation was carried out and the results are the following:

Suhelj check dam (st. 0.92 km) after the reconstruction

A. Basic check dam parameters: 14 points

B. Torrential watershed parameters: 24 points

C. Maintenance and management: 10 points

D. Risks to the environment: 20 points

E. Condition of check dam: 14 points

TOTAL: 82 points → low to medium hazard

With reconstruction we lowered the failure hazard from the "medium to high" ranking class to the "low to medium" hazard class.

3.2.5.2.3 Conclusions

Application of the proposed method shows that failure hazard ranking can be used for analysis how to reduce hazard of existing structures. The method is efficient for determining which parameter, or a group of parameters, is essential for reducing failure hazard.

In the future, this method should be tested on a wider group of structures, using a statistical analysis to confirm the existing rank limits, or to modify them. The method has the potential to be applied on the national level to show the condition of check dams as part of the national water infrastructure. The ranking should be applied for planning maintenance measures and possible reconstructions of the most critical check dams.

3.2.5.3 A physical scale model to investigate torrential filter structures

3.2.5.3.1 Problem setting

Since the seventies, the Forest Technical Service of Austria has been using open bedload sorting (control) dams to control bed load and sediment transport. The reasons for insufficient function fulfilment are found in the structures' unsuitable function, in the woody debris difficulties, in the geological qualities of the sediment or bedload as well as in an inadequate discharge.

With this project we want to find the optimal design of existing bedload sorting (control) dams. This was realized in combination with lab experiments – therefore in order to optimize torrent protection structures, physical scale model experiments are carried out in the hydraulic laboratory of the Institute of Mountain Risk Engineering at the University of Life Sciences in Vienna. The main result should be to analyse the interactions of bedload and sediment with control structures under controlled conditions and the influence of the transport capacity downstream the bedload sorting (control) dams.

3.2.5.3.2 Planning approach – Model setup

Two different types of check dams are investigated. A screen-dam with inclined vertical beams is compared with a beam-dam with horizontal beams (Figure 0). The experiments should evaluate the variation of sediment transport of these structures including the influence of coarse woody debris.

Figure 10: Screen-dam with inclined vertical beams and beam-dam with horizontal beams

Therefore the distance between the steel elements can be adjusted to show their ability to filter sediment. The physical scale of the experiments is 1:30. All experimental runs are Froude-scaled. Both dams are tested in elongated and pear-shaped sediment retention basins in order to investigate the shape effect of the deposition area. The inclination of the basin is 5%.

First the hydraulic effect of the structures is investigated by measuring the flow field and the backwater effects of the protection measures. Then driftwood is added to show the influence of log jams on the hydraulic properties of the different structures.

Experiments with fluvial bedload transport are made for a systematic comparison of the two check dams. First a typical hydrograph for an extreme flood (HQ150) with unlimited sediment supply is modelled. Therefore a typical torrential sediment mixture with a wide grain-size distribution is used. The sediment is fed by a conveyor belt according the transport capacity of the upstream reach. A total sediment volume of 1.05 m^3 is needed for each run. Then the deposition is scanned with a 2-D laser-scan device mounted on a rail above the basin in order to analyze the deposition pattern and the deposited volume. Afterwards a flood with a lower reoccurrence period (HQ5) without sediment transport from upstream is modelled to investigate the ability of the protection structure for self-emptying. Then the basin is scanned again to quantify the volume change in the deposition basin.

To investigate the influence of driftwood on the deposition behaviour experiments with logs are made. The hydro- and sedigraphs are the same as the ones described above, but different log diameters and lengths are added upstream the basin. For the driftwood experiments two scenarios are considered to show different log jam developments. First the experiments are run with a continuous feed rate and afterwards they are rerun with a sudden addition of drift wood. After scanning the surface the more frequent flood without sediment and wood from upstream is modelled to show the self-emptying behaviour of the basins.

3.2.5.3.3 Results, Conclusions and Recommendations to Practitioners

- ✓ For Zollinger (1983) the key parameters to optimize a deposition basin are the size and form as well as the height and size of the openings of a dam. Furthermore, he found out that for self-emptying high discharges with low sediment concentration in comparison with a high content of fine sediment and no presence of cohesive material is needed.

- ✓ Backwater effects reduce the sediment peaks and prefer self-emptying processes.

- ✓ The actual project and the pre-investigations showed that the deposition during the experiments was not controlled by sorting-effects at the location of the dam. The deposition always started from upstream, where the transport capacity was reduced due to the milder slope and the widening of the basin. No grain sorting effects could be identified.

- ✓ Driftwood causes a more chaotic deposition behaviour, but clearly increases the deposition volume. Driftwood causes therefore higher deposition of bedload material. Due to the chaotic behaviour of the log jams, driftwood causes a higher variability in the deposition behaviour.

- ✓ Even if the log jams are removed, the self-emptying efficiency is limited. No statistically significant shape or filter structure type effect could be proofed.

- ✓ Driftwood often causes log jams at the filter structure and therefore increases the trapping efficiency for bedload material. Beam dams with horizontal beams produce worse log jams than screen dams with inclined vertical beams.

- ✓ Screw dams with vertically inclined beams cause less clocking by driftwood than beam dams with horizontal beams.

Figure 11: Different clocking behaviour of the dam types

- ✓ Openings of dams have to be over the whole height, but there may be beams in-between. The key findings of the investigations of torrential filter structures show that the deposition behaviour of bedload can be controlled by the beam distance, if no driftwood is present.

- ✓ The pear shaped basin resulted in higher deposition than the elongated basin.

3.2.5.4 <u>Hydraulic scale model tests for the analysis of bedload transport processes in stepped torrent channels</u>

3.2.5.4.1 Problem setting and objectives

To determine the sediment input into receiving channels and, along with it, the risk of flooding and overbank sedimentation, the knowledge of bedload transport processes is necessary at the functional part of the barrier, as well as in the torrent channel (alluvial cone) to the receiving channel.

A project goal is to generally analyse and further optimize the bedload transport characteristics in the torrent channel to the recipient. Knowing the sediment inputs from the tributaries is very important for the protection of the lower reaches. For this purpose, the existing scale hydraulic model of the Schnannerbach (Tyrol, Austria) in the hydraulic laboratory at the University of Innsbruck was used to make further investigations.

The main aim of the experiments is a qualitative assessment of the capacities in the torrent channel and the confluence zone and, further, the transport rates in the torrent channel in order to define critical sediment loadings and grain size mixtures, which lead to an overload of the torrent channel. Additional experiments within the SedAlp project should investigate the influence of different gradient changes of the torrent channel in combination with different grain size distributions of the sediment input.

4.2.5.4.2 Planning approach – Model setup and targets of the experiments

The Schnannerbach represents a typical Alpine limestone mountain stream which is mainly dominated by fluvial sediment processes. Flood events with a relevant hazard potential for the populated alluvial fan are characterized by long-lasting precipitation events with moderate intensities, leading to medium and high discharges above the critical runoff and, correspondingly, fluvial bedload transport processes.

The main task of the Schnannerbach scale model experiments is the structural optimization of the river channels to fully prevent overbank flooding for the design case of a 150-annual event. Due to the improved database, the design case was changed to the flood event from August 2005. The experimental programme is comprised of various structural measures in the Schnannerbach torrent channel and in the Rosanna river as well. The characteristics of the observed sediment grain sizes correspond to investigations made in the catchment area after the flood event in August 2005. Further, after the reconstruction of the 2005 flood event and with it the validation of the scale model and the definition of critical loading conditions, numerous experiments were simulated under steady-state discharges. They were aimed to determine the effects of different optimization options and to determine the resulting transport capacities in the river channels.

The model was built at a scale of 1:30, and it conforms to Froude similarity. It covers about 280 m of the Schnannerbach torrent to the confluence with the Rosanna river. The latter is covered over a length of 200 m.

Based on the experiments for generally improving flood protection at the alluvial fan of the Schnannerbach torrent, further experiments were executed to examine the sediment transport of the torrent channel without the influence of the receiving water course. The essential factors in this case, the torrent channel gradient and the impacting bedload characteristics, were analysed. In these experiments, the draining channel was completely removed in order to prevent regressive aggradation and backwater effects.

4.2.5.4.3 Construction of the model, methodology and test arrangement

To investigate the influence of the torrent channel gradient, an artificial decrease in the channel was built which is intended to simulate a flatter slope and thus lower transport rates.

Three different gradient changes were tested: The first gradient change was from the original approximately 12% gradient to a 9% gradient, the second from 12% to 7.5% and the third from 12% to 6%.

For each of these situations, steady-state experiments with three different grain size distributions for the sediment input were simulated. The grain size distributions were taken from the event documentation of the 2005 flood event (Rudolf-Miklau et al., 2006) and were adjusted for the model tests. All experiments were documented with photographs and videos. To create a mass balance study of the transported sediment loads, the sediment output of the tests was dried and weighted for every experiment.

4.2.5.4.3 Results, Conclusions and Recommendations to Practitioners

- ✓ Bedload management has to be improved also at the retention structures in the upper catchment of the Schnannerbach torrent:
  Hydraulic scale model tests for the analysis of bedload transport processes in the stepped torrent channel of the Schnannerbach and the confluence with the Rosanna river clearly showed that the optimization in the receiving water is not sufficient enough to transport all the incoming tributary sediment.

- ✓ However, the transported sediment can be significantly improved with a few structural optimizations on the alluvial fan. Overbank flooding and sedimentation during a flood event according to the August 2005 event can be delayed significantly and the damages on the alluvial cone can be minimized with it. The following optimizations in the confluence zone were found to be the best:

  - ✓ Heightening of the sidewalls of the Schnannerbach torrent channel in the near range of the confluence point
  - ✓ Extension of the sidewalls of the Schnannerbach torrent to the confluence point
  - ✓ Optimization (lowering) of the intersection-angle
  - ✓ Lowering of the Schnannerbach mouth to increase the gradient in the last section of the Schnannerbach torrent

- ✓ The additional experiments within the SedAlp project showed the influence of different gradient changes and different grain size distributions on the sediment transport rates in the torrent channel.

  - ✓ With a gradient change from 12% to 9% no overbank occurred in all simulations
  - ✓ A further reduction of the channel gradient to 7.5% leads to flooding, when testing with the two coarser grain size distributions
  - ✓ The experiments with a gradient change from 12% to 6% led to overbank sedimentation with all tested grain size distributions
  - ✓ There could be also a difference in the way of overbanking observed:
    a. While with coarse grain size distributions the flooding appears rapidly, this process is a bit sluggish with finer grain sizes

   b. The overload of the channel occurs in all cases pretty much at the spot where the gradient changes. Starting from this point, similar to the original Schnannerbach experiments, regressive aggradation occurs towards the village bridge further upstream.

- ✓ Further investigations showed that massive structural optimizations at the confluence in the Rosanna river yielded only very small improvements with explicit enhancement of the water-level of the Rosanna. A flat river bed of the torrent channel without steps and pools provided a better transport capacity of the Schnannerbach, but not on the entire system, in which the deposits at the confluence are significant.

- ✓ In general it was established that the transport in the torrent channel is significantly influenced by the conditions in the confluence area. The Schnannerbach torrent channel in its original condition may cope with a sediment fraction of about 12%. The entire system with the confluence zone can dissipate a sediment fraction up to 6% until overbank sedimentation appears firstly just upstream the state road bridge. In order to achieve the clogging of the village bridge a sediment fraction of 12% is necessary. For this reason, these two critical spots along the torrent channel are defined. On the one hand, there is the state road bridge in which in all experiments, as well as in historic flood events, the overbank sedimentation firstly appears. The second spot is the village bridge. All these findings are based on the simulation of the 2005 flood event characteristics.

- ✓ Another interesting process behaviour related to the bedload transport in the stepped torrent channel is surging. Originally suspected as a model scale effect due to an inaccurate sediment supply at the Schnannerbach model boundary, this effect can be mainly related to the hydraulics and the transport process through the steps and pools of the torrent channel. A distinctive surge pattern could be observed as early as the sediment fraction increased by about 1.6%. However a corresponding river bed shape is necessary. With increasing sediment input the steps and pools disappear and a flat river bed develops. On this flat river bed there was no surge observed. A positive aspect of these surges is that it forces the onward movement of bedload in the confluence zone.

- ✓ The additional experiments within the SedAlp project showed the influence of different gradient changes and different grain size distributions on the sediment transport rates in the torrent channel. With a gradient change from 12% to 9% no overbank occurred in all simulations. A further reduction of the channel gradient to 7.5% leads to flooding, when testing with the two coarser grain size distributions. The experiments with a gradient change from 12% to 6% led to overbank sedimentation with all tested grain size distributions.

- ✓ There could be also a difference in the way of overbanking observed: While with coarse grain size distributions the flooding appears rapidly, this process is a bit sluggish with finer grain sizes. The overload of the channel occurs in all cases pretty much at the spot where the gradient changes. Starting from this point, similar to the original Schnannerbach experiments, regressive aggradation occurs towards the village bridge further upstream.

Figure 12: Steady-state conditions in the Schnannerbach torrent channel; situation with a change in gradient from 12% to 6% at the red line – conditions after 16 minutes (prototype dimensions) of modelling

3.2.6 Conclusions and recommendations

The findings of the SedAlp project with respect to the broad problem complex of "planning or designing efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches" clearly indicate that mountain stream systems in particular work at some distance away from the equilibrium. Upon removal of internal constraints within these open systems, irreversible processes take place as drivers towards the local equilibrium. In mountain stream systems, sediment transport processes are driven by available energy gradients in their different forms. Manmade check dams delay and temporarily constrain these irreversible evolution patterns, thereby mitigating flood hazard processes in endangered areas. Sediment connectivity, however, is altered both in space and time.

Adopting a stream network perspective at larger scales by considering also downstream river systems a new set of problems emerges, tightly linked to the insufficient sediment feeding from upstream stream systems.

The problem identification, setting and solution necessarily involve concerted action among policy makers, practitioners and researches, therefore in this section the effort is made to tailor the recommendations accordingly.

3.2.6.1 Recommendations for Policy Makers

Tangible progress with respect to enhanced sediment connectivity between upstream torrential headwaters and downstream river reaches is improbable without excellent work at the policy maker level. The probability of success directly descends from the adopted pre-analytic vision. Public policy oriented toward maximising socio-eco-systemic resilience provides support and funding for analyses at different scales, which are necessary to understand sediment dynamics with sufficient accuracy and precision. In this chapter efforts were made to break down from a methodological perspective the problem complex and indicate the relevant analytic steps to understand from both a qualitative and quantitative standpoint the possible solution patterns and the related management options.

Making possible the application of a balanced strategy of investigation is therefore the first essential recommendation for policy makers.

Policy maker should be aware that solving sediment connectivity related problems, might entail strong modifications of existing protection systems originally designed to retain rather than to activate sediment dynamics.

Though the overall solution might result in a different set of technical artefacts, first a robust and shared vision elaborated by fully engaged stakeholders is needed as a guiding beam throughout the problem solving phase.

Policy makers should acknowledge that sufficient room and commeasured time-frames for negotiation and consensus building must be provided. In this context, restoring sediment dynamics necessarily involves "giving space" to both headwaters and downstream river reaches. Policy makers should therefore set the basis for a mature envisioning-problem setting-problem solving cycle.

3.2.6.2 Recommendations for practitioners

In this chapter the SedAlp working group explored the field of possible technical solutions. Practitioners should be aware, however, that the product is not a compilation of ready to use solution patterns.

Rather, it is a methodological guideline to correctly identify the problem to be solved, to perform the convenient system-analytic steps and to tune accordingly the level of detail of the analysis. Depending on the problem complexity practitioners should be open to consider deriving knowledge for the planning process from (i) backward-oriented indication, (ii) mathematical modelling and (ii) physical lab experiments.

An augmented flexibility in the planning approach is necessary. Recipe-like solutions can be readily applied only to standard problems. Planning or designing efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches involves providing verifications of the obtained solutions with respect to the system performance at different scales.

3.2.6.3 Recommendations for Researchers/Academics

In the light of the identified problem complexities we identified four main research fields: (i) interdisciplinary research at the interface between processes, risk consequences and resilience, (ii) applied research targeted at improving the quality of protection system design, (iii) specific research to better understand river morphology, ecohydraulics, system functions and the related, monetarily quantified, system services, and (iv) research activities supporting the effectiveness of the decision, communication and participation process.

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3.3 Guideline for improved planning of hydropower plants aimed to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches

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3.3.1 Background

Most natural river reaches are approximately balanced with respect to sediment inflow and outflow. Dam construction dramatically alters this balance, by creating a reservoir, thereby often resulting in substantially reduced velocities and relatively efficient sediment trapping. The reservoir accumulates sediment and loses storage capacity until a balance is again achieved, which would normally occur after the reservoir fills with sediment. The rate and extent of sediment deposition depends on factors influencing sediment yield, sediment transport and the reservoir's trapping efficiency. The distribution of sediment deposition in different reservoir regions is equally important. Depending upon the shape of the reservoir, mode of reservoir operation, sediment-inflow rates and grain-size distributions, the incoming sediment may settle in different areas of the reservoir. Reservoirs are subjected to several types of sedimentation as a function of the geomorphology (geology, slope, topography and land use, drainage density, climate, etc.) of the watershed and the biological cycles in the reservoir or the drainage basin, in the following order of importance:

1) Erosion of the drainage basin produces dissolved substances and mineral particles with an assortment of sizes, shapes and types that are related to the rock type and slope of the drainage basin. In addition, landslides produce debris flows. Sediment is delivered to the reservoir both as suspended sediment load and as bed load;

2) Sedimentation occurs due to plant debris from the drainage basin and from vascular plants and phytoplankton in the reservoir. The debris decomposes very slowly and often forms alternating layers with mineral deposits. The mud resulting from this type of sedimentation is very fine and extremely fluid, often with a gelatinous texture. Accumulation of mud at a rate of several centimetres per year often causes problems when a reservoir is drawn down or drained. It has a very high organic content resulting in heavy consumption of dissolved oxygen. The proportion of sedimentation caused by each type may be assessed by on-site visual observations and by analyses of the sediment deposit.

The effects of dam construction on the river system can be synthetically explained as follows:

- downstream water and sediment input reduction: various effects;
- in the reservoir sediment trapping: reservoir storage loss;
- upstream over-aggradation: possible inundation phenomena.

Declining storage reduces and eventually eliminates the capacity for flow regulation and concomitant benefits such as water supply, flood control, hydropower, navigation, recreation, and environmental aspects that depend on releases from storage. Water resource professionals are concerned with the prediction of sediment deposition rates and the probable time when the reservoir would be affected in serving its intended functions. The estimation of sediment deposition is also important in the design and planning of storage reservoirs. However, it is difficult to estimate the volume and rate of sediment deposition accurately from the known criteria and available sediment transport equations. Reservoir capacity surveys indicate patterns and rates of sedimentation, which help in improving estimation of capacity-loss rates. Storage reservoirs built across rivers or streams lose their capacity on account of deposition of sediment. Surveys indicate that world-wide reservoirs are losing their storage capacity, at an annual rate of about one percent, due to accumulation of sediments. The impacts of sedimentation on the performance of the reservoir project are manifold. Some of the important aspects are:

- reduction in live storage capacity of the reservoir;
- accumulation of sediment at or near the dam may interfere with the functioning of water intakes and hence is an important parameter in deciding the location and level of various outlets;
- increased inflow of sediment into the water conveyance systems and hence to be considered in the design of water conductor systems, desilting basins, turbines etc.;
- sediment deposition in the head reaches may cause rise in flood levels;
- the location and quantity of sediment deposition affects the performance of the sediment sluicing and flushing measures used to restore the storage capacity.

The prediction of sediment distribution in reservoirs is essential in feasibility studies during planning/design of components of new projects and performance assessment of existing projects. Pressures on sediment continuity are due to hydropower physical structures (weirs, barrages, impoundments, diversions) and hydropower operations (hydropeaking, residual flow, reservoir flushing). Ecological impacts of a disruption of longitudinal and lateral river continuity determine the reduction of dynamic processes and habitat diversity, changes in groundwater levels, sediment regime and water temperature, etc. Ecological challenges are closely linked to hydromorphology because living organisms react to abiotic factors of their habitat, like flow velocity, bed material, and suspended sediment concentration. The reservoir sedimentation:

- in the alpine part of Europe has received scientific attention over the last decades in numerous research publications and conferences;
- in the future, climate change might be a further component in this system affecting sediment input, from long-term erosion processes to catastrophic events;
- might affect strategies for hydropower development, for example by reducing the useable hydropower potential.

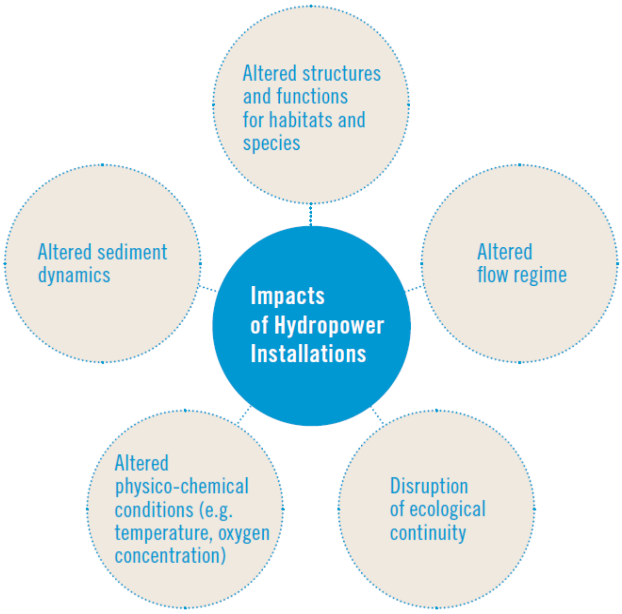


Figure 1: Possible key ecological impacts of hydropower installations; illustrative range of possible alterations typically associated with hydropower dams (from: ICPDR – Sustainable Hydropower Development in the Danube Basin, Guiding Principles, 2013)

3.3.1.1 Overview of types of hydropower plants and main operations

3.3.1.2 A great variety of different hydropower types exists, and a clear distinction is impeded by close relationships and smooth transitions. However, the majority of classification schemes cover one or more aspects of the following criteria (Giesecke and Mosonyi, 2009; IPCC, 2011):

- installed capacity (in general distinction between small and large hydropower; sometimes also division into pico, micro, mini, small, medium and large hydropower);
- construction type (run-of-river plant, storage plant or pumped-storage plant) (Fig. 3);
- storage volume (daily, weekly, seasonal or annual storage reservoir);
- location of the powerhouse (in case of run-of-river plants: river power plant or diversion plan; in case of storage / pumped-storage plant: barrage plant or diversion plant);
- operation (run-of-river operation, peaking operation, storage operation or pumped-storage operation);
- drop height (low pressure, medium pressure or high pressure plants);
- electricity supply (base load, medium load or peak load power plants);
- purpose / water resource management (single-purpose or multi-purpose plants);
- feed-in type (plants that feed into the grid or auxiliary plants);
- special types (e.g. hydrokinetic energy conversion systems).

Figure 2 shows a classification scheme of the most common types of hydropower plants in Austria, based on the criteria installed capacity, construction type, storage volume, location of the powerhouse and operation mode (Habersack et al., 2011; Wagner et al., 2015).

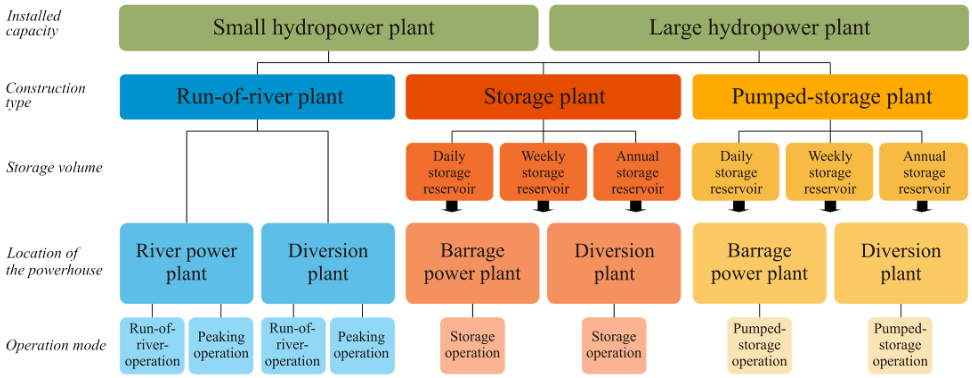


Figure 2: Classification scheme of hydropower plants in Austria according to the research project DSS_KLIM:EN (from: Habersack et al., 2011; Wagner et al., 2015)

According to the criteria "installed capacity", generally small and large hydropower plants can be distinguished. Within the European Union no common definition of a "small hydropower" exists. It is often connected to legal definitions concerning subsidies for "green" electricity. While for example plants with an installed capacity of less than 1 MW fall into this category in Germany, the boundary is usually drawn at 10 MW in Austria (Giesecke and Mosonyi, 2009; Habersack et al., 2011). In the following section, the three main categories of hydropower plants according to operation (run-of-river plant, storage plant and pumped-storage plant) will be described (Fig. 3).

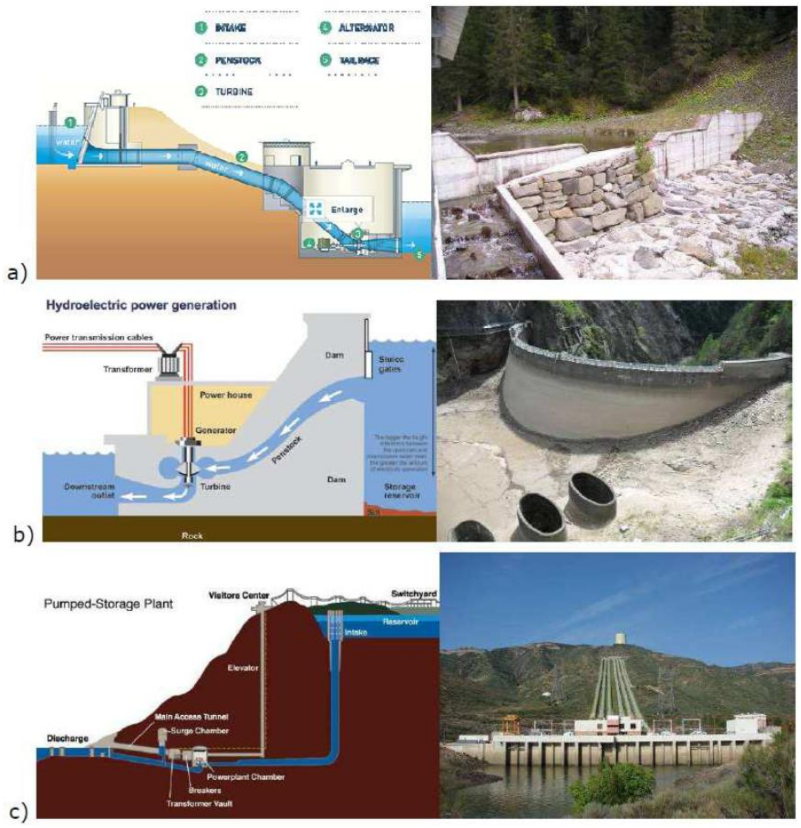


Figure 3: Types of dams; a) Cordon stream (Veneto Region, Italy; photo by: ARPAV); b) Comelico dam, Piave River (Veneto Region, Italy; photo by: ARPAV); c) pumped storage plant (images from: Internet)

Run-of-river plants (Fig. 4) make use of the height difference of the water level upstream and downstream of a weir. They convert both potential and kinetic energy of the water into hydroelectric energy. In the case of a river power plant the powerhouse and the weir system (which fulfils the purpose of controlled flood discharge) are situated directly in the river (instream) and form a single unit. Thus, all essential components for power generation are located within the river flow. In the case of a diversion plant water is abstracted from the main river channel to be utilized for electricity generation (off-stream), and subsequently returned into the river concerned or into a different water body. A reduced discharge (residual flow) can be observed in the main channel. For run-of-river operation the storage of water is not possible (e.g. due to a lack of impoundment space or permit). Electricity generation depends on the current discharge and cannot be adapted to demand. Thus, the run-of-river operation is generally suitable for providing base load electricity. In the case of peaking operation ("hydropeaking"), water is temporarily stored in the upstream impoundment. This operation mode allows the adaptation of discharge rates and is therefore generally suited for daily peak load electricity generation or for balancing short-term fluctuations. Moreover, additional purposes like flood protection (limited retention of flood waves) can be fulfilled (Habersack et al., 2011).

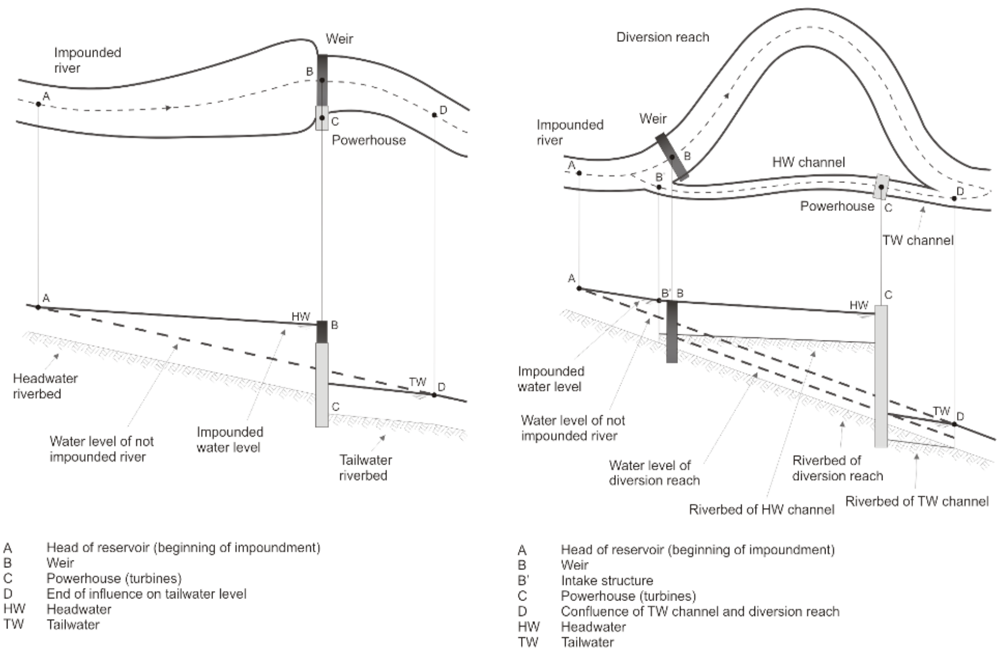


Figure 4: Schematic overview of a run-of-river hydropower plant: river power plant (left) and diversion plant (right) (after Habersack et al., 2011)

Storage plants (Fig. 5) use the height difference between one or more reservoirs with natural inflow in higher altitude and a lower-lying hydropower plant. Water flows from the reservoir through pressure tunnels and penstocks to the turbines located in the powerhouse. Storage plants are relatively independent from current discharge – the useable amount of discharge is stored in the reservoir and can be released in times of high demand (storage operation). Therefore, they are suited for providing peak load electricity and ancillary services (e.g. energy to balance grid fluctuations). According to the storage volume related to inflow, a differentiation between diurnal, weekly, and annual reservoirs can be made; seasonal storage would be a further option. In the case of a barrage power plant the powerhouse is located directly at the downstream side of the dam. In the case of a diversion plant, the powerhouse and dam are spatially separated (Habersack et al., 2011).

In the case of pumped-storage plants (Fig. 6) the upper reservoir is (partially) filled with water that is pumped from a lower reservoir. Also pumped-storage plants with a natural inflow exist. In times of high electricity demand, water flows from the upper reservoir through pressure tunnels and penstocks to the powerhouse and subsequently into the lower reservoir. In contrast to "normal" storage plants, pumped-storage plants can also use electricity from the grid during periods of low demand to pump the water into the upper reservoir (pumped-storage operation), which is thus saved for peak load periods or for providing ancillary services. Thereby, they can serve as "storage batteries" for more volatile forms of renewable energy (e.g. wind and photovoltaics). Definitions concerning the other aspects of classification (storage volume, location of the powerhouse) are equal to the specifications for storage plants (Habersack et al., 2011). Regarding the volume stored and size, the Italian norms on dams specify that:

- great dams: H > 15 m; Volume > 1 Mm^3;
- small dams: H < 15 m; Volume < 1 Mm^3.

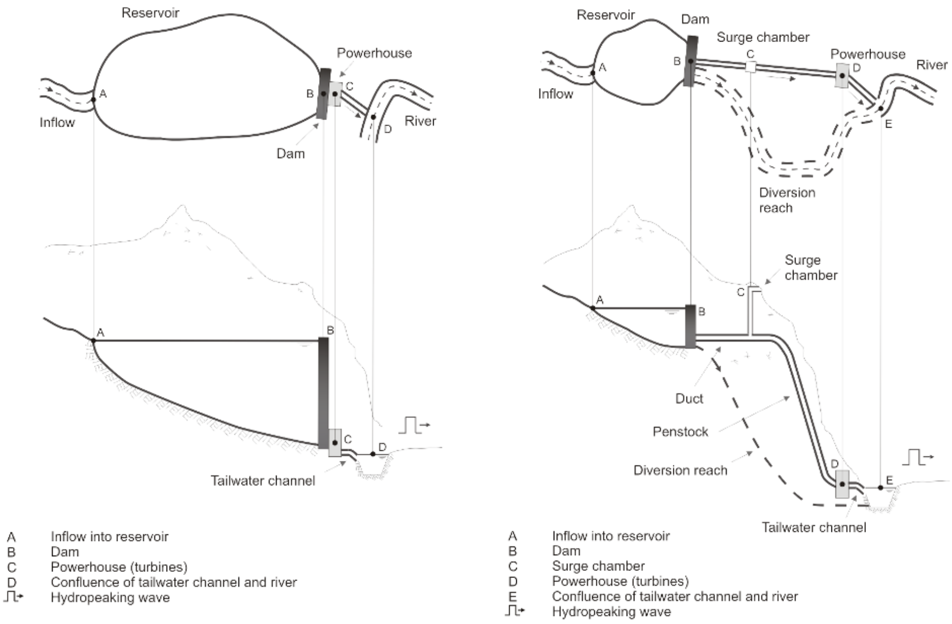


Figure 5: Schematic overview of a storage hydropower plant: barrage power plant (left) and diversion plant (right) (after Habersack et al., 2011)

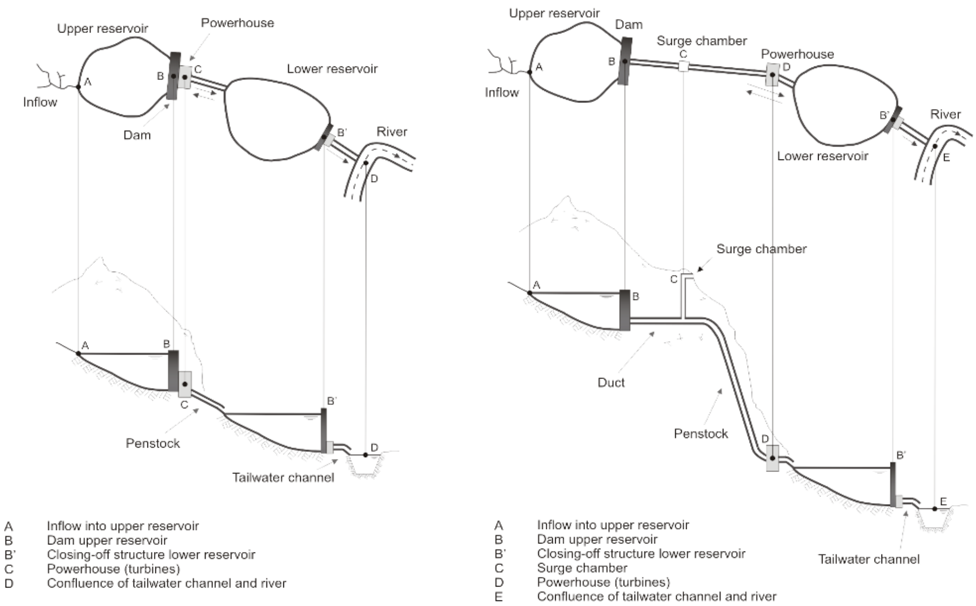


Figure 6: Schematic overview of a pumped-storage hydropower plant: barrage power plant (left) and diversion plant (right) (after Habersack et al., 2011)

3.3.2 Problem and processes description

The presence of a transversal obstacle like a dam affects the natural river processes such as liquid discharge and sediment transfer from upstream to downstream. The natural equilibrium tendency of the river, driven to a balance between erosion and depositional processes, becomes altered, thus affecting all the components of the river system. For this reason, downstream the dams, the effects of sediment continuum interruption on the river system regard several aspects; the most important are:

- hydro-morphological alterations due to the lack of sediment that is stored into the artificial upstream reservoir;
- ecological alterations: fish, macro/micro invertebrates, bank vegetation;
- other aspects: touristic, social river uses/fruition.

The negative effects of the sediment non-continuum regard not only the portion downstream the dam, but also the upper part (artificial reservoir); the sediment stored limits, during the time, the potential energy production, due to the reduction of reservoir volume effective for the water storage. The reservoir sedimentation generates other effects, such as:

- loss of effectiveness of the dam's bottom sluices and of captation points;
- increasing stress to the dam's structure, due to the sediment stored pressure.

Nevertheless, the artificial dam operations of reservoir cleaning (flushing, de-siltation) give a negative impact on the river habitat (above all fish fauna) and to the chemical-physical quality of the water.

Generally speaking, there is a problem of surplus sediments on the one side and of a sediment deficit on the other side (Habersack, 2011), an imbalance to which hydropower contributes its share. Looking at a hydropower plant (Fig. 7), this overarching problem manifests itself mainly in reservoir sedimentation, riverbed degradation, and other morphological changes. However, it is important to always regard hydropower in context with other management and engineering interventions in a fluvial system (Schober, 2006). The division into the two parts upstream and downstream of the hydropower plant should not leave the impression that they can be seen separately from each other – on the contrary, sediment surplus and deficit represent two sides of one problem of sediment continuity.

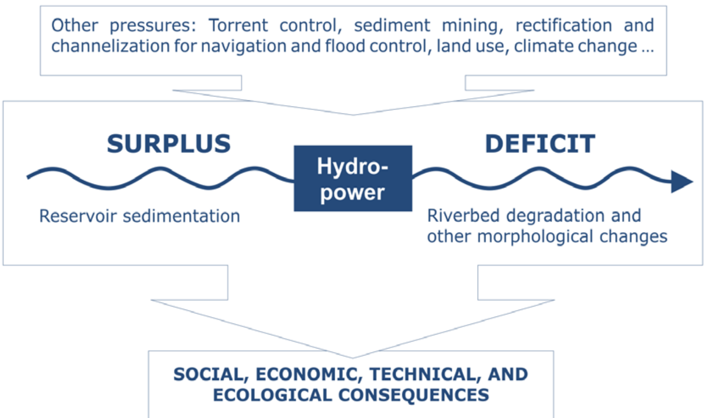


Figure 7: The interaction of hydropower with a river's sediment regime and morphology and its larger context (from: Schoder, 2013)

3.3.2.1 Impacts of hydropower plants on sediment continuity: river morphology implications

Along a natural river system there is a sort of dynamic equilibrium between erosion, deposition and remobilization of material. Such natural dynamic equilibrium is disturbed by hydropower impact, leading in many cases to sedimentation upstream and riverbed degradation downstream; the problem of surplus sediments on the one side and of a sediment deficit on the other side leads to reservoir sedimentation, riverbed degradation, and other morphological changes. Sedimentation processes are balanced in most of the natural rivers. The construction of dams and reservoirs influences this balance, giving a sediment surplus due to reservoir sedimentation. In reservoirs the flow velocities, turbulences and bed shear stresses are reduced and this leads to sedimentation of the transported bed and suspended load. In further consequence the bed levels rise and reduce the storage volume by "filling up" the reservoir (Harb et al., 2010). Decreased reservoir volume reduces and – in extreme cases – eliminates the capacity of hydropower production, water supply, irrigation and flood control benefits (Morris and Fan, 1998). The presence of a dam determines the rising of 2 processes:

***1 - reservoir sedimentation** (**aggradation** **processes**)*: just upstream the dam. This process depends on several factors:

- physical reservoir characteristics: (size, topography, hydrology, geology, and vegetation cover of the catchment) and climate change (affecting erosion rates);
- tendency to erosion of drainage contributing areas to the reservoir;
- hydrogeological watershed hazards.

Sedimentation poses a threat to the sustainability of reservoirs around the world – not only for hydropower generation but also for other purposes such as irrigation, drinking water supply, fishing, and recreation – because the annual loss of storage capacity due to sedimentation already exceeds the additional capacity of newly constructed reservoirs (Figure 8; Schleiss et al., 2010; Boes, 2011). Pumped-storage as well as run-of-river plants can be affected by sedimentation problems, depending on the material input from tributaries (Gaisbauer and Knoblauch, 2001). Consequences of reservoir sedimentation for the former are, on the one hand, the obstruction of outlet structures, and thus affecting the operation and security of the whole power plant, and, on the other hand, the reduction of available reservoir volume (Boes, 2011). Moreover, abrasion of turbines and other technical equipment can occur if material is evacuated through the intake (Habersack et al., 2002; Doujak and Götsch, 2010). From the impoundments of run-of-river plants considerable amounts of fine material can be remobilized during flood events, which aggravates the damage caused by inundations. In spite of these serious technical, economic, and social implications, planners and operators of reservoirs are not yet sufficiently aware of the problem, or focus on short-term solutions (Schleiss et al., 2010).

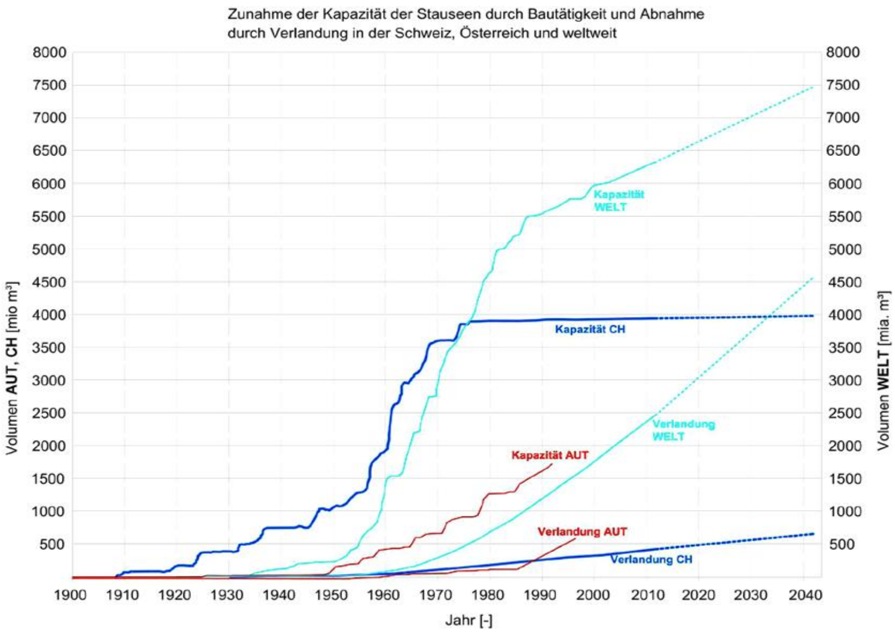


Figure 8: Increase of reservoir capacity due to construction, and decrease due to sedimentation in Austria (A), Switzerland (CH), and globally (WORLD) (after Schleiss and Oehy, 2002; Boes and Reindl, 2006; cited in: Boes, 2011)

The highest sedimentation rates of hydropower reservoirs are reported for arid regions in the Middle East (1.02% per year), Australia and Oceania (0.94% per year), and Africa (0.85% per year). In Asia, 80% of the useable hydropower reservoir volume will be lost to sedimentation by 2035 (Basson, 2009). Figure 9 shows some examples of reservoir sedimentation, in Central Europe and globally. Although rates of only 0.2% per year have been estimated for Switzerland and Austria, this does not mean that sedimentation is a minor problem in these countries, because operational and security issues can already arise at a very early stage, when for example turbidity currents are rapidly growing a layer of sediments near the dam and affect the outlets (Schleiss et al., 2010).

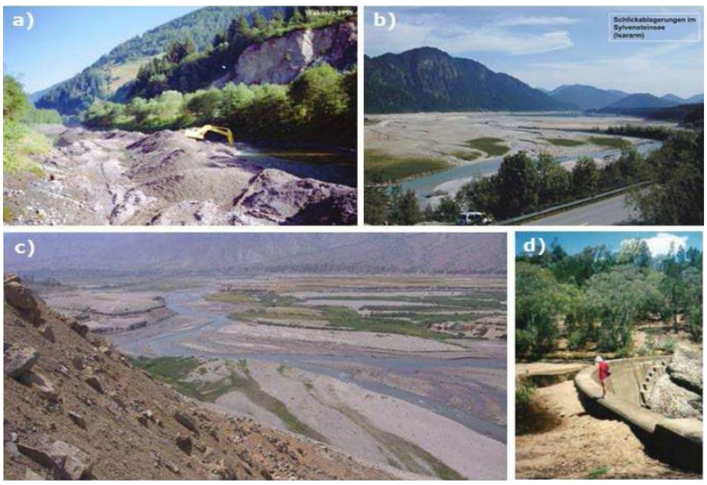
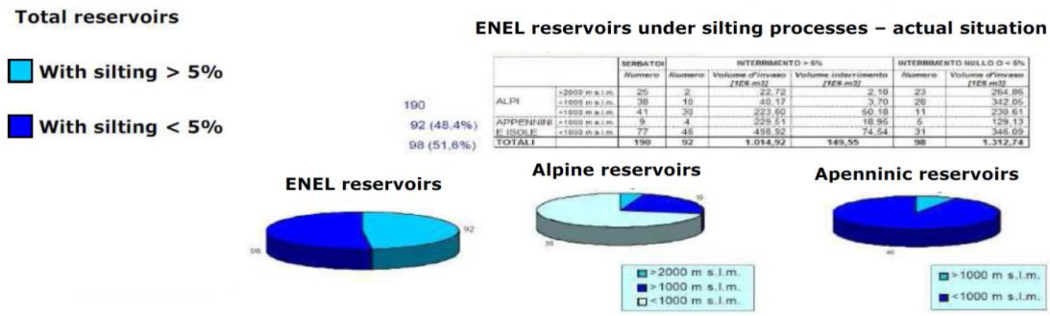


Figure 9: Examples of reservoir sedimentation. a) Großsölk, Austria (Habersack et al. (2002)); b) Sylvenstein, Germany (ALPRESERV (2012)); c) Gallito Ciego, Peru (Jacobsen (2012)); d) Koorawatha, Australia (Chanson, 1998; cited in: Boes, 2011)

The solid sediment yield is extremely variable; in Italy, for instance, a sediment yield included between 1% and 7% of the total volume capacity has been evacuated for a large number of reservoirs (Fig. 10); it means that, in absence of sediment management operations limiting the sedimentation effects, the mean effective life of such reservoirs is included between 100 and 150 years. The silting of Italian great dams has been estimated as the 52% of the total great reservoirs (that is, the 55% of the total storage capacity).



		SERBATOI	INTERRIMENTO > 5%			INTERRIMENTO NULLO O < 5%	
		Numero	Numero	Volume d'invaso [1E6 m3]	Volume interrimento [1E6 m3]	Numero	Volume d'invaso [1E6 m3]
ALPI	>2000 m s.l.m.	25	2	22,72	2,18	23	264,86
	>1000 m s.l.m.	38	10	40,17	3,70	28	342,05
	<1000 m s.l.m.	41	30	223,60	50,18	11	230,61
APPENNINI E ISOLE	>1000 m s.l.m.	9	4	229,51	18,95	5	129,13
	<1000 m s.l.m.	77	46	498,92	74,54	31	346,09
TOTALI		190	92	1.014,92	149,55	98	1.312,74

Figure 10: Overview of sedimentation of Italian reservoirs managed by ENEL (from: Bizzini et al., 2009; modified)

Three sedimentation zones (Fig. 11) can be distinguished along the longitudinal section of a reservoir (Morris and Fan, 1998):

a) upstream portion ("topset bed"): this is where the coarser sediments are usually deposited. However, depending on the morphology of the delta, finer and very fine grain sizes are also possible;

b) middle portion ("foreset bed"): this is actually the head of the delta, which is characterized by an increasing longitudinal gradient along with decreasing grain sizes;

c) downstream portion ("bottomset bed"): this is the area next to the dam structure where the fine particles carried to this point by the density currents and stochastic transport are deposited; the provision of additional dead storage would allow for this additional volume and can thus help reduce the sedimentation of the reservoir.

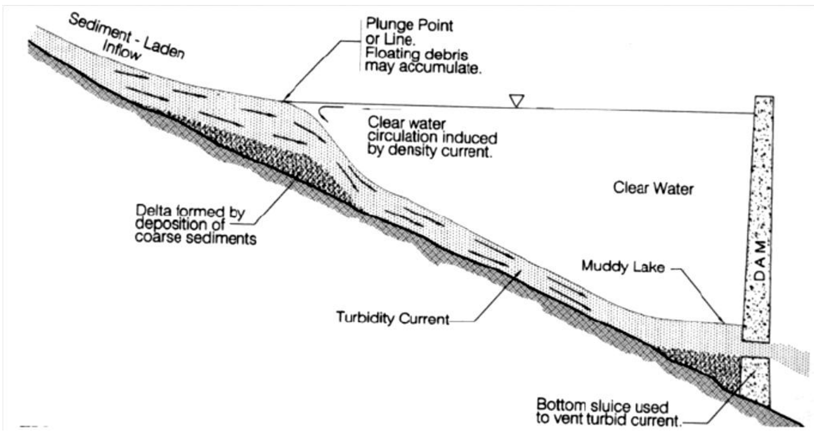


Figure 11: Schematic representation of a turbidity current in a reservoir (from: Morris and Fan, 1998)

Important elements for evaluating the tendency and rate of sedimentation in reservoirs are:

- Trap efficiency of reservoirs and importance of bedload and suspended load for sedimentation. The largest fraction of the sediments carried into a reservoir usually consists of suspended matter (80 to 90% in the case of smaller and medium-sized reservoirs, 90 to nearly 100% in the case of larger reservoirs). The bed load is usually of less significance. Large suspended-sediment loads are usually transported in flowing water bodies during periods of flood. The inflow from the catchment area, which is heavily loaded with fine sediments, has a higher unit weight than the stagnant water in the reservoir. The turbidity current moves at considerable speed along the inclined lake floor towards the lowest point of the dam (De Cesare, 2006). Turbidity flows are often the decisive process for the re-distribution of sediments within a reservoir. The following conditions lead to the development of turbidity currents (Oehy et al., 2000):

- high concentrations of suspended particles in the inflow;
- great water depths at the entrance of the inflow;
- nearly stagnant water in the reservoir;
- steep slope of the reservoir floor;
- pipe-shaped, straight reservoir geometry.

These conditions are present in Alpine reservoir lakes so that even minor annual floods may lead to the formation of turbidity flows.

- Spatial and temporal development of reservoir sedimentation. Typical turbidity currents may reach flow velocities of up to 0.5 to 0.8 m/s, allowing them to transport fractions with a maximum diameter between 0.01 to 0.03 mm. Turbidity currents normally occur already during the annual floods. They are thus the main cause for the transport of fine sediments along the thalweg of alpine reservoir lakes down to the dam, where they are deposited. While the sediment volume is only small compared with the overall volume of the reservoir lake, the sediments concentrated near the dam may considerably affect the operation of the outlet works such as bottom outlet und power intake after a few years of operation (De Cesare, 2006). Depending on the gradient of the thalweg, turbidity currents may reach high velocities. This may re-mobilize the already deposited sediments and carry them towards the dam. The introduction of additional fine sediments into the suspension increases the density of the turbidity current, which in turn increases its velocity. It slows down again in shallow sections so as to deposit sediments, which eventually leads to the disappearance of the turbidity flow (De Cesare, 2006).

- Long-term course of sedimentation of non-flushed reservoirs.

2 - sediment deficit: <u>degradation</u> processes downstream the dams. Rivers reach a state of quasi-equilibrium after decades to centuries of adjustment. This quasi-equilibrium state is defined as having no net accumulation or depletion of sediment in the bed, banks, or floodplain and nearly constant average hydraulic characteristics (width, depth, velocity, roughness, slope, and channel pattern) through a reach of channel at a given discharge (Andrews, 1986). Modifications in the natural flow regime can drive morphological changes in channel form, disrupting the existing quasi-equilibrium state (Petts and Gurnell, 2005) (Figure 12).

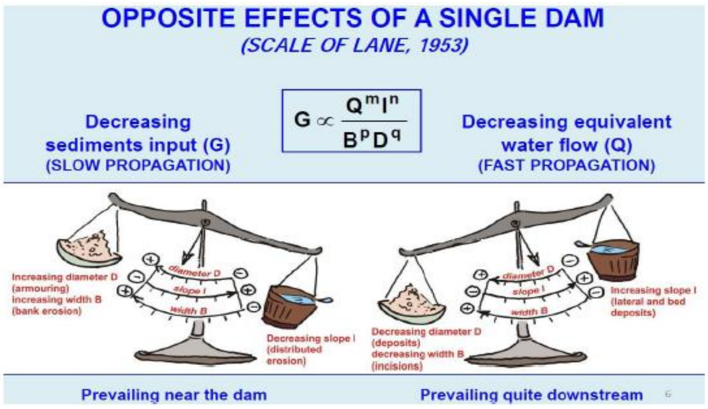


Figure 12: Schematic representation of the alteration of balance between erosion tendency and sediment supply, using the Balance of Lane (1953) theory

The magnitude of flood events can be reduced by dams that alter seasonal variability (Petts and Gurnell, 2005). Flow regulation can affect different locations along a river in different ways, depending on reach characteristics. Aggradation may occur in slow moving, wide channel reaches while degradation tends to occur in the faster moving, narrow channel reaches. A river channel and floodplain are dynamic features that constitute a single hydrologic and geomorphic unit characterized by frequent transfers of water and sediment between the two components. The failure to appreciate the integral connection between floodplain and channel underlies many environmental problems in river management today. By changing flow regime and sediment load, dams can produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads. Dams disrupt the longitudinal continuity of the river system and interrupt the action of the conveyor belt of sediment transport (Kondolf, 1997). Downstream the dam, water released from the dam possesses the energy to move sediment, but has little or no sediment load. This clear water released from the dam is often referred to as hungry water, because the excess energy is typically expended on erosion of the channel bed and banks for some years following dam construction, resulting in incision (bed 'down-cutting') and coarsening of the bed material until equilibrium is reached and the material cannot be moved by the flows. Reservoirs also may reduce flood peaks downstream, potentially reducing the effects of hungry water, inducing channel shrinking, or allowing fine sediments to accumulate in the bed (Kondolf, 1997). Incision below dams is most pronounced in rivers with fine-grained bed materials and where impacts on flood peaks are relatively minor (Williams and Wolman, 1984). The magnitude of incision depends upon the reservoir operation, channel characteristics, bed material size, and the sequence of flood events following dam closure. Channel erosion below dams is frequently accompanied by a change in particle size on the bed, as gravels and finer materials are winnowed from the bed and transported downstream, leaving an armour layer, a coarse lag deposit of large gravel, cobbles, or boulders. Development of an armour layer is an adjustment by the river to changed conditions because the larger particles are less easily mobilized by the hungry water flows below the dam (Kondolf, 1997).

During the last century most of the Italian rivers, like many other rivers throughout the world (e.g. Williams and Wolman, 1984; Wyzga, 1993; Kondolf, 1994; Winterbottom, 2000; Liebault and Piegay, 2001), have experienced considerable morphological changes in response to various types of human interventions. Two recent papers, about the rivers of Tuscany (central Italy) (Rinaldi, 2003) and Italian rivers (Surian and Rinaldi, 2003), have documented that: (a) incision and narrowing have been the dominant processes in river channels; and (b) these processes have been mainly induced by a dramatic reduction in sediment supply. The main sedimentological and morphological effects downstream of hydropower dams can be resumed as:

- *longitudinal riverbed degradation*. The reduction of sediment transport along a channel reach due to the dam presence generally determines the tendency to erosion, i.e. the tendency to erosion made by liquid discharge higher than sediment supply. Some analyses made along gravel bed Italian rivers revealed this tendency to longitudinal and transversal degradation (incision) (Figures 13 and 14).

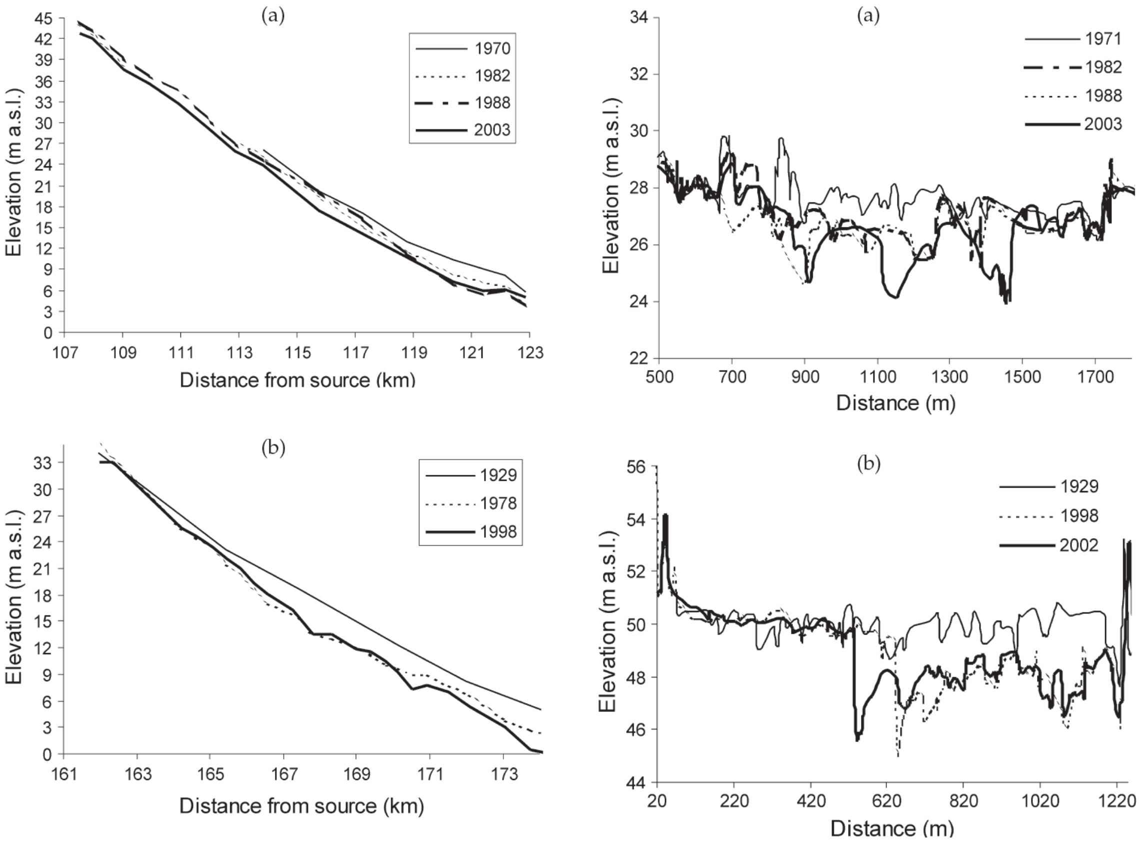


Figure 13: Variations of longitudinal profile and channel section along the Piave River and the Tagliamento River (Northern Italy) (from: Surian, 2006)

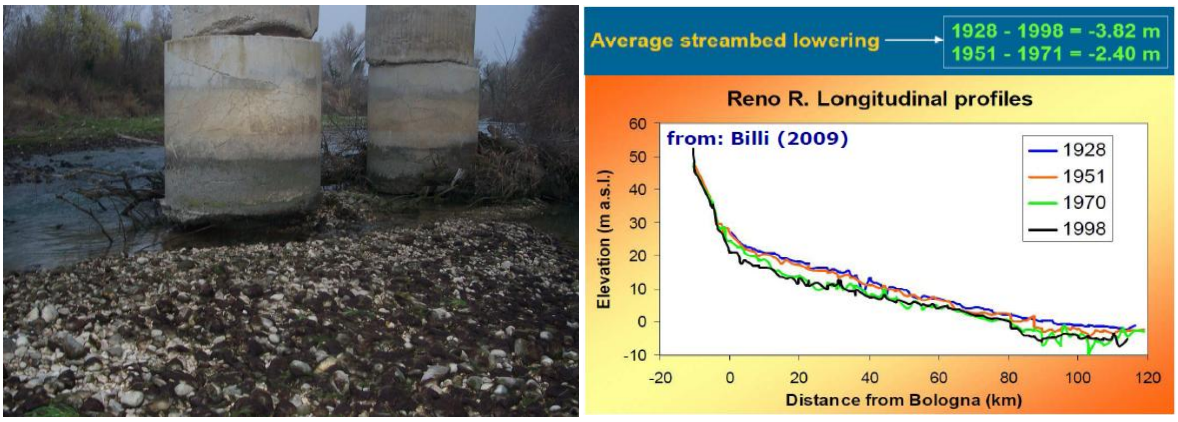


Figure 14: Left: channel bed erosion (degradation process) downstream a dam (Sangro River, Italy; photo from: ARPAV). Right: evolution of longitudinal channel bed elevation over time (Reno River, Italy; from: Billi, 2009)

- *channel width variation*. The presence of a dam determines, over time, the general channel width narrowing. As analyzed by Surian and Rinaldi (2004) in some Italian rivers, channel width has undergone dramatic changes over the last two centuries; average channel width has decreased by several hundreds of metres. It is worth noting that the selected rivers show very similar temporal trends, in particular two phases of narrowing followed by a very recent phase of widening (Figure 15; Table 1).

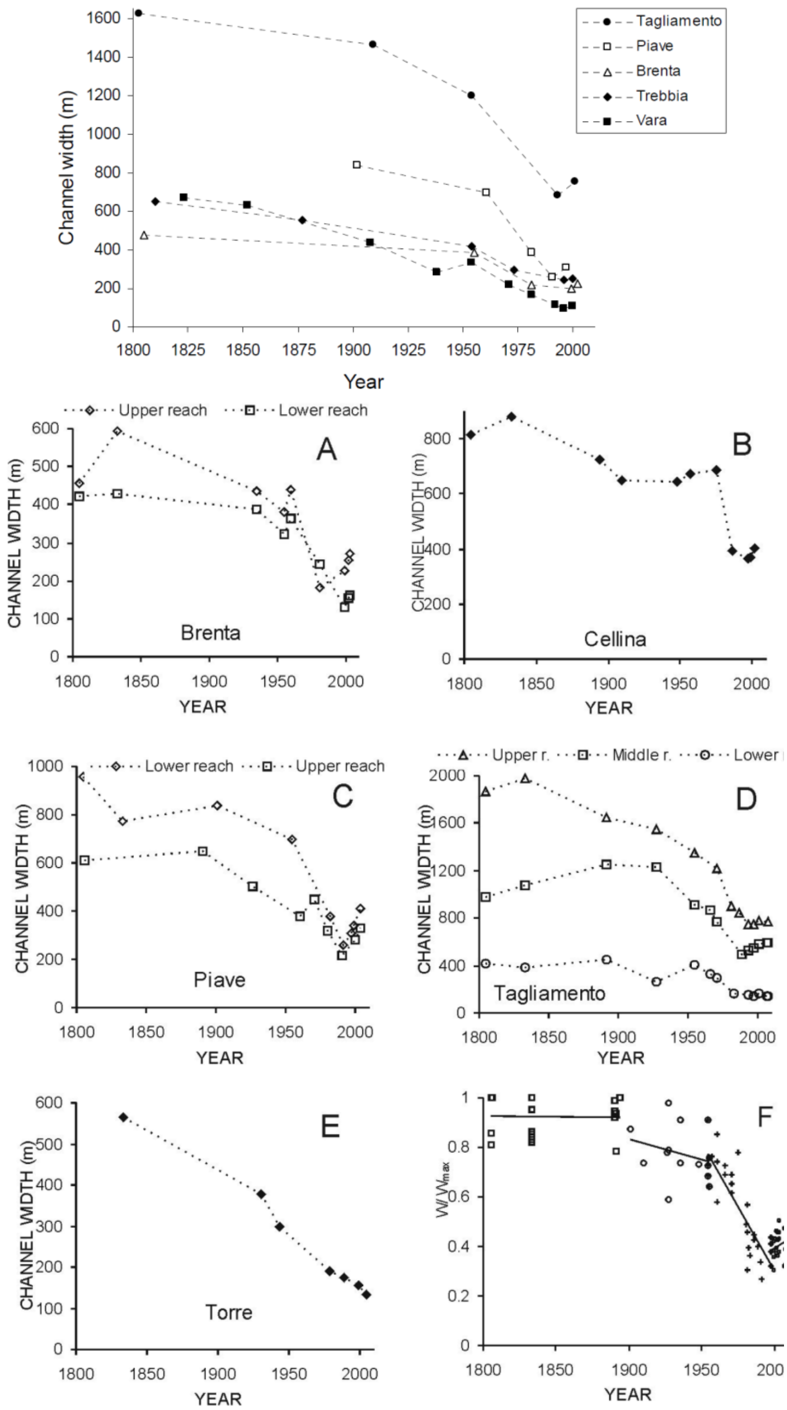


Figure 15: Changes in channel width during the last 200 years in selected rivers of the Italian Alps (from: Surian and Rinaldi, 2004; Surian, 2008)

Table 1: Average channel width of the Piave River between Longarone and Ponte di Piave and in five sub-reaches, for five time periods (Veneto Region, Italy). The figures in parentheses indicate the channel width on different dates as a percentage of the initial width (1894–1910 or, for the Fener-Nervesa reach, 1910–1927) (from: Surian, 1999)

Reach	Reach length (km)	Number of transects	Channel width (m)				
			1894–1910	1910–1927	1954–1967	1980–1983	1990–1991
Longarone–Soverzene	8·8	8	635	455 (72%)	420 (66%)	320 (50%)	245 (39%)
Soverzene–Busche	34·8	31	555	445 (80%)	365 (66%)	275 (50%)	195 (35%)
Busche–Fener	19·0	20	465	380 (82%)	330 (71%)	215 (46%)	195 (42%)
Fener–Nervesa	24·7	16	–	775	635 (82%)	355 (46%)	235 (30%)
Nervesa–Ponte di Piave	22·5	19	840	–	695 (83%)	385 (46%)	260 (31%)
Longarone–Ponte di Piave	109·8	94	625	515 (78%)	490 (74%)	310 (48%)	225 (35%)

Regarding the channel width variations, four stages of channel evolution can be recognized in some selected braided rivers of Italy (Figure 16). Considering the channel morphology in the early 19th or 20th century as the initial stage (stage I), a second stage of channel evolution (stage II) can be identified after a first phase of narrowing and incision (in such phase bed-level changes are not well documented, but there is evidence that, at least during the first half of the 20th century, some incision occurred). Stage III represents the channel morphology after the major phase of narrowing and incision, which took place from the 1950s to the 1990s, whereas stage IV represents the present morphology which is the result of some widening processes. The recognition of the very recent channel adjustments that occurred in the last 10–15 years (channel evolution from stage III to stage IV) is meaningful since it indicated that the relatively long period of narrowing and incision should be exhausted and other processes, in particular channel widening, can become dominant at present (Surian and Rinaldi, 2004).

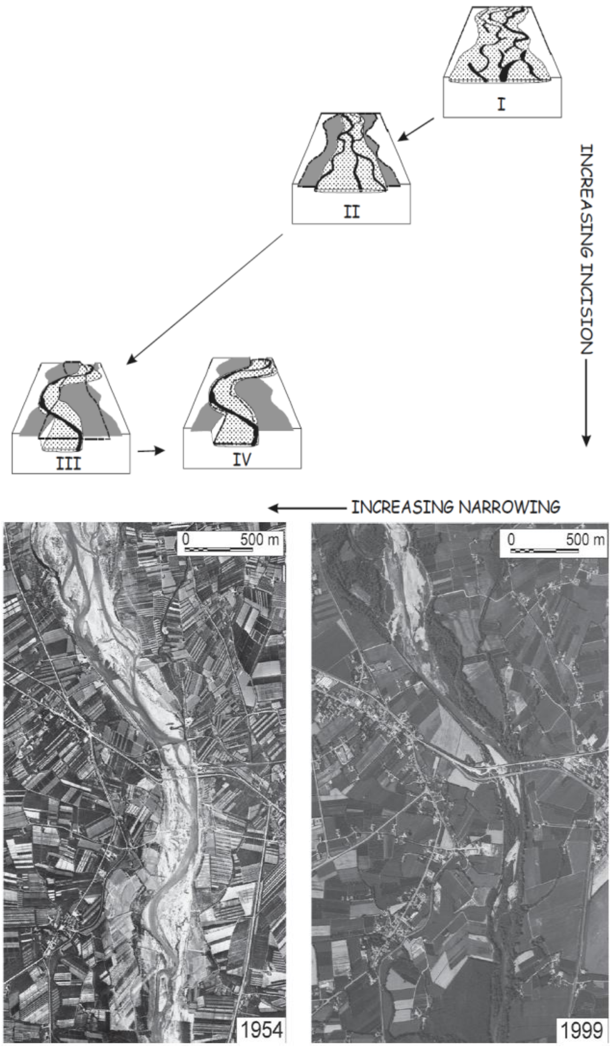


Figure 16: Left: channel evolution model for Italian braided rivers; "stage I" represents channel morphology in the early 19th or 20th century, "stage IV" represents the present morphology (from: Surian and Rinaldi, 2004); right, upstream migration of the transition from braided to single-thread morphology in the Piave River (Veneto Region, Italy) (from: Surian, 2006)

On the basis of these considerations about morphological modification of channel beds in response to artificial sediment supply reduction, the two most important parameters to be analyzed as indicators of such morphological adaptations are:

- channel bed longitudinal variation of elevation (aggradation/degradation analysis);
- channel width (at bankfull scale).

In Austria, riverbed degradation due to bedload deficits as a consequence of inhibited sediment continuity (for which hydropower is but one of the drivers) is an important challenge (Habersack, 2009). However, at a global scale morphological changes downstream of hydropower dams are not limited to this single effect, but can manifest themselves in largely different ways. Table 2 provides an overview of some sedimentological and morphological effects downstream of hydropower dams observed for certain rivers. It has to be noted that this list is neither exclusive nor representative, but shall only give an impression of the wide range of possible effects. Not only geographic location, sedimentological properties, and other anthropogenic influences determine the observed changes, but the studies also vary in their focus and methodology, which must necessarily have an impact on their findings. In general, a "shrunken" and "simplified" river morphology can be observed downstream of dams (Graf, 2006).

Table 2: Examples for possible river morphological changes downstream of dams.

Author(s)	River, country	Observed sedimentological / morphological changes downstream of dams
DonauConsult, 2006	Danube, Austria	Bed degradation
Hartmann, 2001	Salzach, Austria	Bed degradation
Assani and Petit, 2004	Warche, Belgium	Increase of width, reduction of riffles and pools; increase of gravel bars and islets; increase of bedrock outcrops; increase in bed-material size sorting; reduction of sinuosity; decrease of bed roughness
Draut et al., 2011	Elwha, Washington (USA)	Armouring; increase in bed-material size sorting; few changes in bank erosion, bed-elevation, and channel mobility
Phillips et al., 2005	Trinity, Texas (USA)	Bed degradation; increase of width; decrease of slope; coarsening of sediments
Ronco et al., 2010	Zambezi, Mozambique	Bed degradation; bank collapse; shoreline erosion
Swanson et al., 2010	Rio Grande, New Mexico (USA)	Channel narrowing; bed degradation; shift from wide, braided river with large active floodplain to single-thread channel with disconnected floodplain
Vericat et al., 2006	Ebro, Spain	Bed degradation

Two analytical methods are now introduced below, to be applied depending on the problem and the data. The selection of a suitable method of analysis depends on the problem, and also significantly on the data available. The different methods are:

- In-depth method of analysis (Hengl and Stephan, 2008): for detailed statements on the current state of a section of a water body and on anticipated changes to the bed in the medium to longer term. Detailed knowledge and data on the sediment regime are required.
- Simplified method of analysis (*flussbau iC*, 2014): this allows for basic statements to be made on the current condition of the bed, or stress and sections of a water body with a tendency to erosion or sediment formation may be identified. Changes to the river bed following interventions in the water body system may be deduced. An evaluation requires only the data generated by a runoff survey, supplemented by information on water body maintenance.
  This simplified method is no substitute for in-depth analyses. This method was developed for quick response to a problem, without a prior need for in-depth analyses. The method will provide information on problem areas in general and potential effects following system changes (e.g. construction of hydro power plant). This allows more precise definitions for in-depth analyses.

Both methods are based on identified "dynamically stable" sections of the water body. For the in-depth analysis method, this is used as the basis for finding the *equilibrium gradient* (INPUT=OUTPUT), but in the simplified method, a *state of equilibrium* is defined. The essential ingredient is that both methods take into account the time factor. In their paper, Hengl and Stephan (2008) are presenting a calculation method for determining the anticipated equilibrium gradient. Data on the equilibrium gradient of a section of a water body are required to allow a sound evaluation of the effects of bed development. Changing the sediment regime will change the equilibrium gradient. Interventions in the sediment regime of a water body may therefore cause new problems, but they may also be the key to solving a problem. Sections or profiles in equilibrium where actual bed load discharge occurs (INPUT=OUTPUT) are identified for input to the in-depth method, based on comparative measurements (cross-sectional records), inspections and information by water body maintenance authorities.
These equilibrium profiles represent the basis for working on a section of a water body.

Changes to the hydrology, sediment infeed, geometry, geology, etc., will change the characteristics of the water body and thus require a re-evaluation of each section.

The simplified method requires the same data on equilibrium sections or profiles. Additional information (load determination, balancing gradient) is not required, however. The determination of total sediment loads and grain characteristics for the river bed material is therefore not required.

The average annual duration curve of a section of a water body is the basis of the method applied. This serves as the basis for calculating the average annual bed material load and also for assessment of the average annual river bed stress. The duration curve describes the temporal change of the hydrology and the associated sediment transport processes. The average annual duration curve was therefore also used for the simplified analytical method in order to also describe the river bed stress versus time curve. Changes to the duration curve following the construction of a hydro power plant thus constitute a significant parameter for assessing changes in the system overall (Figure 17). Figure 18 shows the general procedure for the two methods of analysis. Both methods require identification of areas of equilibrium. Further processing follows, depending on the problem and the available basic data.

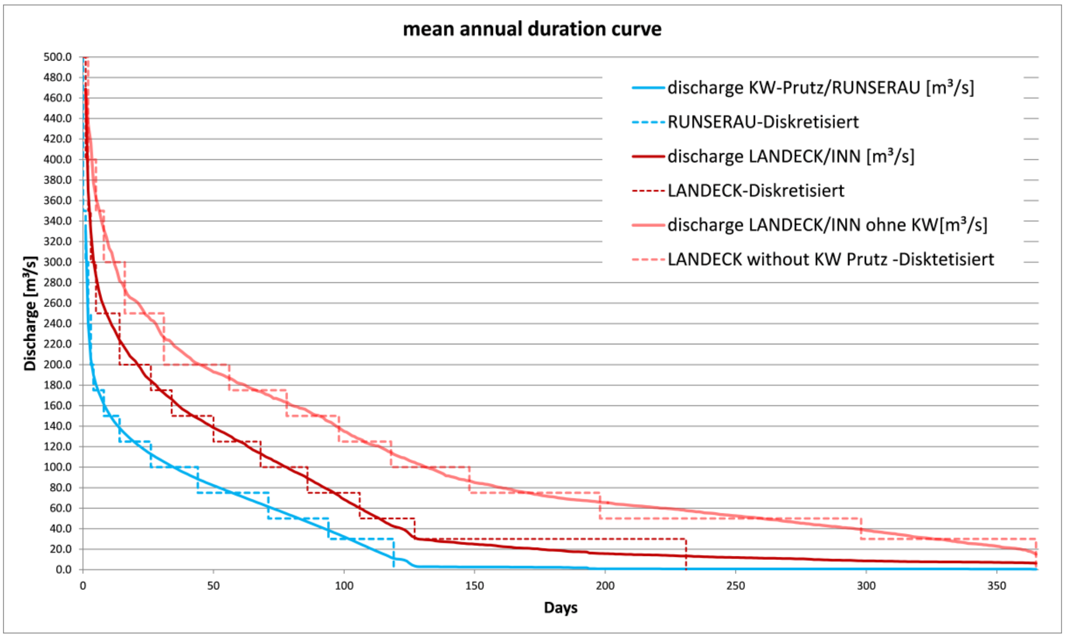


Figure 17: Duration curves along a section of a water body (Example Inn River – gauge power station Prutz/Runserau up to gauge Landeck/Sanna) – red line: with hydropower station; orange line: without hydropower station

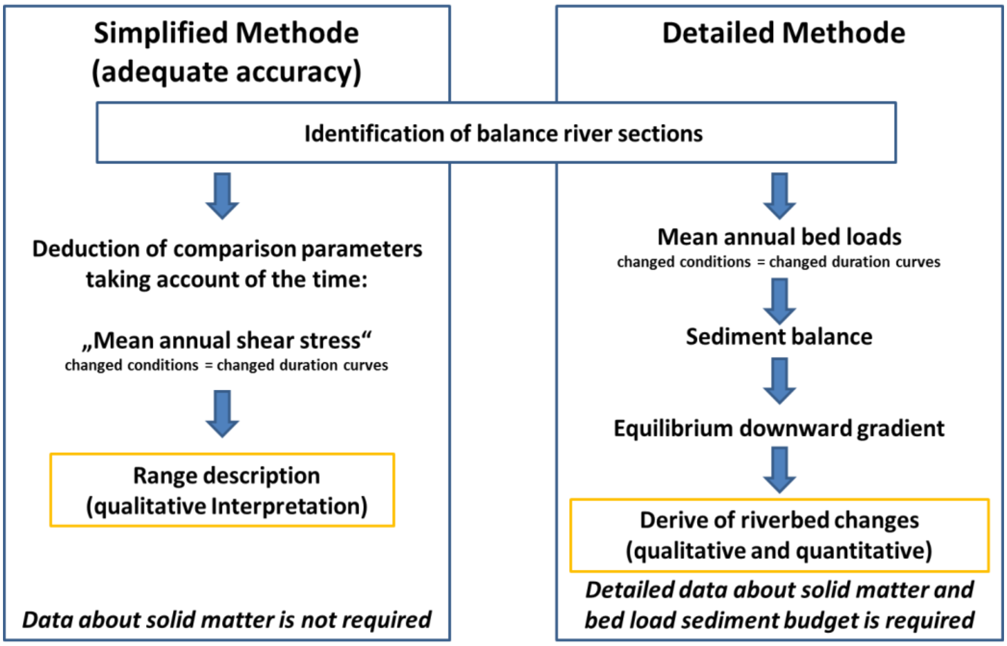


Figure 18: Schematic analysis procedure

Simplified method: the simplified evaluation method is a method of analysis developed for a specific project of *flussbau iC* by order and on account of the Regional Government of Tyrol (2014). In addition to the technical requirements, the simplified method is capable of calculating runoff for research purposes and for planning of potential danger zone avoidance.

Rationale: if a section of a water body is in equilibrium, the parameters affecting potential river bed changes lie within a range which will not change the equilibrium of this section. If such a section of a water body can be uniquely identified, conclusions may be drawn about the river bed conditions in other sections of a water body, based on the calculated ranges of the parameters. Valid or equal framework conditions (hydrology, grain composition, bed load infeed, etc.) for the entire section are the prerequisite here. The river bed stress may be calculated by examining the runoff and calculating the river bed shear stress. The river bed shear stress quantifies the relevant river bed stresses (shear stress τ, in N/m²) for a specific runoff. Figure 19 shows the shear stress at an HQ_1 along the Inn (water body section kilometer 371.5–373.2).

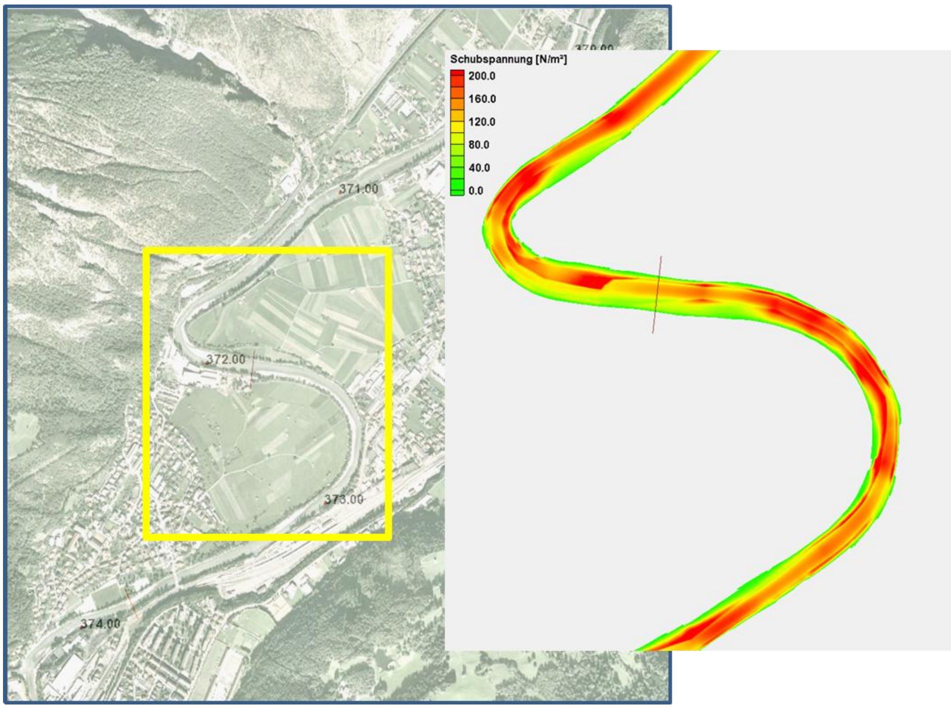


Figure 19: River bed shear stresses (τ, in N/m^2) – the Inn River, approx. kilometer 371 to 373

Shear stress is a snap-shot description, however. To evaluate the stress, the critical shear stress τ_{crit} is required. This, in turn, requires data on the composition of the river bed.

τ_{crit} is calculated as: $\tau_{cr} = 0.047 * (\rho_F - \rho_W) * g * dm$

This type of evaluation is also a snap-shot, however, further analyses for an evaluation is required. In the simplified method, the time factor was therefore included for the evaluation of stress.

As a parameter to describe the system, an average annual river bed shear stress (MJτ) is defined as: $MJ\tau = \frac{\Sigma \quad (d\tau * dt)}{t}$. Time weighting (dt) over time is a function of the duration curve. The calculation of the river bed shear stress (dτ) is carried out in runoff steps up to MJHQ stationary (discretised) (Figure 20).

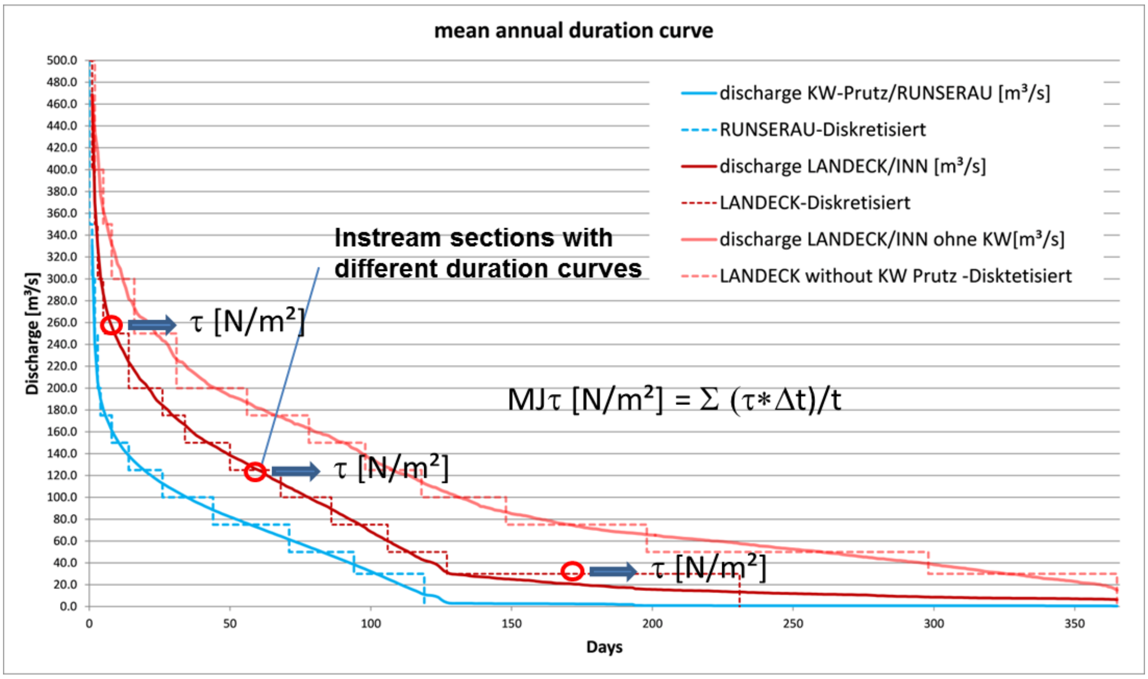


Figure 20: Relationship of discharge (in m^3/s) duration curve and MJτ (in N/m^2)

Figure 21 shows the MJHτ calculation result for a water body profile identified as an equilibrium profile. The river bed shear stress at MJHQ is also shown. The MJHτ includes the time component, the shear stress considers only the stress condition at MJHQ. The MJHτ therefore describes the river bed stress over an average year. Based on this assumption it may now be assumed that the water body system tolerates this stress. Some of the present input parameters (hydrology, grain composition of the river bed and transported material, etc.) exhibit clear variations depending on measuring and sampling methods. A spread of +/- 25% around the maximum value of the calculated MJHτ is thus proposed for the evaluation, to account for typical uncertainties inherent in empirical data. It may now be assumed that a water body section is in equilibrium within this range of parameters. (The deviation of +/- 25% is thus currently an assumption. These values should be discussed in the course of verifying the method and adjusted if necessary.) The values above or below this indicate corresponding trends. When stress is exceeded, the river bed composition is decisive to the assessment of potentially adverse river bed developments. Increased river bed stresses may lead to river bed armouring or to a river bed that is rougher, thus more resistant to degradation. The results should in each case be checked for plausibility.

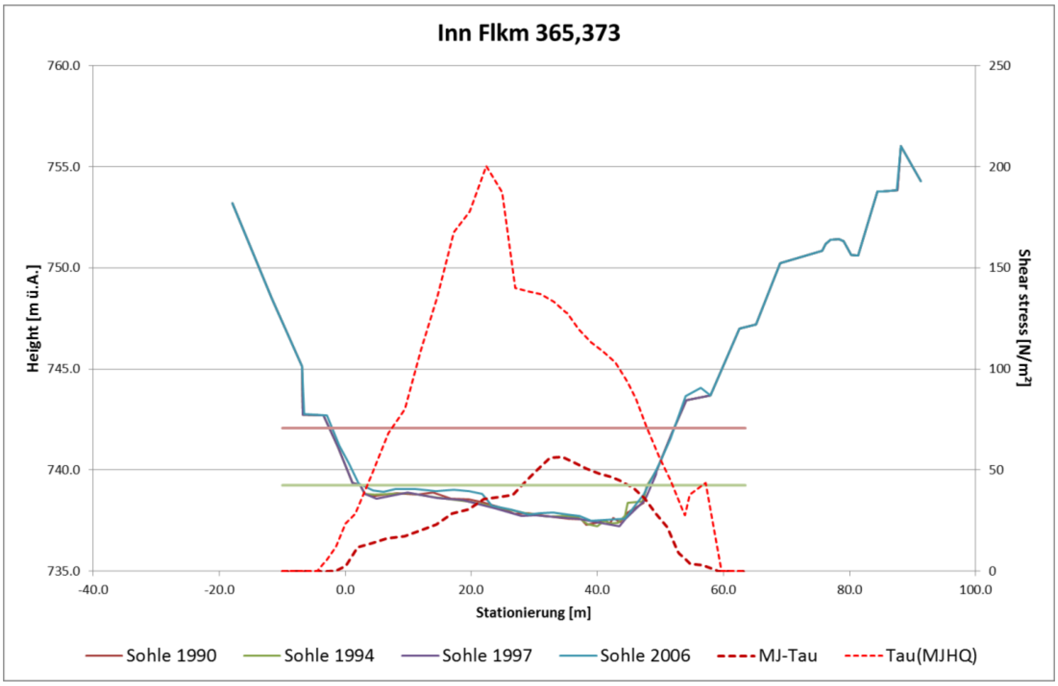


Figure 21: Illustration of shear stress (max., in N/m^2) and MJτ with the range of interpretation.

3.3.2.2 Ecological implications

In case of impounded rivers the reduction of flow velocity can impact fish due to the loss of orientation. Changed width–depth variations and reduced riverine habitats can shift the species composition. Reduction of flow velocity also results in other negative impacts like increase of water temperature and decrease of oxygen concentration, decrease of self-purification capacity, increased deposition of fine sediment in the impoundment as well as disturbed bed load discharges and sediment transport, leading to erosion and deepening processes downstream of the impounded section. A series of impoundments (chain of hydropower plants) has strong cumulative effects on the aquatic ecosystem of the whole (sub-basin). In case of hydropower generation by diversion plants, nonsufficient ecological flow in the affected stretches causes a number of impacts on the river ecology, notably: homogenization of the flow character and degradation of habitat, continuity disruptions for migrating fish and changes of the natural temperature conditions. Another impact stemming from hydropower can be hydro-peaking, which is mainly caused by large hydropower plants in combination with reservoirs. Hydro-peaking can have severe ecological effects on a river. The effects on ecological components of the river system can derive from:

- alteration of the water regime downstream a dam;
- alteration of sediment continuum – morphological alterations (modification of habitat);
- flushing operations; their effects are: Water quality degradation, turbidity increasing, oxygen depletion, toxics, habitat alteration (deposition of fine sediments, clogging of river bed (Figure 22).

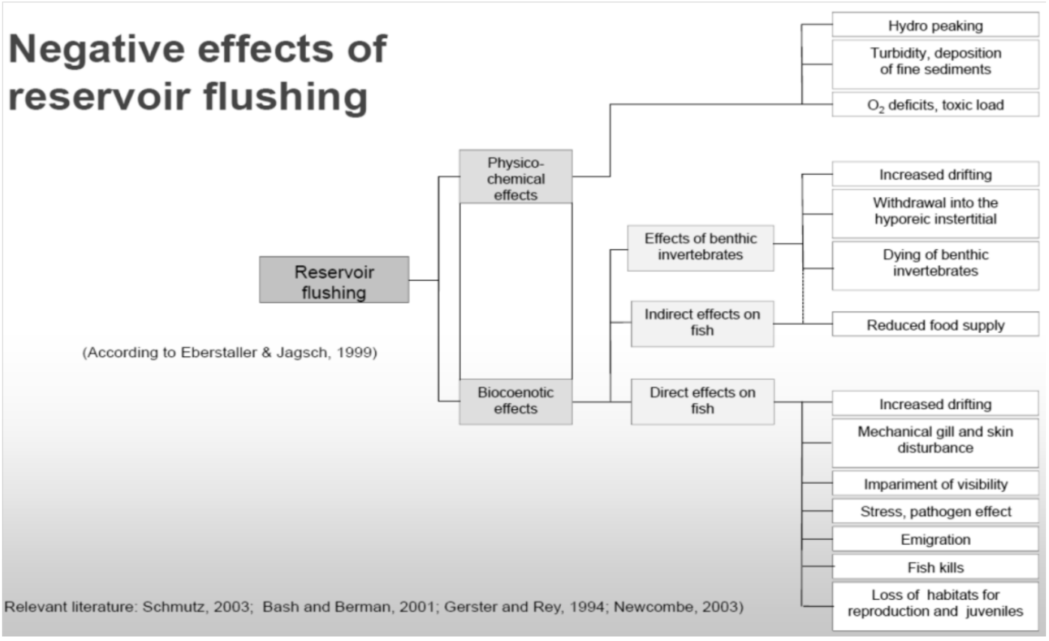


Figure 22: Effects of flushing operations on the ecological aspects of a river system (from: Mielach et al., 2012)

In relation to hydromorphological variations due to dam presence, and to hydropower sediment management operations, analyzing their variations as a response to such artificial impacts, the main ecological indicators to be considered must be: fish fauna; macro/micro invertebrates; vegetation; physical/chemical water quality. Over the last one and a half centuries Austrian rivers have undergone tremendous changes due to the extensive development of hydropower, combined with other measures of river engineering. Disruption of longitudinal and lateral river continuity, reduction of dynamic processes and habitat diversity, as well as changes in groundwater levels, sediment regime, and water temperature are the most important ecological challenges associated with hydropower plants. These are caused on the one hand by their physical structure (weir or barrage, impoundment, diversion) and on the other hand by their operation (hydropeaking, residual flow, reservoir flushing; Jungwirth et al., 2003). Taking the Austrian Danube as an example, only two free flowing river sections remain, while the greater part of the river is influenced by the ten hydropower plants that form a chain of impoundments (Jungwirth et al., 2003; Schmutz et al., 2010). Nowadays the species composition at the Danube is altered compared to the period before massive anthropogenic interventions took place, with a disappearance or strong reduction of formerly typical fish species and the appearance of new species that are better adapted to the new conditions (Haidvogl, 2010). These ecological challenges are closely connected to hydromorphology, because living organisms react to the abiotic factors of their habitat, like flow velocity, bed material, and suspended sediment concentration (Jungwirth et al., 2003). The interaction of hydropower with these features is very complex and mainly due to the changed flow regime and sediment input caused by structural and operational aspects of the plant (Brandt, 2000).

3.3.2.3 Economic implications

Sediment management related to hydropower reservoir has huge economic implications concerning operations and measures that have to be carried out by the hydropower plant manager. One basic aspect is that the reservoir sedimentation reduces the total water storage and the hydropower production is affected by the sediment volume that subtracts a useful amount of water for energy production. The hydropower manager and public bodies involved in river management have a massive interest in maintaining the reservoir storage capacity at a later time, thus extending the sedimentation period and keeping the efficiency of dam outlets, both for dam safety and flood risk reduction in the areas located downstream the dam; indeed, another topic that has to be taken into account is the potential economic losses that should be caused by a flood downstream the dam: if the reservoir has a reduced capacity in flood peak attenuation the downstream river reach and adjacent areas are more exposed to damages.

Flushing operations are performed mainly by opening the dam outlets or through mechanical removal by means of excavators and dredges. Usually, flushing operations are not well accepted and supported by local communities and river users because fine sediments inundate huge areas of the river downstream the dam. The cost-benefit analysis has to be carefully carried out in order to choose the best sediment management solution; in fact, mechanical removal carried out with excavators and trucks is in most cases not possible for logistical reasons and the lack of suitable access roads.

Furthermore, Reservoir Management Projects (RMP) impose an accurate and meticulous sediment characterization in order to understand which kind of storage location (e.g. landfill) or reuse has to be assigned to the removed sediments. The analyses are often very expensive and in many cases the procedure can be simplified and sediment should be removed following less expensive and more effective operations.

Experimental operations concerning mechanical removal of sediment from the reservoir and the redistribution in the downstream reach have positive implications for river morphology and river restoration; also in this case a cost-benefit analysis has to be carefully carried out in order to better understand the real costs of this kind of procedures and the net value that the sediment continuity has for the entire catchment and river reach considered, taking into account also flood risk management and other issues underlined by all stakeholders involved.

Several indicators about economy and energy productions can be included in the Multi Criteria Analysis (MCA) for choosing the best alternative that is able to maximize energy production and economic profits; the main suitable energy and economy indicators are: financial outcomes and degree of satisfaction of HP producer, energy production loss, and costs of sediment removal.

3.3.2.4 Social aspects

Social aspects are deeply linked with sediment management and more generally with catchment administration, especially in non-urban areas of the Alpine Space where the agricultural and rural culture is more embedded within the local communities. Populations located along a river reach downstream a dam are used to see “clean” water (without sediment) along the water course for the most part of the year and the turbidity arises only during floods. Flushing operations create problems and conflicts with local authorities, populations and fisherman or, more in general, with activities related to river fruition as tourism or landscape conservation, even if it is only because of the colour (usually dark) of the sediment and consequently of the river. Moreover mechanical removal procedures carried out by means of trucks and excavators cause problems with local communities: pollution along main access roads, vibrations with damages to houses and public infrastructures, low levels of the reservoir for long periods. For example, some years ago this kind of procedures for removing sediments from the Mis reservoir (Province of Belluno, Veneto Region, Italy) provoked a huge protest from the local communities with the arrangement of a local committee against pubic bodies and the reservoir concessionaire. In some cases local communities are opposed to sediment removal: they suppose that if the effective water volume that can be stored in the artificial lake is increased by the flushing operations, the concessionaire should maintain lower water levels for longer periods during the year with huge repercussions for tourism and lake fruition. Increasing the frequency of the flushing operations and carrying out the sediment release during high water discharge will improve the level of agreement within the population, fishermen and other stakeholders. Improving the mass-media information’s quality about reservoir operations is a crucial topic; indeed, there are often many discrepancies between how the events are described in newspapers and what really happened. For example during the summer 2013 a huge storm occurred in the upper part of the Piave river basin (Veneto Region, Italy) causing local flash floods in small mountain basins; fine sediment was rapidly transported along streams and reached the Piave river's main course in a few hours. The Piave river was considerably coloured by fine sediments also in the lower part of the basin where no precipitation occurred: the local population and public authorities supposed that the concessionaire released a huge amount of sediment in the period with low discharge values; local media publicized and magnified the false information giving a distorted point of view concerning sediment management operations and procedures managed by public bodies and hydropower concessionaires. Education courses for media, local administrators, public bodies, fishermen, local population, schoolchildren and, more broadly, for all the stakeholders involved in river management will improve the level of knowledge and avoid misunderstandings and false information. Educational and didactic activities have several aims and objectives: divulge main cultural contents related to aquatic ecosystems, river ecology, sediment management issues and water resources administration; develop a great awareness on artificial reservoir management among the local communities (sediment removal, flood risk, river and lake fruition) and consequences on river morphology and ecosystems; compose specific brochures and short books for schoolchildren and encourage activities in the field. Some indicators about river fruition, landscape and social implications for local populations have to be included in the Multi Criteria Analysis (MCA) for choosing the best alternative that is able to balance all the needs from each stakeholder involved in the decision-making process: fishing, landforms, costs related to tourism, sports and river fruition.

3.3.3 Procedures for improved planning: actual Sediment Management Plans

3.3.3.1 <u>Description of mechanical removal and flushing operations</u>

The sediment management methods referred to artificial reservoirs have to be applied both to the reservoir and the upstream portion (reduction of silting problem), and also to the downstream reach (reduction of erosion processes). The measures against reservoir sedimentation can be divided into 2 groups (Batuca and Jordan, 2000) (Figure 23):

1- *<u>Deposition control</u>*

2- *<u>Removal of deposited sediments</u>*

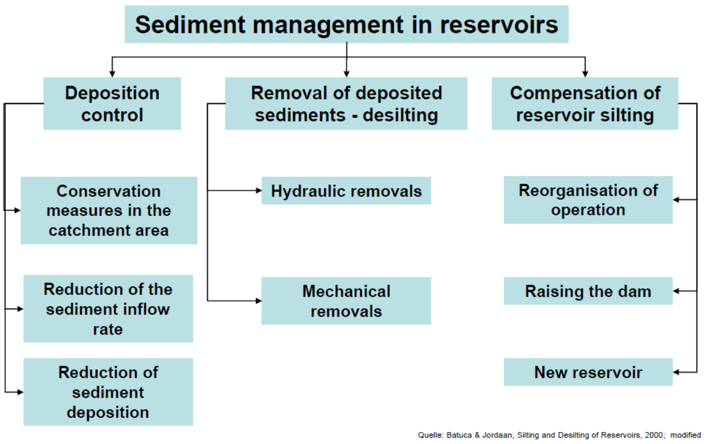


Figure 23: Sediment management in reservoirs (from: Batuca and Jordan, 2000)

1 - <u>Deposition control</u>: the methods for controlling the sediment reaching the reservoir are summarized in Figure 24. Deposition control means, in fact, the control of sediment deposition in a reservoir. It consists of various agricultural and engineering practices and working aims (active methods), focused on the catchment, the channel reach and the tributaries upstream the dam, thus controlling the erosional processes in the catchment and reducing the sediment inflow in the reservoir:

- slope and bank protection works;
- channel bed erosional protection works (check dams);
- methods of sediment trapping, bypass.

The following measures can be considered for this purpose; in many cases a combination of more than one will prove most efficient economically:

- stabilization of the banks;
- reduction of flow rate;
- training works;
- stabilization of the transition zone between streambed and bank;
- energy dissipation works;
- stabilization of the river bed;
- ramps;
- artificial riverbed widening;
- gravel and sand traps.

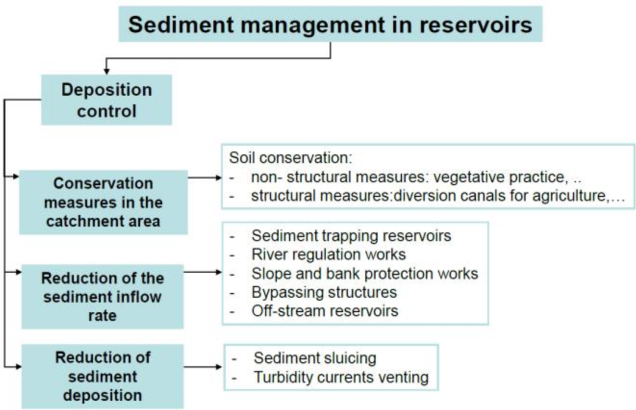


Figure 24: Reservoir deposition control methods (from: Batuca and Jordan, 2000)

2 - <u>Removal of deposited sediments</u>: these methods are finalized to the direct removal of the deposited sediment into the reservoir, through hydraulic (flushing) and/or mechanical removal (Fig. 25). Once sediments have reached the reservoir, only retro-active or passive measures can be taken in order to remove them or to limit their negative effects. Sedimentation can be delayed or prevented by periodical removal of the deposited material.

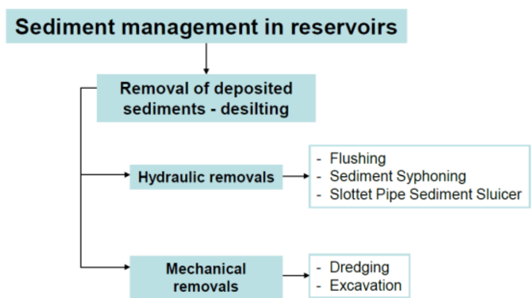


Figure 25: Sediment management in the reservoirs (from: Batuca and Jordan, 2000)

Hydraulic removal – Flushing: one of the most effective ways to maintain the storage capacity of small-medium size mountain hydropower reservoirs is to evacuate the accumulated sediments by flushing (Figure 30). Good results may be achieved with "free-flow" flushing, i.e. by letting inflow water to run over the bottom of the reservoir and to outflow through bottom sluices, after the complete emptying of the reservoir (Morris and Fan, 1997; Brandt, 2000). Usually this operation does not imply excessive technical difficulties and the water loss may be acceptable for reservoirs with small storage volume compared with mean annual runoff. This may involve ecological problems and sedimentation downstream from the dam. Given the fact that the purpose of reservoir flushing is the remobilization of the sediments that were trapped during longer periods of time, flushing leads to a higher sediment concentration in the downstream section of the river. This concentration could be harmful to the downstream ecosystem (e.g. fish fauna). Therefore reservoir flushing programs often require extensive regulations and monitoring (Figure 31). The hydraulic removal of sediments by flushing the reservoir (Figure 26) is usually regarded as the simplest and most economic measure to deal with reservoir sedimentation. However, to reach the required shear stress a complete drawdown of the water level (Figure 26a) is necessary, which causes high losses in energy generation. Therefore, in the case of annual storage reservoirs, it is usually combined with other maintenance work. Moreover, reservoir morphology has to be taken into account: V-shaped valleys are more suitable for flushing, while in broad valleys a canyon will be eroded and thus the efficiency is very low (Figures 26c and 27). This occurs especially if coarser fractions cannot be fully mobilized – in this case it is impossible to avoid a complete sedimentation of the reservoir if flushing is the only measure taken (Figure 27b). Usually mechanical dredging is used as a supporting measure to achieve a higher efficiency. The resulting peak in the suspended sediment concentration downstream of the dam can cause ecological problems, and limits have to be observed and monitored (ÖWAV, 2000; Gaisbauer and Knoblauch, 2001; Boes, 2011). An additional difficulty can be encountered if bedload is moving into the reservoir during periods of high flow, producing an armouring layer on top of the fine sediments and making flushing very difficult. On the other hand, however, a kind of natural flushing can take place during flooding events, and it would be possible to make use of this effect and to intensify it by optimizing dams of run-of-river reservoirs (Elsner and Hartmann, 2001). As opposed to free-flow flushing of a reservoir, pressure flushing does not involve a complete drawdown of the water level. Thus, it has only marginal effects on the useable reservoir volume, but it can help to keep intake structures free of sediments by developing a local erosion cone (Figure 28) in the natural friction angle of the material under buoyant force (Figure 29). After its formation this cone remains relatively stable if no additional material is transported into the reservoir and the water level, respectively, the flow velocity in the vicinity of the outlet stays the same. If the water level is lowered in the course of flushing, however, the cone's rim will be eroded and retrograde channel erosion will occur. Apart from flow velocity, the geometry of the bottom outlet is an important parameter for determining the resulting scour (Emamgholizadeh et al., 2006; Jugovic et al., 2009; Meshkati et al., 2010; Boes, 2011).

Figure 26: Flushing of the Großsölk reservoir, a) during drawdown, b) bottom outlet and water intake during flushing, and c) erosion canyon after flushing (Habersack et al., 2002)

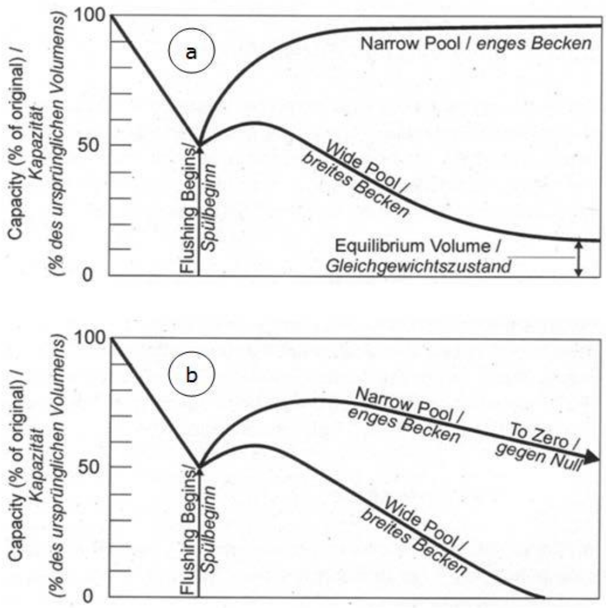


Figure 27: Development of reservoir capacity during flushing for a) complete and b) incomplete sediment remobilization (after Morris and Fan, 1997; cited in: Boes, 2011)

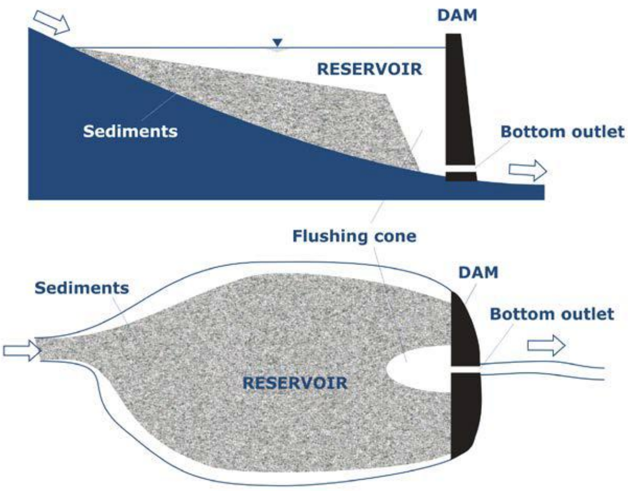


Figure 28: Development of a flushing cone in the vicinity of the bottom outlets, longitudinal section (top) and plan view (bottom) (after Meshkati et al., 2010)

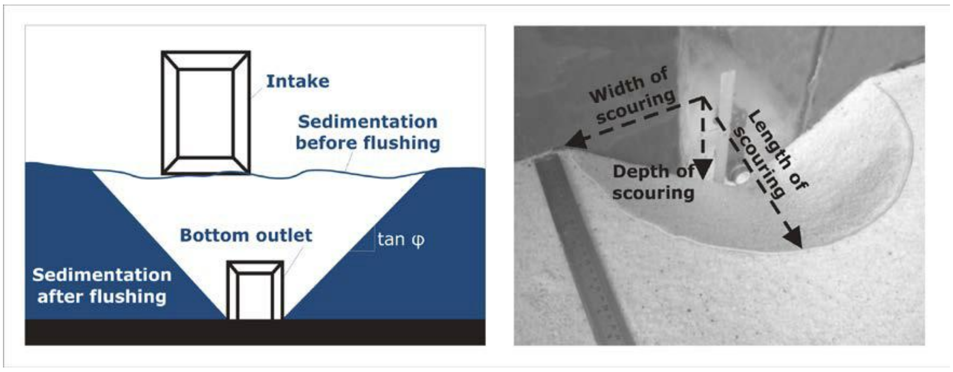


Figure 29: Left: dimensions of the flushing cone in the vicinity of the bottom outlets, schematic drawing (after Boes, 2011); right: 3D representation (after Meshkati et al., 2009)

In some cases flushing can increase the flood risk downstream, if the flushed sediments accumulate in a specific river section. For this reason a so-called "soft flushing" could be performed. Soft flushing is a kind of pressure flushing, which can be performed in instream-reservoirs with high inflow in relation to the reservoir volume and relatively shallow water depth in case of flood. During soft flushing the reservoir level is drawn down for some metres to a lower operation level with spillway gates opened. By the lower water level the velocities and the bed shear stress in the reservoir are higher than in a normal flood situation and result in erosion of sediment deposits (Harb et al., 2010). A decisive factor here is the level of sediment load during the relatively short flushing process.

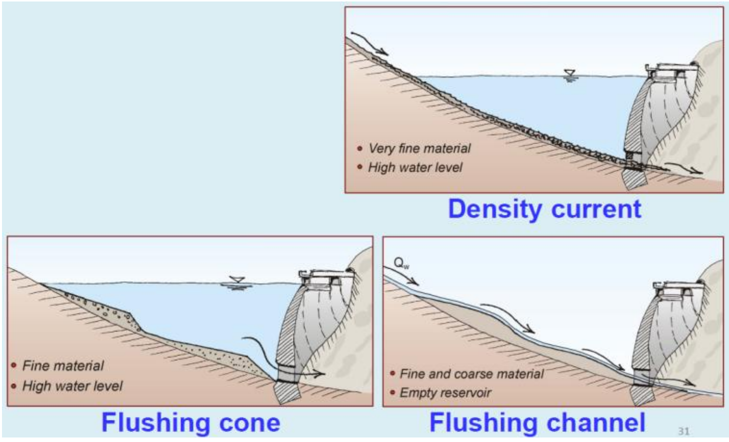


Figure 30: Schematic representation of flushing operations (from: Di Silvio)

For flushing and other sediment management methods, a perpetuation of evidence and monitoring has to be carried out to ensure that no technical and legal aspects were ignored, while the requested effect was obtained.

before flushing	during flushing	after flushing
Morphology in the reservoir/tailwater/downstream	Oxygen concentration	
Photo documentation		Photo documentation
Sediment concentration	Sediment concentration	
Fish population in the reservoir and downstream		Fish population in the reservoir and downstream
Fish population in a reference stretch		
Macrobenthos		Macrobenthos
Water quality		
Acoustic sounding of the river bed		Acoustic sounding of the river bed
Grain-size-distribution in the reservoir		Grain-size-distribution in the reservoir
Oxygen conditions		

Figure 31: Evaluation of the flushing effects (from: Harb and Zenz, 2011)

To perform sediment removal by free flow flushing some operational constraints should be accounted for:

- when the dead storage of the reservoir is filled, the volumes to be evacuated are of the order of annual deposition;
- except when water of other reservoirs may be employed, discharges available for dilution and transport of sediment depend on the hydrologic characteristics of the catchment and on previous precipitations (i.e., on average, on the selected season);
- the powerhouse supplied by the reservoir is out of order during the operations.

Technical guidelines for sediment release management and for related monitoring activities represent still controversial issues. Prescriptions on the key quantities necessary to plan and operate a flushing event (peak and average allowable SSCs, peak and average allowable flow rates, duration of the event), balancing technical, ecological and economical aspects, have not been provided so far.

The main aspects to consider in the flushing operations are (Fig. 32):

- min. discharge approx. 50%–70% of the 1-year-flood;
- forecast inflow from the upstream sections and forecasted duration of the event;
- reservoir draw-down with monitoring of:
  - aggravation of the flood situation;
  - start of flushing during the rising part of the flood wave to prevent an increase of the flood risk downstream;
  - stability of reservoir slopes (pore water pressure development and stabilisation structures).
- monitoring of suspended load concentration on the basis of continual monitoring in the downstream water section.

Consideration should also be given to the timing of the flushing process. Depending on the hydrological conditions, the snowmelt period in spring seems to be suitable in the case of alpine rivers. The advantage lies here in high flows over a major period, when the ecological conditions are good and approach the effects of artificial flushing (turbidity, flow velocities, river bed dynamics, etc.). Referred to the solid concentration during flushing (turbidity in suspended solid concentration, SSC), the negative effects to the river system are due to:

- high fluctuations;
- high average SSC (4-5 g/l).

Some proposed SSC values to consider in management sediment guidelines are:

- < 25 mg/l (according to Fish Directive);
- max. 4.5 g/l;
- max. of 30 g/l for 2 hrs and a mean of 6 g/l (Regional Government of Veneto, 2006).

Recommendations are:

- flushing regularly during high flows (floods events):
  - during summer periods (Alpine rivers);
  - not during winter (natural low flow/turbidity);
  - not during reproductive periods or immediately afterwards (eggs/larvae).
- consideration of natural turbidity conditions;
- monitoring and supervision of SS concentrations;
- improving sediment transport at existing and new HPPs.

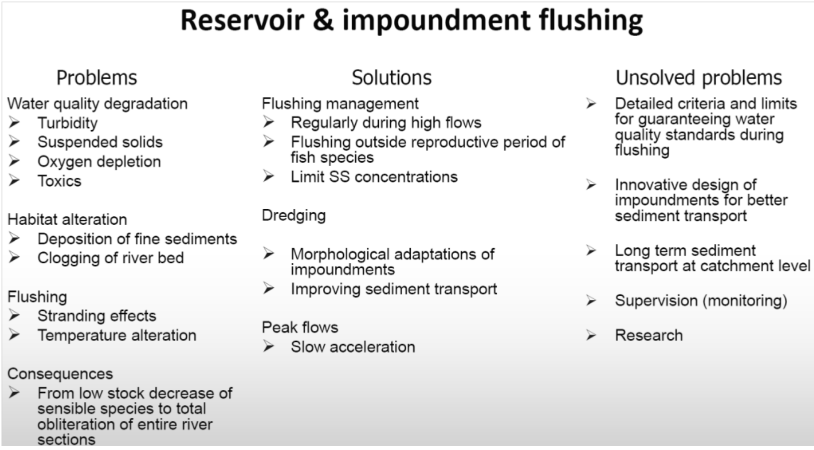


Figure 32: Problems and solutions for flushing operations (from: Mielach et al., 2012)

Figure 33: Left: flushing operations in three reservoirs of the Italian Alps; a) Prampèr reservoir (Veneto Region; photo: ARPAV); b) Valgrosina reservoir (Lombardia Region; from: Espa et al.: *Sediment flushing from an Alpine reservoir: hydraulic monitoring and biological impact* (2008)). Right: flushing operations, Comelico reservoir (Veneto Region, Italy; photos by: ENEL)

Mechanical removal: removals such as dredging or excavation, with a full reservoir or with the water level drawn down, from the banks or from boats may also be a solution. Depending on the grain size of sediments and the depth to be dredged, suction dredgers or conventional, purely mechanical dredgers can be used (Fig. 34). The main methods are those called dredging: removal of deposited sediments from the reservoir area. This method includes the removal of coarse and fine sediments by technical means without support from the drag of the flow. It is one of the last methods where conditions such as inflow, gradient, particle-size distribution, duration of peak flow, etc., make other reservoir de-siltation measures appear inefficient. The evacuation method should be selected with due allowance for the type of plant under consideration, while weighing advantages against disadvantages (Hartmann, 2007).

- *Dry dredging:* The sediments are removed from the sediment-filled reservoir area by use of conventional construction equipment with the maximum possible water-level draw-down and under low-flow conditions, while turbine operation is maintained.
    - 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 and suction dredging:* wet dredging (scraper, pontoon dredgers and suction dredging) can be carried out without the need for water level draw-down and the work can be carried out not only at times of low flow, but also during medium flow (Figure 35).
    - Advantages: continuous evacuation at top water level, less adverse ecological impact, flexible timing possible
    - Disadvantages: higher costs, longer duration of work, special equipment required

Dry dredging uses conventional construction machines, but requires a maximum drawdown of the reservoir that can be achieved while at the same time keeping the turbines operating. Thus, the measure is limited to areas near the embankments. For wet dredging, no drawdown is necessary and sediments can be removed from the whole reservoir area, but special machines (pontoon dredge, suction dredge) are required and dredging efficiency is much lower. While bedload (gravel) can be easily reused for construction purposes, fine sediments and contaminated material pose serious problems for disposal, and can make this measure very expensive (Vischer, 1981; ÖWAV, 2000; Gaisbauer and Knoblauch, 2001).

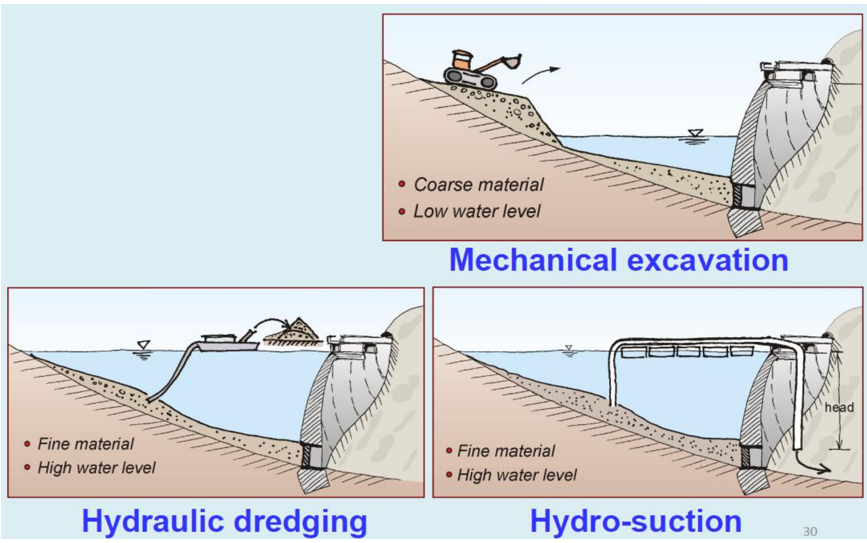
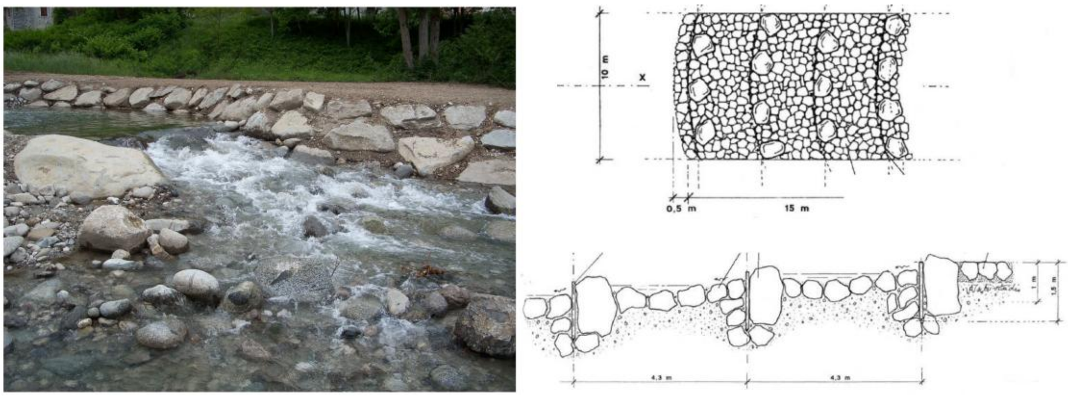


Figure 34: Schematic representation of mechanical sediment removal methods (from: Di Silvio)

Figure 35: Suction dredging operation, Alleghe reservoir (Veneto Region, Italy; photos by: ARPAV)

The erosional processes along the channel reaches downstream the dam can be limited by active methods:

- increase of bed resistance: bed pavement, open cover, adding coarse material, granulometric bed improvement;
- reduction of energy slope: bed fixation, steps (steps, rock ramps, cascade step-pool ramps), weirs (Fig. 36);
- minimization of bed shear stress: improved inundation, river widening, reduction of discharge;
- stabilization of the banks; advantages: for flood protection this is often required, in most cases relatively economical, protection of land (agricultural area); disadvantages: forces the stream to be trapped; if downstream of hydro development, the lack of the eroding process in the banks causes less bed load and therefore a deepening of the river bed.



a)

b)

Figure 36: Channel banks and bed stabilisation works downstream a dam; a) ramps; b) boulder steps, the Maè stream (Veneto Region, Italy; photos by: ARPAV)

3.3.3.2 Sediment Management Projects

The Management Plans describe all the manoeuvres on the bottom outlets, which are allowed during the flood event to maintain the functionality of outlets in silting conditions, to replenish the sediment downstream the barrage and/or to modulate the flow conditions downstream the dam. Generally, under certain conditions (specific geometry of the reservoir, not excessive quantity of sediment transport), the bottom outlets' cleaning could be ensured through their opening during the final stage of the flood. These manoeuvres are defined in the Management Plans and approved by local Authorities. Several dams in Friuli-Venezia Giulia and Veneto (Comelico and Pontesei dams, for instance) perform this kind of manoeuvres.

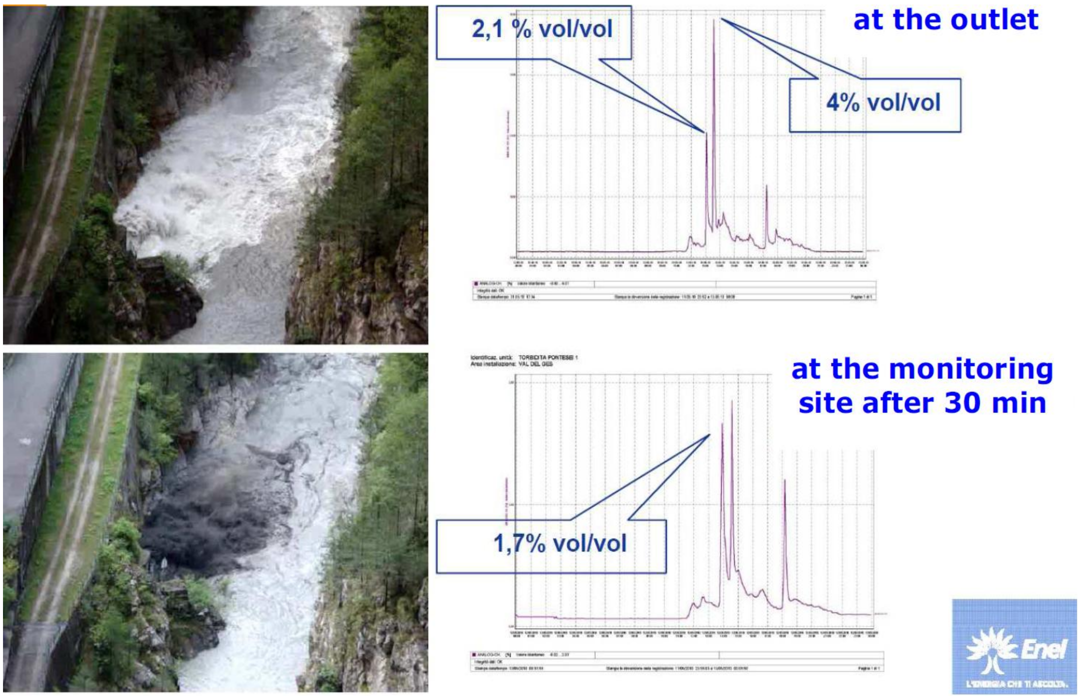
The experience of Veneto Region (Italy): an overview on actual reservoir sediment management plans in Veneto Region is described in the WP7 Output Report - *Sediment retention management and policy*). The DM 30/06/2004 fixes the criteria for the preparation of Management Reservoir Projects (MRP); the Decree aims to define how to conduct the sediment management operations. According to the Decree, the reservoir management plan defines:

- the sediment volume trapped inside the reservoir before the editing of the plan;
- the average annual sedimentation rate;
- the physical and chemical characteristic of sediment, and their degree of pollution (Figures 37 and 38).

The operative phases of a MRP are summarized in Table 4.

Table 4: Example of a Management Plan for a small reservoir in the Veneto Region (from: ENEL)

1. HP, reservoir and dam description
1.1 characteristic dam's data
1.2 characteristic reservoir's data
1.3 hydraulic scheme
2. Preliminary investigations
2.1 Sediments characteristics and quality analyses
2.2 Results of the analyses
3. Management project
a) Sediments volume stored
b) Sediments quality characterization
c) Modalities and times for the reservoir capacity volume restoration
3.1 Operative modalities
a) SSC persistance levels during the desilting operations
b) operative program
c) sediment volume to be removed during the desilting operation
d) monitoring systems along the channel reaches
e) actions made for preservino the downstream river uses and habitats
4. Fulfillment and notices
5. Other eventual desilting operations into the catchment
6. Cases of not applicability of the management plan
7. Photographic documentation



a)

b)

Figure 37: a) flushing operation in the Pontesei reservoir (Veneto Region; from ENEL, modified); b) turbidity monitoring downstream the dam (photos by: ENEL)

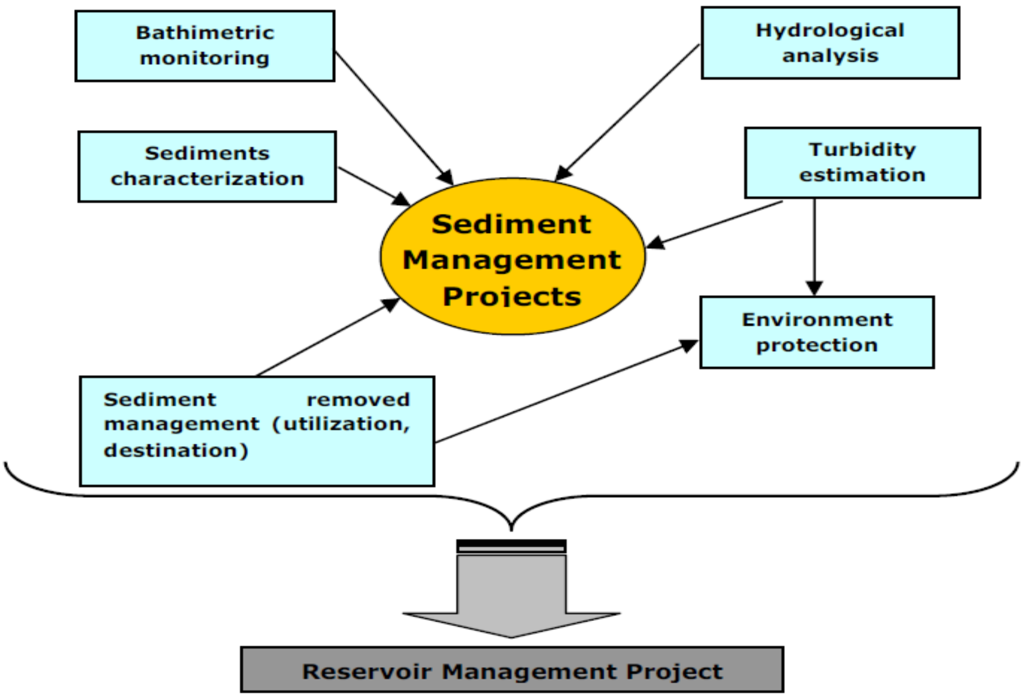


Figure 38: Schematic representation of the main functions defining a Sediment Management Plan

3.3.4 Good practices: Management Plans' optimizations

This paragraph aims to explain and analyze new proposals to the existing management plans, in order to define the optimisation of the sediment management in the artificial reservoirs which take into account not only the silting regulation and the respect of solid concentration limits during the operations of de-siltation, but economical, ecological, morphological and social aspects related to the river system. Actually, in the Veneto Region (Italy), the Management Plans are focused on the flushing operations removing the finer sediments of the reservoir and, in the downstream reaches, on the respect of turbidity limits, in order to preserve the quality of water and the ecological aspect of the river (above all, the fish fauna). However, the respect of river system must consider other aspects and variables, which can be deeply affected by the presence of a dam and by these types of operations:

- morphological parameters, which response to the dam's effects can affect the natural river ecosystem too (fish fauna and macroinvertebrates are sensible to morphological changes of the channel bed);
- economic and social aspects connected to the river system (fishing, tourism, etc.).

On the basis of such assumptions, integrations and new technical analyses and operations to the present Management Plans can be useful for giving a better management of the sediment stored in the reservoir taking into account all the aspects belonging to the river system.

3.3.4.1 Technical/economical/ecological optimisations (innovations, new proposal to the existing Management Plans)

- Proposal of ***coarse sediment removal and introduction downstream the dam channel reach*** and implications

  One possible integration and new type of operation to the actual management plans can be the coarse sediments – when stored into the reservoir - mechanical removal from the basin (dry dredging) and introduction downstream the dam where the channel reach is subjected to erosion. The lack of sediment continuum (bedload) shifts the natural balance between tendency to erosion and to sediment supply towards the erosional processes, causing as effect:

  - the channel bed incision;
  - the bed coarsening tendency and armour layer formation;
  - the lateral width narrowing and bank erosion.

  Furthermore, the operations of de-siltation (flushing, for instance), cause to the downstream dam reach a 'shocking' temporal increase of discharge, contributing to the excess of stream power, not balanced by the fine sediments transported (Fig. 39).

Figure 39: Left: channel reach degradation process; vertical incision and lateral bank erosion and narrowing process (Sangro River tributary, Italy; photo by: ARPAV). Right: channel bed coarsening as effect of stream power excess; superficial armour layer (Meduna River, Friuli Venezia Giulia Region, Italy; photo by: ARPAV)

The introduction of the coarse portion of sediment stored into the reservoir (which, if present, cannot be removed using only flushing operations), into the channel reach downstream the dam could, during the time, limit the tendency to erosion and shift to recover the original morphological quasi-equilibrium of the river (Figure 40). The tendency to erosion (product between liquid discharge Q_l and channel slope S) will be balanced by the increasing of the coarse sediment reintroduced into the channel, and able to be removed during ordinary floods (Q_s x D_{50}, where D_{50} is the mean diameter of the channel bed coarse sediment).

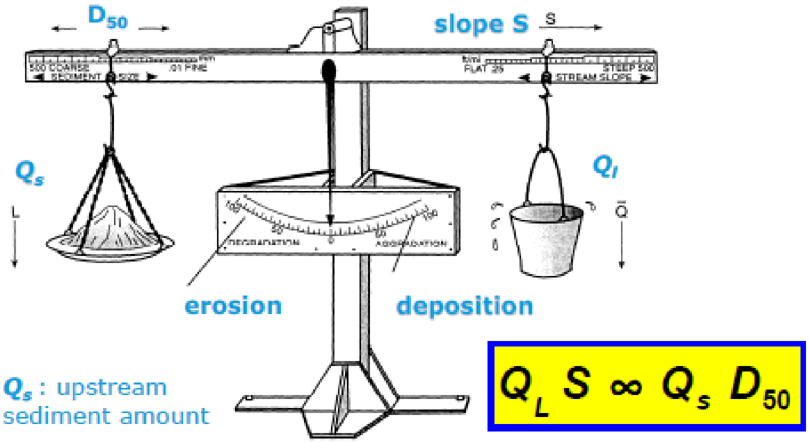


Figure 40: Morphological equilibrium in a natural channel reach, according to the balance conceptual model proposed by Lane (1953)

The possibility to reintroduce sediments to the downstream channel reach is connected to the transport capacity of the reach; in the Italian context, the DM 30/06/2004 (Art. 3) points out the sediment removal through flushing operations; both fine and coarse sediment introduction downstream the dam must respect the morphological characteristics of the river channel and the liquid and solid discharges processes. The introduction of dredged coarse sediments should be done only respecting the morphological and ecological status (fish fauna and benthos) of the river system, in the same manner of the finer sediment removal through flushing operations. The coarse sediment removal and introduction operation, if considered as an integration to the actual management reservoir projects, should be accompanied to analyses and monitoring actions, such as:

1) reservoir sediment stored characteristics and analyses:
    - stored volumes estimation;
    - granulometric characterization.
2) quantification of the coarse sediment to be introduced along dam's downstream reaches:
    - analysis of sediment transport rate and processes characteristic of the specific river/stream (catchment sediment production, transport, tributaries sediment contribution, etc.):
        - individuation of reaches with aggradation or degradation tendency;
        - source of sediments' individuation and estimation;
        - propagation of sediments evaluation along the channel reach.
    - solid transport processes evaluation without an artificial dam.
3) monitoring, at a long period scale, of the morphological variations due to the input of coarse sediment from upstream (bed elevation, channel width adaptations). The effects of coarse sediment introduction downstream the dam, during the time, are reported in Table 5.

Table 5: Effects of coarse sediment introduction into the channel reach downstream the dam

Negative effects	channel aggradation --> hydraulic risk - *presence of sediment input from tributaries* - *when too much sediments are introduced downstream*
Positive effects	downstream dam reach sediment recharge - *morphological quality increasing* - *aggradation/degradation equilibrium*
	inside the reservoir - *prevention of reservoir effective volume reduction*

- ***Multi Criteria Analysis (MCA)*** is a further instrument of management plans. The application of a Multi Criteria Analysis to the actual Management Reservoir Project can be an useful instrument for evaluating the best sediment management technical operations taking into account several aspects (or criteria) of the river system. A Multi Criteria Analysis (MCA) can be applied to assess different management alternatives where a 'single-criterion' approach falls short, especially where technical, economic, environmental and social criteria must be evaluated and considered in the analysis. The MCA allows to analyze the problem (in the specific case: the sediment management in a reservoir) through an evaluative process articulated by 3 questions:

- What to evaluate? --> different Alternatives of management
- How to evaluate it? --> using Criteria and Indicators

- Who is involved? --> different Stakeholders

The problem can be broken into Criteria and Indicators that describe it; the MCA allows to analyze how such criteria and indicators respond to different alternatives of management; so MCA is a tool that helps the decision maker (the stakeholder, the manager and public bodies/local administrations) to choose the best alternative.

The MCA can be resumed in the following points:

- identification of the Objectives and Stakeholders involved;
- identification of different Alternatives to be considered;
- identification of Criteria and Indicators explaining the problem;
- indicators' data normalization;
- criteria and Indicators weighting (involving stakeholders): the weights represent the relative importance of the objectives for the decision maker;
- performance evaluation of each Alternative;
- sensitivity analysis, in order to evaluate the robustness of the best Alternative respecting approximation of weights.

Each Alternative is evaluated on the Performance of each indicator, using a Matrix linking the Indicators and the Alternatives.

The MCA structure can be schematized like a tree (Fig. 41), where the branches are the Criteria explaining the problem to be analyzed, and the leaves are the indicators afferent to each criterion. The value of each Indicator changes as a response to each different Alternative of management chosen by the decision maker.

The Alternatives for a better sediment management can focus, for example, on:

- flushing: different levels of outlet discharge; different levels of solid concentrations released;
- coarse sediment removal downstream the dam (new proposal): different % of volume stored in the reservoir and put into the downstream channel reach.

Each different management Alternative affects the value of the Indicators which explain the Criteria.

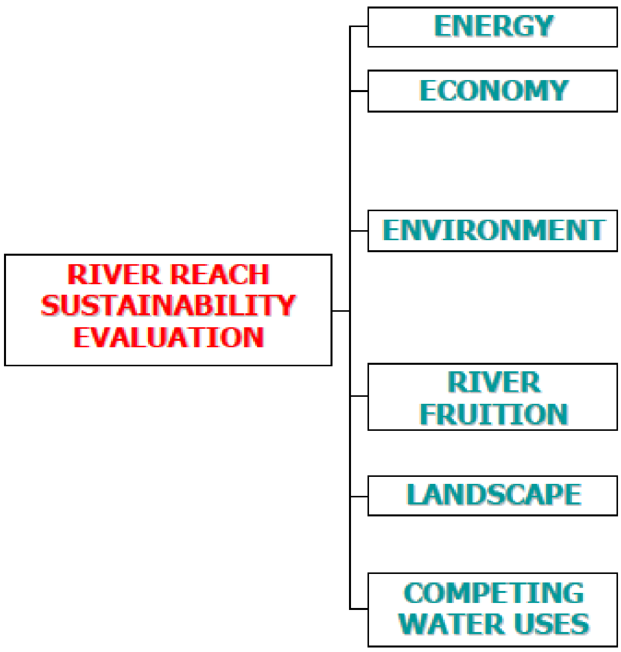


Figure 41: Schematic representation of the MCA structure. The problem to be analyzed, and explanation of the main Criteria

The Criteria explaining the sediment management of a reservoir (objective of analysis) include all the aspects of the river system and of hydropower production, affected by variations in response to a different Alternative of the sediment management choice. Such Criteria, sub-criteria and Indicators to be considered are:

- **Energy**
  - Energy hydropower production
  - National energy improvement
- **HP producer economy**
  - Financial outcomes for the collectivity
  - Costs of sediment removal
  - Specific investments
- **Economy**
  - Costs for sediment downstream input
- **Environment**
  - River ecosystem
    - *Fish*
    - *Macrobenthos*
  - Morphology
- **Social uses**
  - River fruition
    - *Fishing*
    - *Tourism*
    - *Landscape*
    - *……*

The application of an MCA to the Management Reservoir Project can help the decision maker (reservoir manager, competent authority, etc.) to choose the best alternative of sediment management (flushing of fine sediment, removal of coarse sediments and introduction into the downstream reach) taking into account all the aspects (criteria) involved in the river system, and affected by the reservoir operations. The aim should be the choice of the management Alternative which can minimize the negative effects on the environment, social uses (river fruition, fishing, etc.), morphological and and economic aspects.

3.3.5 Conclusions and Recommendations

The problems referred to 'planning of hydropower plants aimed to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches' point out that river systems subjected to human pressure are generally far from a condition of natural dynamic equilibrium between erosion and deposition processes. In a river system, the presence of dams for hydropower production alters the natural tendency to the morphological quasi-equilibrium which maximizes the flow resistance giving stability to the system itself, due to the sediment connectivity alteration in space and time. So, problem identification and solutions focused on sediment management in artificial reservoirs should involve concerted actions and strategies between policy makers, managers and researches.

3.3.5.1 Recommendations for Policy Makers

The aim of the SedAlp project, that is to maintain and/or restore the sediment connectivity between upstream and downstream river reaches altered by artificial works, becomes difficult to obtain without a good effort at the policy maker level.

The Public Bodies involved in the environment and river systems' protection measures should take into great consideration not only the hydrological/hydraulic and ecological aspects affected by hydropower exploitation, but the morphological channel features too, being the last ones altered during the time; this is taking into account the Water Framework Directive (WFD-2000/60) of good qualitative and quantitative status of all water bodies, and the RES Directive (DIRECTIVE 2009/28) on electricity production from sources of renewable energy.

The actual Reservoir Sediment Management Projects (RMP) fixed by the Norms at Regional scale (see Par. 3.3.3.2), and merely based on the management of the finer sediment stored into the reservoir and on the monitoring of its concentration during flushing operations, should be integrated by analyses and management strategies of the coarse sediments, too (Par. 3.3.4.1), with the aim to provide sediment connectivity and then to reach, during the time, a channel morphological pattern next to the balance between erosion and sediment supply tendency.

Furthermore, the Public Bodies involved should consider the Multi Criteria Analysis (MCA) as a useful instrument for the choice of better sediment management strategies, considering all the aspects involved (see Par. 3.3.4.1). The Criteria and Indicators explaining the various aspects of the problem (energy production and economy, environment, morphological variations, social aspects) and their evaluations, the Alternatives of management, and the level of importance (weight) to assign to each indicator/criterion, should be concerted among Policy Makers, hydropower production Managers, and the directly involved stakeholders.

Moreover, the Public policy should give support to all the analyses necessary to understand the hydraulic and sediment dynamics in the river systems, both for downstream (analyses of sediment continuum alterations) and upstream dam reaches (in order to take measures for reducing the sediment storage into the reservoirs).

3.3.5.2 Recommendations for Hydropower Production Managers

HP Managers should apply the sediment Management Plans together with the Public Bodies involved in the environment and soil defence. New analyses and approaches which consider the sediment continuum and the impact of the dams on channel morphology, must be considered. The new approaches should be an integration with the existing reservoir management projects (RMP), such as the proposal of coarse sediment removal and its introduction downstream the dam channel reach and/or the application of a Multi Criteria Analysis (MCA) for the choice of the better management Alternative, in coordination with both the Public Bodies and Authorities involved in the river system ecological and morphological maintenance as well as the stakeholders (economic and social aspects included).

Furthermore, the HP Managers should, inside the Management Plans, focus on: reservoir and dam characteristics, morphological and hydraulic parameters variations, ecosystem aspects and responses, catchment geological characteristics (to know the typology of sediment supply into the reservoir), analysis of the amount of catchment area that can increase the sediment transport and deposition into the reservoir, sediments analysis and removal operations, prevention measures for the river system (aquatic ecosystem protection, fishing and activities connected to the river system downstream the dam). The Managers should develop techniques which supply the sediments into the channel reaches downstream the dam, such as all the techniques of hydraulic and mechanic reservoir sediment removal; finally, they should define the suspended transport rate and concentration to be released for different stages of discharge, and its intensity and duration on the basis of the catchment characteristics, lithology and hydrological regime, considering a long period of observation.

3.3.5.3 Recommendations for Researchers/Academics

Researchers and Academics should help and support the Policy Makers and the hydropower production Managers to achieve the best strategies/alternatives of sediment management in order to promote the sediment continuum between upstream and downstream dams' channel reaches, through specific analyses of hydrological/hydraulic variables, sediment production and transport processes, morphological river patterns and variations, ecological aspects. The approach of a Multi Criteria Analysis, for example, needs the definition, quantification and range/type of variation of the Criteria and Indicators to be considered and analyzed for the choice of the better management alternative, making the MCA a useful tool for Policy-makers and HP Managers to integrate the actual Management Plans.

The studies have to be carried out through field and flume surveys, and monitoring analyses. They should be made at different spatial (catchment, hydrographic network, channel reach) and time (short- and long-term variations of hydromorphological and ecological parameters) scales, in order to better understand the response of the various river system aspects to the human impacts (hydropower exploitation). The findings of long-term analyses should be taken by the Government Authorities directly involved in the problem.

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3.4 Guideline for planning and designing of effective flood protection systems, river training and restoration projects that have lower impact on sediment continuity

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3.4.1 Background

The sediment transport in a river is part of the natural sediment cycle. The interaction of aggradation and erosion constitutes the river's morphological appearance and its habitats for a variety of adapted, aqueous, as well as non-aqueous, species. Within the last centuries, man increasingly made use of rivers and its adjacent landscapes. River channels were increasingly used for ship navigation, for operating mills or producing electrical energy in hydropower plants, while floodplains were converted into agricultural areas. Gravel and sand were extracted for the construction trade. Additionally, river training and sediment retention with torrent controls served to reduce risks of inundation, aggradation, bank erosion and lateral channel shift during flood events. Moreover, the sediment transport in the river depends on the sediment production in the catchment, which is altered by anthropogenic changes of land usage as well as by effects from climate change.

In the last century, the anthropogenic changes increasingly caused ecological, economical and technical problems. Sediment retention in torrents as well as interruptions of the sediment continuum by weirs reduced the sediment supply to downstream reaches. Simultaneously, channel narrowing increased the river's capacity to transport sediment. As a result, many alpine rivers suffer from bed incision, which may affect the groundwater level and therefore floodplain vegetation and depending fauna, agriculture as well as drinking water supply. Channel narrowing was achieved by fixing the banks with riprap and/or groynes, which inhibit lateral dynamics and the formation of natural riverbanks and according habitats. Considering the increasing exploitation of the rivers, there is an urgent need for improving river engineering measures to maintain or re-establish the sediment continuity.

The presented guideline aims to identify the problems that arise with the alteration of sediment transport and the underlying processes. Procedures for improved planning of river engineering measures are suggested and are exemplified by good practice examples.

3.4.2 Problem description

Alteration of sediment transport causes a variety of problems that may have negative ecological, technical and economic effects as well as effects on flood risk, possibly endangering human life. In most cases, alpine rivers are affected by a variety of anthropogenic impacts (Table 1).

Table 1: Main impacts on processes and channel structure at selected rivers located in the European Alps and their surrounding areas during the last two centuries (Habersack and Piégay, 2008). Copyright Elsevier 2008. Reprinted with permission

	Countries	Peak flow lowering by upstream dam	Upstream sediment trapping	In-channel works provoking degradation (mining, groins for navigation)	Bank protections to prevent channel movement	Embankment/ impact on flooding	Discharge lowering in a by-passed channel	Riparian encroachment in the active bars	Groundwater lowering and riparian dewatering
Rhine River	G–F	X	X	X	X	X	X		X
Upper Rhine River	A–CH		X	X	X	X			X
Rhône River	F			X		X	X	X	X
Arve River	F		X	X	X				
Drôme River	F		X	X					
Durance River	F	X	X				X	X	
Isère River	F							X	
Doubs River	F			X					
Ain River	F	X	X						
Danube River	G–A		X	X	X	X			X
Drau River	A		X	X	X	X			X
Sulm River	A				X	X			
Lech River	G–A		X		X	X			
Großache River	A		X		X	X			
Gail River	A		X	X	X	X			
Salzach River	G–A		X	X	X	X			X
Isar River	G		X	X	X	X	X	X	X
Thur River	CH		X	X	X	X			X
Emme River	CH		X	X	X	X			X
Tagliamento River	I			X	X	X		X	X
Piave River	I		X	X	X	X		X	X
Brenta River	I		X	X	X	X		X	X
Gesso River	I	X	X	X	X	X			X
Adda River	I	X	X	X	X	X			X
Dora Baltea River	I			X	X			X	X

Note: G, Germany; A, Austria; F, France; CH, Switzerland; I, Italy; rivers selected based on existing restoration projects.
Acknowledgement: M. Rinaldi, D. Sogni, N. Surian (Italy); M. Jaeggi, B. Zarn (Switzerland); Schaipp (Bavaria); J.N. Gautier (France).

As a result of these impacts, surpluses as well as deficits may occur in the same river (Table 2). It is therefore the challenge to re-establish continuity of sediment transport between river reaches and their upstream catchments.

Table 2: Deficits and surpluses of sediments in large Austrian rivers (Habersack and Piégay, 2008). Copyright Elsevier 2008. Reprinted with permission

River	Gauging station	Mean discharge (m^3s^{-1})	Analysed length (km)	Deficit (% length)	Excess (% length)
Danube	Wien Reichsbr.	1931	350	30	70
Drau	Drauhofen	112	214	27	59
Mur	Bruck/Mur	105	280	66	24
Enns	Steyr	202	186	33	47
Inn	Kirchbichl	289	258	44	29
Salzach	Golling	142	182	49	13

The problems that arise from these various impacts and from associated sediment deficits and surpluses are described below.

3.4.2.1 Decrease of lateral dynamics

Next to severe ecological problems, a reduction of lateral dynamics may over long term also affect the sediment continuum and flood protection. In natural rivers, erosion and accretion of bars and banks usually balance out. In contrast, if the banks cannot be eroded, sediment accumulates on the floodplain which will rarely be subjected to erosion. Repeated deposition of sediment behind the bank edges increases the bank height and hence bankfull discharge and the bed shear stresses. Bed degradation may start or accelerate. If higher discharges remain in-bank, flood waves may propagate faster downstream and increase flood risk in downstream reaches.

Figure 1: a) Bank protected from erosion by riprap, b) Floodplain forest after flooding showing sediment deposition, c) footprints in freshly deposited mud

In most cases the bank protections were also used to strongly reduce the original width of the river. Extreme flood events showed that this artificial narrowing increased the probability of excessive bank erosion or lateral shifts of the river, accompanied by severe damages to settlements or infrastructure.

Figure 2: Lateral erosion and destruction of infrastructure along the former regulated Trisanna River (Austria) during an extreme flood event in 2005 (source: Baubezirksamt Imst)

3.4.2.2 Bed degradation

Bed degradation decreases the frequency of inundation of the adjacent floodplain and lowers the adjacent groundwater level. Both lead to a decrease or loss of wetland habitats and corresponding flora and fauna.

A lowering of the groundwater level may additionally have negative effects on drinking water supply with respect to quantity and quality, as well as problems for agricultural areas.

Moreover, bed degradation may cause severe problems by destabilizing engineering structures such as bridge piers (Figure 3) or riverbank protection, endangering human life and causing excessive maintenance and reconstruction costs.

The increased sediment transport out of degrading reaches may cause downstream reaches to suffer from surpluses in sediment supply.

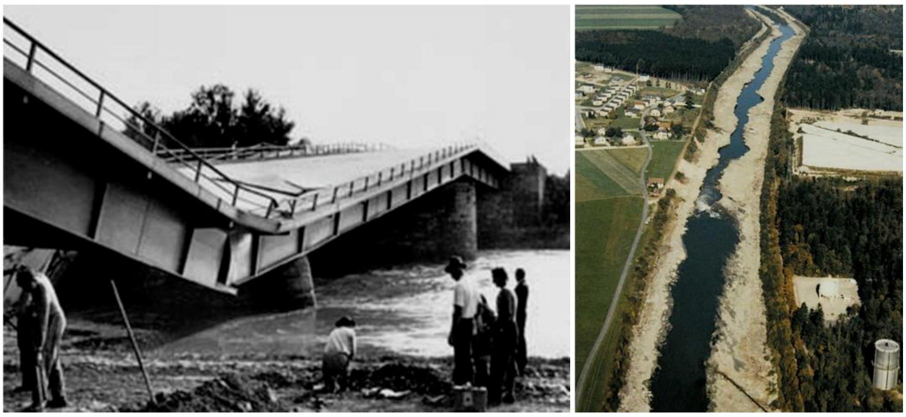


Figure 3: Left: Destabilization of a bridge pier and subsequent collapse of the bridge. Right: Riverbed breakthrough at the Salzach River, Austria (Hengl 2004)

In riverbeds with limited thickness of the gravel layer, bed degradation may lead to a complete loss of the gravel bed. In case of an underlying layer with higher erodibility, bed degradation may end in an abrupt riverbed breakthrough (e.g. Salzach River, Figure) with severe ecological, economical and technical consequences. Then, restoration measures based on channel widening would no longer be possible.

3.4.2.3 Bed aggradation

Bed aggradation causes the river bed to elevate, reducing the cross sectional area and the bankfull discharge. As a result, inundations increase in magnitude and frequency. Moreover, the probability of sudden channel shifts increases. At the same time, sediment depositing in aggrading reaches may be lacking in downstream reaches, there causing degradation problems.

Aggradations in reservoirs affect the functionality of river engineering structures such as flood retention basins or hydropower plants. Once deposited, silts and clays are difficult to remobilize, limiting the efficiency of flushing.

Figure 4: Dredging in the aggrading river section upstream the hydropower plants

3.4.3 Processes and relations

The Alpine rivers are the transport paths for sediment from their sources in the Alps down to their forelands. Over thousands of years, the morphology of the rivers and their floodplains adjusted to the amount of sediment delivered into the river network, so that – over the engineering timescale (10 to 100 years) – sections of natural rivers possess a balanced sediment budget. Anthropogenic impacts started in the last centuries, with the highest activity in the 19th and 20th centuries. The problems from impacting the sediment budget were already recognized a few decades later. However, even with unknown long-term effects of the existing structures, the activities affecting the sediment budget continue. This chapter aims to provide an understanding of the processes which are affected by anthropogenic impacts and the consequences.

The sediment budget of a river section is determined by the factors abstracted in Figure.

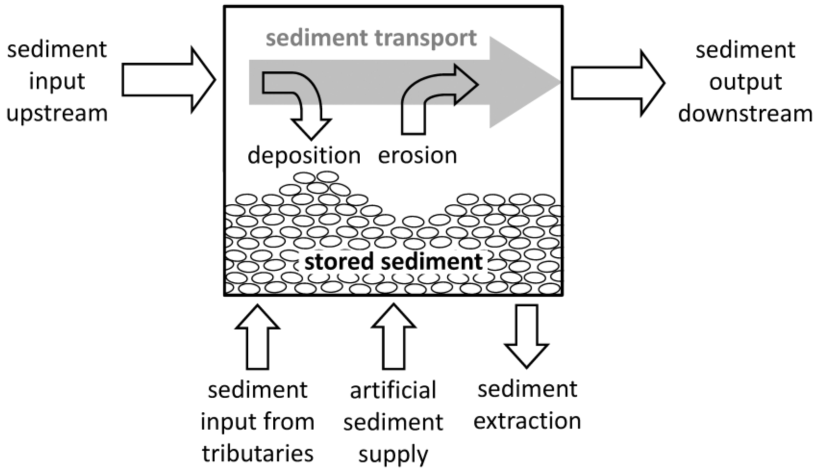


Figure 5: Factors and processes controlling the sediment budget of a river section

In a balanced state, the sediment load which exits the river section downstream equals the sediment load which is supplied to the river section upstream and from tributaries. In river sections with unaltered sediment supply and self-formed morphology, the mobility of the bed sediment and the shear stresses acting onto the bed are well adjusted to the sediment input. The amount of sediment that is deposited equals the amount of eroded sediment. Consequently, the average geometric parameters of the river section (e.g., bed levels) remain constant.

The bed shear stress is a well-established factor for explaining the sediment transport over a moveable bed. It can easily be estimated via

$$\tau = \rho g I R_h \tag{1}$$

where τ= shear stress (Nm^{-2}), ρ = density of water (kg m^{-3}), g = gravitational acceleration (m s^{-2}), I = energy slope (m m^{-1}) and R_h = hydraulic radius (m).

Shields (1936) investigated the equilibrium conditions between the driving forces for mobilisation and the resistance of the grain based on laboratory experiments and dimensional analyses. He found a dimensionless parameter (the Shields-Parameter θ), which has a similar value for all cohesionless grains at the threshold to motion. Meyer-Peter and Müller (1948) established a still widely used bedload transport formula from laboratory experiments and assigned a threshold value of 0.047 to θ. Using this parameter, the critical shear stress for motion of uniform grains can be calculated via:

$$\tau_c = \theta_c(\rho_s - \rho) g d \tag{2}$$

where τ_c = critical shear stress (N m^{-2}), θ_c = critical Shields parameter (dimensionless), ρ_s = particle density (kg m^{-3}), ρ = density of water (kg m^{-3}), g = gravitational acceleration (m s^{-2}) und d = grain size (m).

The ratio η relates the actual Shields parameter to the critical Shields parameter at the threshold to motion:

$$\eta = \frac{\theta}{\theta_c} = \frac{R_h I}{(s-1)d\theta_c} \quad \text{with } s = \rho_s/\rho \qquad (3)$$

Anthropogenic impacts affect factors and/or processes controlling the sediment budget, with the result of causing aggrading or degrading tendencies of the river bed. Considering Eq. 3 the effect of diverse anthropogenic impacts on the sediment transport can be estimated. A decrease of η leads to smaller erosion tendencies and higher deposition tendencies of transported sediment, while an increase of η may lead to higher erosion tendencies or to a development of a more resistant top layer of the river bed (armouring layer).

The effects of various anthropogenic impacts are described below while referring to the processes and relations outlined above.

3.4.3.1 Longitudinal river training

Most river training activities were a combination of river straightening and river narrowing, severely affecting the river's morphology (Figure 6). Both impacts are described separately below with respect to their effects on the sediment budget of a river section.

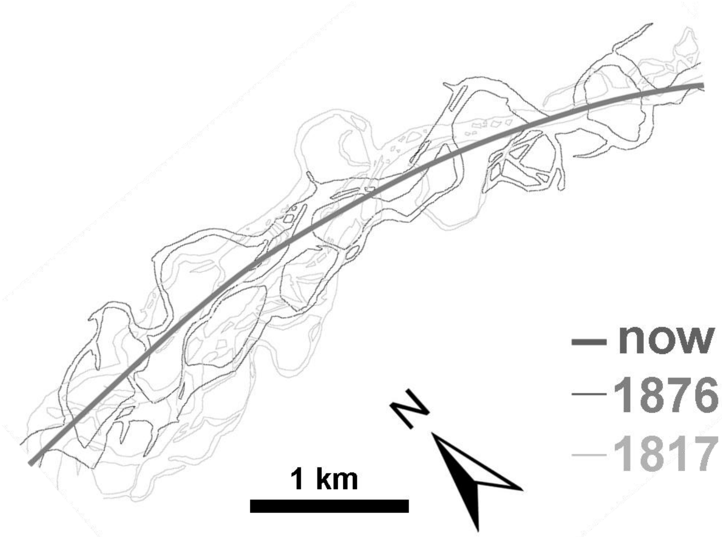


Figure 6: River narrowing and straightening at the Mur River along the border between Austria and Slovenia

3.4.3.1.1 River straightening

Rivers were straightened to gain land mainly for agricultural use, to reduce the costs for the training works or to reduce the travel lengths for ship navigation. Especially the formerly meandering rivers, straightened via meander cutoffs, obtained a much steeper slope, which increased the shear stresses acting on the river bed. An increase of the channel slope I and consequently of η (Eq. 3) leads to higher erosion tendencies and/or development of a coarsened armour layer. Net erosion of the riverbed leads to bed degradation and produces a negative sediment budget, and increases the sediment delivery to downstream river sections.

3.4.3.1.2 River narrowing

Next to fixing the riverbanks in their position, the construction of bank protections or instream structures such as groynes most often also served to narrow the river. River narrowing provided land for agricultural use and for settlements. A reduction of channel width increases the water depth and the hydraulic radius Rh in Eq. 3, again resulting in an increase of η.

In fact, some river engineers intentionally used river narrowing to increase sediment transport rates for triggering bed incision and increase the capability of transporting water and sediment within the banks. However, the degrading trends continued at many rivers, leading to the problems that resulted from bed degradation. Moreover, channel narrowing increases the hydraulic load onto the riverbanks, which – in case of failure of bank protections during extreme events – may cause excessive lateral erosion and/or channel shifts.

Additionally, as channel narrowing is established by installing non-erodible bank protection, the river cannot erode its floodplain through lateral erosion and channel migration. This leads to increasing bank height with every inundation and deposition of sediment on the floodplain, which during floods increases the Rh in Eq. 3 and hence increases the hydraulic load exerted onto the river bed.

3.4.3.2 Transverse structures

There is a variety of transverse structures affecting the sediment continuum of Alpine rivers. Sediment is retained already at its sources with torrent control structures. Weirs or dams from different types of hydropower plants or retention basins discontinue sediment transport downstream. Transverse structures such as ramps or steps are constructed to reduce the channel slope and stabilize the river bed. These types of transverse structures are discussed below with respect to their effect on the processes of sediment transport.

3.4.3.2.1 Weirs and dams

Weirs and dams from hydropower plants or flood protection structures generally lower the flow velocities upstream, strongly reducing the energy slope I in Eq. 3, reducing the ratio η and hence leading to increased deposition of sediment. Sedimentation in the reservoir reduces the volume available for storing water, which affects the functionality of the structure.

Downstream from the barrier, the retained sediment is then missing. There, the sediment input into river sections is reduced (Figure 5) and the stored sediment is eroded instead of the recently deposited sediment. This not only produces a negative sediment budget (causing bed degradation and eventually increased bank destabilization), but also affects the morphology of the river. A decrease of sediment supply leads to a self-initiated straightening of all morphological types of rivers (Figure 7).

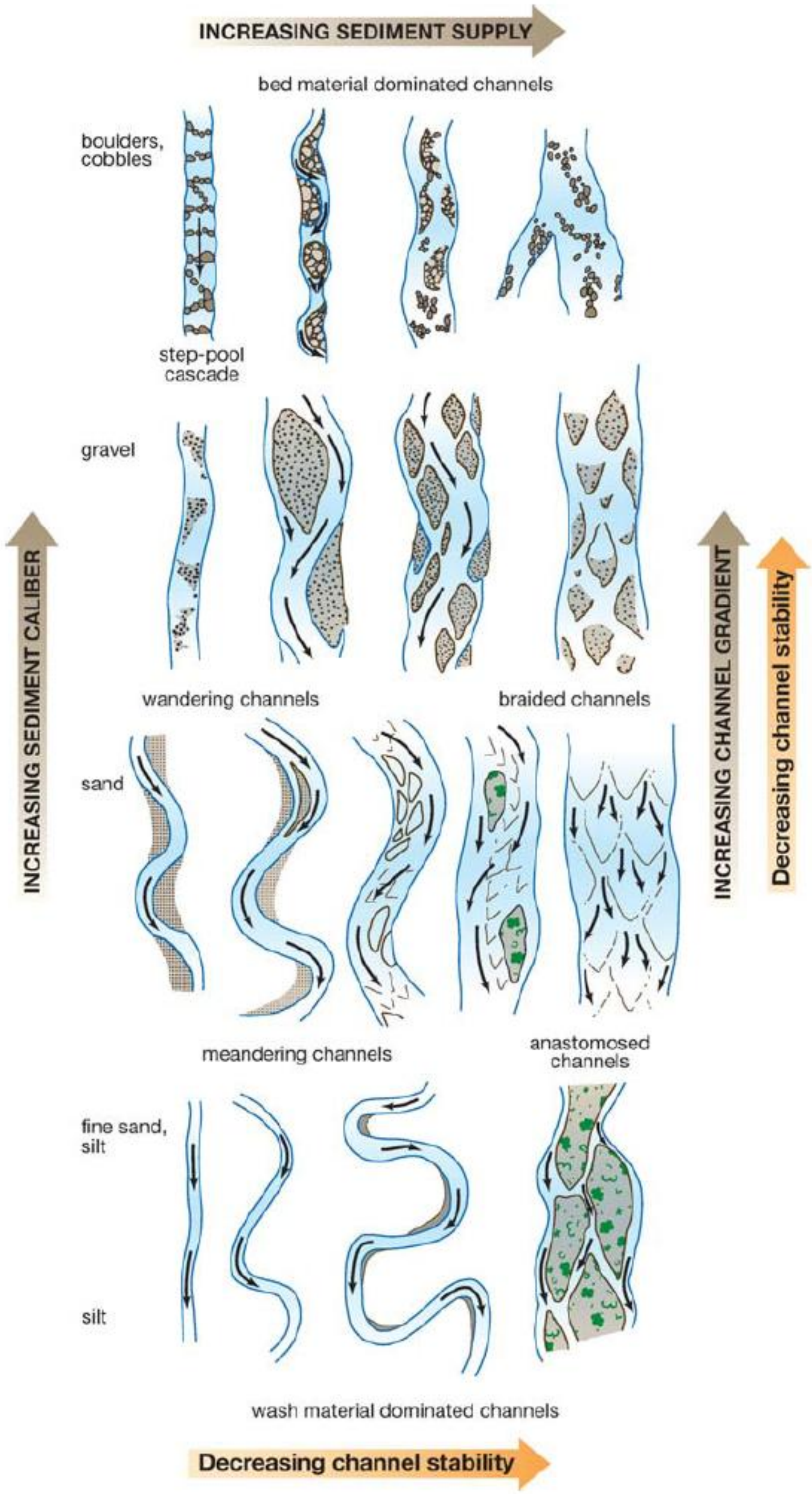


Figure 7: River morphology depending on sediment caliber, channel gradient and sediment supply (Church, 2006). Reprinted with permission from the Annual Review of Earth and Planetary Sciences, Volume 34 © 2006 by Annual Reviews, http://www.annualreviews.org

3.4.3.2.2 Ramps and steps

Ramps and steps reduce the energy slope I in Eq. 3 upstream and downstream from the structure of a riverbed that would be degrading otherwise. Most energy is converted in close distance downstream from the structure, where eventually a bed protection prevents from local scour. Given the reduction of energy slope, the bed aggrades upstream the structure, until a balanced sediment budget is achieved. However, as this budget is forced into balance, the river morphology is in a severely altered condition. Moreover, given the risk of damage of the structure(s) during floods and sudden bed lowering, these structures are not sustainable in terms of re-establishing a functioning sediment continuum.

Mountain streams with mean slopes between 4% and 15% tend to naturally form step-pool sequences, which provide an increased level of stability. Characteristic morphological relationships may be derived from these natural steps and rapids and may be used in the design of artificial steps or ramps in reaches with low bed stability (D'Agostino and Vianello, 2008).

3.4.3.3 Gravel mining

Gravel mining directly reduces the stored sediment (Figure 5). When sediment is taken out of the riverbed (including bars), it immediately causes a lowering of the riverbed. Excessive extraction of sediment (e.g. near and/or in cities for flood protection) may also affect the sediment transport given a change of energy slope I in Eq. 3. Gravel mining caused 69% of the bed lowering at the Drau River (Habersack, 1997).

3.4.3.4 Levees

Levees protect settlements and sometimes agricultural areas from inundation, but increase the hydraulic load within the levees by increasing R_h in Eq. 3, especially when levees are installed close to the riverbanks.

3.4.4 Procedures for improved planning

This chapter includes a range of measure types and procedures for countering different problems of sediment management.

3.4.4.1 Counter measures for mitigating bed degradation

Several measure types are available for mitigating channel incision. All measure types should be evaluated in the planning stages. The range of measure types appropriate for a specific problem will then be found to be restricted based on the boundary conditions of the certain river section. A preference should be given to ecologically oriented measure types to maintain or improve the ecological integrity of the river section and to meet the requirements of the EU Water Framework Directive.

The catalogue of counter measures comprises measures which affect the sediment regime, measures which increase the bed resistance to erosion, measures to reduce the energy slope and measures to reduce the bed shear stress (Figure 8). These types are discussed separately below.

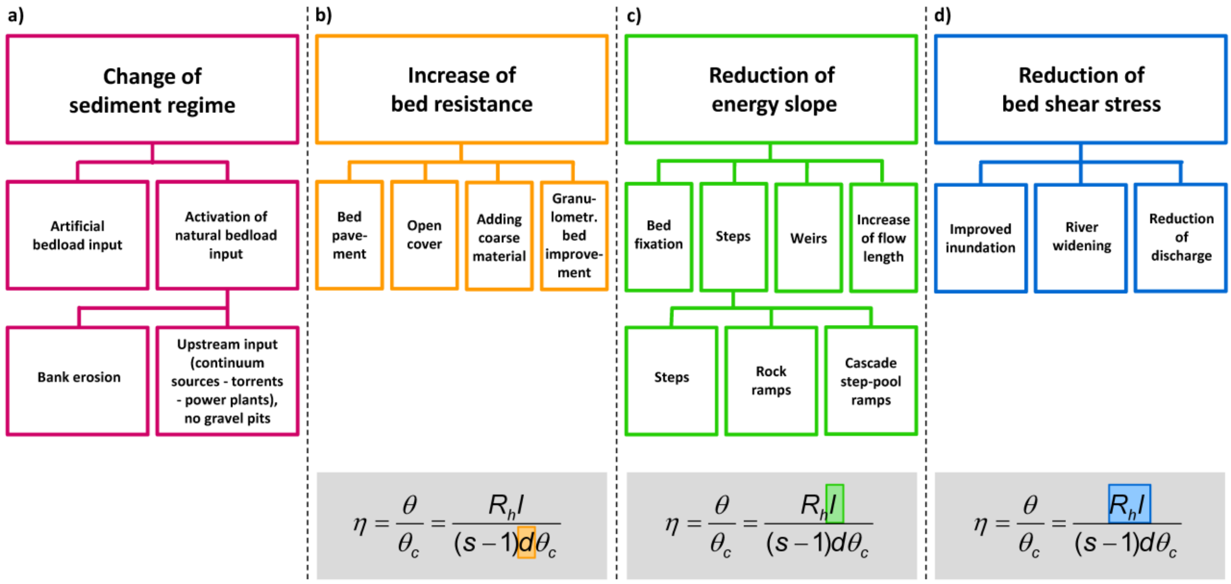


Figure 8: Principle measures for river bed stabilisation (based on Habersack et al., 2013)

3.4.4.1.1 Change of sediment regime (Figure 8a)

This type of measures aims to increase the sediment supply into the river section to re-establish a balanced sediment budget. The supplied sediment has to be of an appropriate quality (grain size distribution) as it has to configure the river bed. Sediment may be artificially supplied, e.g. downstream from weirs to compensate the retained sediment. However, it is more sustainable if the original sediment supply can be re-established, e.g. by removing sediment barriers or by increasing the sediment throughput of these structures. Initiated bank erosion may also deliver sediment for bedload transport or bed configuration. However, the supply from bank erosion is time-constraint, as bank erosion causes widening. Widening reduces the bed shear stresses. In case of residual sediment supply from upstream, after some initial widening the river bed starts to aggrade, thus balancing out the sediment coming from bank erosion before it reaches an equilibrium condition. In case of no sediment supply to the widened section, the near bank shear stresses decrease with widening until they fall below a threshold and the widening stops.

3.4.4.1.2 Increase of bed resistance (Figure 8b)

By increasing the grain diameter (d in Eq. 3) the Shields stress θ is decreased. Bed pavement aims for an inerodible river bed, but involves the danger of unexpected severe damages during extreme events and strongly alters the ecological integrity of the river. Adding coarse sediment increases the bed resistance, but still allows some residual morphodynamics. If the diameter of the added coarse sediment is selected within the natural spectrum of the grain sizes encountered at the specific river (within the coarser end of the natural grain size distribution), the bed resistance is increased with little alteration of morphodynamics (granulometric bed improvement).

3.4.4.1.3 Reduction of energy slope (Figure 8c)

With decreasing energy slope the Shields stress of gravel particles decreases (Eq. 3). While the energy slope may be reduced by fixing the bed in sections or by constructing crossing structures such as steps or weirs, especially former meandering rivers are suitable for reducing the energy slope by constructing or reconnecting meanders (measure type: increase the flow length).

3.4.4.1.4 Reduction of bed shear stress (Figure 8d)

A reduction of bed shear stress may be achieved by increasing the area for overbank flow (e.g., by setting back levees), which decreases the water depth during floods, and, as a consequence, the bed shear stresses (see also chapter 3.4).

Widening of the river bed is effective for many regulated rivers, as most river training works came along with channel narrowing. Widening is most effective at formerly braided rivers, as they tended to have much larger channel widths before river training. In the formerly anastomosing rivers widening may allow the establishment of multiple channels. However, for a sustainable, self-developed widening a minimum sediment supply has to be provided (compare Figure 7). In case of lacking sediment supply, widening may be combined with measures listed in Figure 8a.

A reduction of discharge may be achieved by constructing or reconnecting side channels, which overtake a significant proportion of the discharge and unload the main channel.

3.4.4.2 Tools for planning river bed widening

Planning of effective bed widenings requires knowledge of the minimum channel width that has to be provided for achieving the desired condition after restoration. This may be done using the following tools (Habersack et al., 2013):

3.4.4.2.1 Historic maps

Historic maps or aerial images show the morphological condition of the river before regulation and may serve as reference for planning of restoration measures (Figure 9). The use of maps or images from more than one point in time additionally helps to understand the dynamics of the river. It has to be considered that the boundary conditions (i.e. the sediment regime) which produced the morphology found in the historic sources are very likely to have changed given an alteration of sediment supply. Additional measures at the catchment scale may be required, when attempting to re-establish the historic condition.

Depending on the space available for restoration, the bank protection structures may be set back to provide the historic channel width (but without re-establishing lateral mobility); or an entire corridor may be provided which additionally allows the historic lateral dynamics (e.g., bank erosion, meander migration, development and shifts of side-channels).

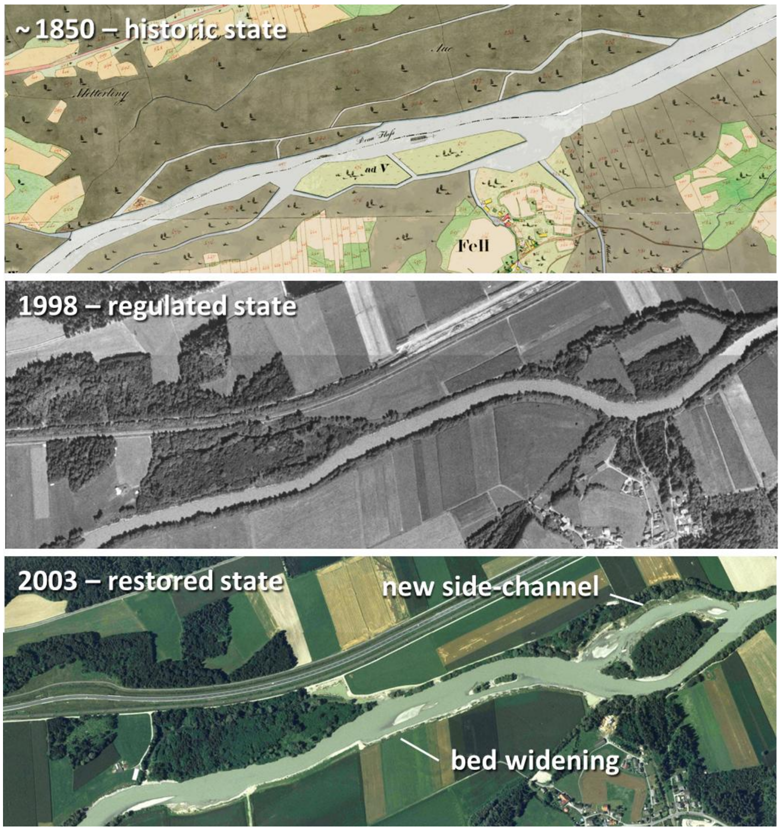


Figure 9: Historic maps may serve as a reference for restoration plans (image sources: Regional Government of Carinthia)

3.4.4.2.2 Regime equations

Regime equations (e.g. Lane, 1955) were derived from unconstraint river sections with a balanced sediment budget. Relations that were found between e.g. discharge and river width may now be used here to estimate an appropriate channel width. Also, classification schemes (e.g. Leopold and Wolman, 1957 and Da Silva, 1991) display the relation of river parameters of different morphological types. Ahmari and Da Silva (2011) derived the following formulas for thresholds between different morphological types from laboratory and field data, relating the width/depth ratios (B/h) to ratios between flow depth to grain size (h/D) (Figure 10):

Threshold between braiding and alternate bars/meandering:

If $\left(\frac{h}{D}\right) \leq 200$, then: $$\left(\frac{B}{h}\right) = 25\left(\frac{h}{D}\right)^{\frac{1}{3}} \qquad (4)$$

If $\left(\frac{h}{D}\right) \geq 200$, then: $\left(\frac{B}{h}\right) = 146\,(\approx 150)$ (5)

Threshold between alternate bars/meandering and meandering:

If $25 \leq \left(\frac{h}{D}\right) \leq 130$, then: $\left(\frac{B}{h}\right) = \frac{2}{13}\left(\frac{h}{D}\right)$ (6)

If $\frac{h}{D} \geq 130$, then: $\left(\frac{B}{h}\right) = 20$ (7)

Threshold between alternate bars/meandering and plane bed:

If $\left(\frac{h}{D}\right) \leq 25$, then: $\left(\frac{B}{h}\right) = 25\left(\frac{h}{D}\right)^{-0.55}$ (8)

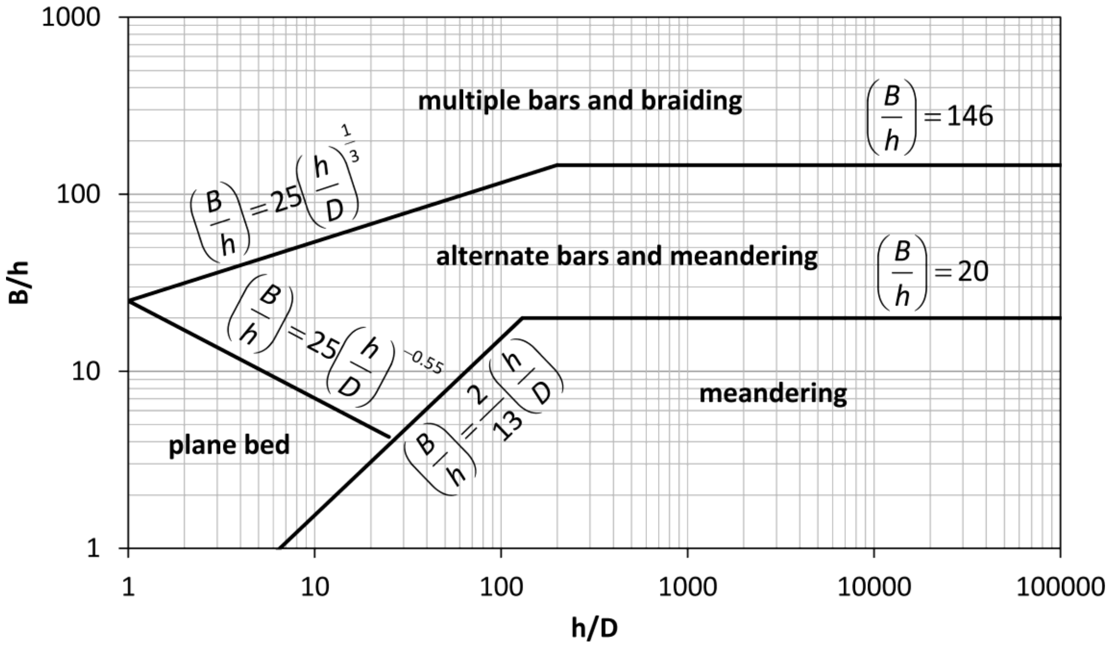


Figure 10: The Da Silva (1991) plan (displayed here in its revised form by Ahmari and Da Silva (2011)) provides an understanding of thresholds in river morphology useful in planning bed widenings. B: flow width, h: flow depth, and D: grain size

Again, deviations from a balanced sediment budget have to be accounted for when applying these tools. If the restoration also aims to re-establish lateral dynamics, additional width has to be provided to allow erosion of floodplain, lateral channel shift or braiding/anastomosing morphologies.

(Hunzinger (1998) and Schmautz (2003) derived equations directly for the design of bed widenings (e.g., to calculate the minimum length for a functioning widening) from laboratory experiments. Here, it has to be considered that the mechanisms of bank failure, an important process contributing to channel widening, generally cannot be reconstructed in scaled flume models for cohesive banks (Klösch et al., 2015).

3.4.4.2.3 Calculations in representative cross section

Using shallow water equations (e.g. Manning's equation), the effect of widening on water surface elevations can easily be estimated within a cross-section representative for the investigated river section. Applying Eq. 1 in a next step allows estimating the widening needed to reduce the bed shear stress below a defined threshold value. Bedload transport formulas may be applied to calculate the corresponding bedload transport capacity. However, eventual bed aggradation including the development of bars and resulting cross-sectional variation of geometry is not considered in this approach.

3.4.4.2.4 Numerical modeling

In case of sufficient data availability, numerical models may be applied to test different scenarios of bed widening (e.g. different channel widths). Using sediment transport models, the effect on bed development can be estimated. Additionally to investigations on channel width, scenarios of different temporal sequences of implementation can be tested in case of more than one measure.

Depending on the scale and complexity of the problem, one-, two- or three-dimensional models may be applied. Near-bank shear stresses or flow velocities derived from the hydrodynamic-numerical model may be used for an external bank erosion model. In best case, the processes of bank erosion are fully integrated into the hydrodynamic and sediment transport model to account for possible effects from intra-event scale bed-bank interactions, which may lead to unexpected outcomes such as excessive bank erosion near mid-channel bars (Klösch et al., 2015).

3.4.4.3 Implementation of bed widening

The bedload tends to deposit in the widened section until the bed level and slope adjust to the new channel width. As a result, the downstream section may suffer a temporary bedload deficit. To overcome this, the widening may be initiated by just removing the bank protection structures. It is then established self-dynamically through bank erosion and temporarily delivers sediment downstream. In case the eroding banks consist of coarse sediment, they support the supply of the downstream section with bedload.

Groynes may be embedded in the hinterland to avoid unintended bank retreat. The lower part of the bank protection may be left in the bank to reduce bank erosion rates. Moreover, as largest retreat rates can be expected along the outer bank of river bends, the overall lateral morphodynamics may be limited by removing bank protection structures in straight river sections and along to the inner bank of river bends only. However, developing bars may produce excessive bank erosion rates at unexpected locations (Klösch et al., 2015). If groynes have to maintain a fairway for ship navigation, groynes with heads directed downstream may help to increase bank erosion rates.

3.4.4.4 Consideration of sediment transport in flood risk management

3.4.4.4.1 Positioning of levees

Levees protect settlements and infrastructure from being flooded, but reduce the width available for the flood discharge, resulting in higher water levels (Schober et al., 2015). Figure 11 displays the flood water levels for different levee positions.

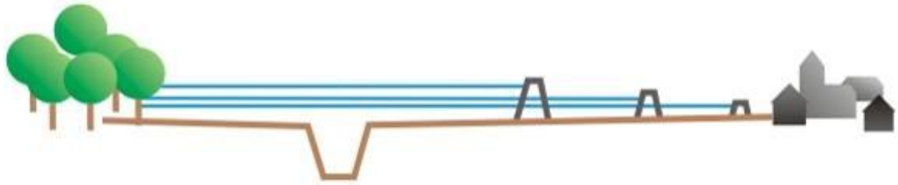


Figure 11: Different positions of levees in relation to the river and corresponding flood water levels (Habersack et al., 2014)

The elevated water levels increase the hydraulic radius Rh in Eq. 1, resulting in increased shear stresses and therefore affecting sediment transport. As the increase of shear stresses depends on the distance of the levees from the banks (Figure 12), the effect of the levees should be tested and the consequences for sediment transport evaluated. In order to reduce the effects for sediment transport, but also to maintain floodplain width for flood retention and to reduce residual risks, positioning in larger distance to the riverbank should be preferred.

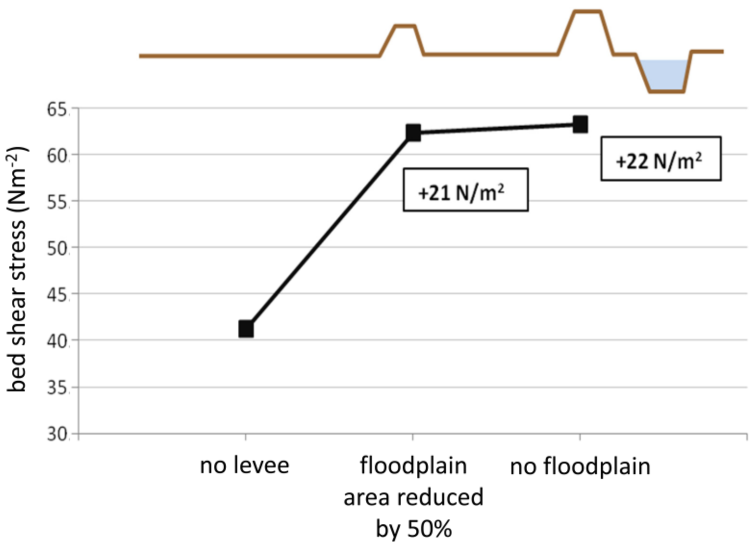


Figure 12: Bed shear stress acting onto riverbed depending on the distance of the levees to the riverbank (example from the Krems River, Habersack et al., 2014)

3.4.4.4.2 Sediment deposition in flood retention basins

The functioning of retention basins depends on their capability in storing water. Eventual deposition of sediment reduces the volume of the basin and causes a sediment deficit downstream. However, strategies exist to increase bedload throughput during flood events:

- Designing the retention basin parallel to the main channel, with the main channel transporting the bedload
- Allow continuous sediment transport through the channel also at normal flow in a uniform channel with appropriate slope
- Optimized, automatic control of the basin outlet based on runoff forecasting, which allows restricting the effects of the basin to the flood discharges
- A lifting rake decreases the impact on sediment throughput

3.4.4.5 Assessing the morphological spatial demand of rivers

In most cases, regulation of alpine rivers reduced channel width, increasing the shear stresses acting onto the riverbed. During extreme events in 2005 five alpine gravel bed rivers in Tyrol and Vorarlberg caused severe damage to adjacent settlements and infrastructure (Krapesch et al., 2011). The bank protection structures were not able to withstand the hydraulic load, so that these rivers freely adjusted to the hydraulic forces via widening through massive bank erosion. The hydraulic load acting onto the wetted perimeter can be expressed in terms of the stream power Ω (Wm^{-1}):

$$\Omega = \gamma Q I \tag{9}$$

where γ is the specific weight of water (9810 Nm^{-3}), Q is peak discharge (m^3s^{-1}) and I is energy slope. The corresponding stream power acting on a unit bed area (specific stream power ω) is:

$$\omega = \frac{\Omega}{B} \tag{10}$$

with B = channel width (m).

The specific stream power well explained the widening that occurred during extreme events at alpine rivers in 2005 (Figure 13).

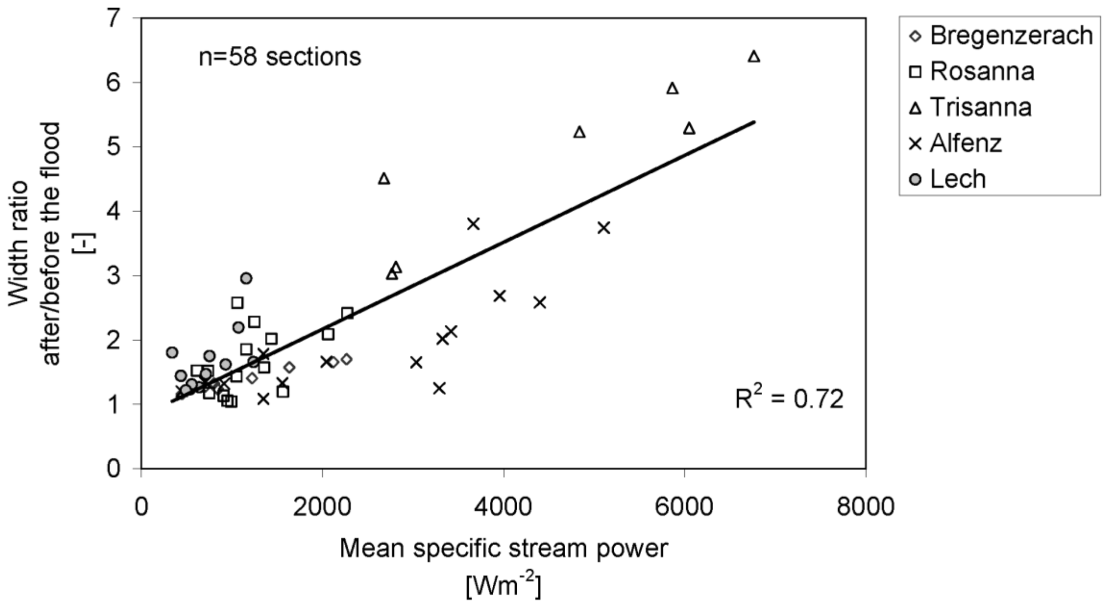


Figure 13: Width ratios and mean specific stream power values in 58 sections at the Trisanna, Rosanna, Lech, Bregenzerach and Alfenz Rivers on the sub reach scale (Krapesch et al., 2011)

Considering that any bank protection structure may be destroyed during extreme events, an appropriate width (a minimum morphological spatial demand) should be provided to the rivers to avoid the serious damages that occurred in Tyrol and Vorarlberg in 2005. For the investigated rivers, Krapesch et al. found this spatial demand to approximately correspond to three to seven times the width of the regulated channel. The specific stream power may also help to identify the sections of other rivers that are possibly endangered during flood events.

3.4.4.6 Design of step-pool sequences and rapids in mountain streams (D'Agostino and Vianello, 2008)

The assessment of the characteristic morphologic relationships in natural step-pool sequences of mountain streams may serve as a basis for the design of artificial steps or ramps to stabilize mountain streams with low environmental impact. D'Agostino and Vianello (2008) measured the mean channel slope (I), the step spacing (L) and height (H), mean bankfull channel width (W) as well as the grain sizes of d_{50} and d_{90}, for 85 step-pool sequences and 319 rapid typologies (Table 5):

Table 5: Mean reach slope (I) values, bankfull channel width (W) and characteristic grain sizes (D50 and D90) relative to natural step-pool and rapid morphologies surveyed in the field (D'Agostino and Vianello, 2008)

Morphologies	N°	I (-)	W (m)	D_{50} (m)	D_{90} (m)
step-pools - StP	85	0.13	6.45	0.33	0.43
stepped cascades - SC	233	0.10	8.47	0.22	0.57
glide cascades - GC	86	0.11	4.85	0.11	0.29

For these morphologies, D'Agostino and Vianello (2008) derived envelope curves for stable geometric relations, such as:

$$W_{max} \cong 2.5 I^{-0.9} \tag{11}$$

where W_{max} = maximum bankfull width. Alternatively, based on the finding by D'Agostino and Vianello (2008), that $L_{max} \cong I^{-1}$, W_{max} may be calculated as:

$$W_{max} \cong 2.5 L_{max}^{\;0.9} \tag{12}$$

With L_{max} = maximum step spacing. Step-pool sequences minimize the flow velocity when (Abrahams et al., 1995):

$$1 < \frac{(H/L)}{I} < 2 \tag{13}$$

While these equations already show a tendency of natural step-pool geometries, other literature may additionally be consulted (e.g. Rosport, 1998; Zimmermann, 2009).

3.4.5 Practice examples

3.4.5.1 River restoration at the Drau River via bed widening

3.4.5.1.1 Estimating the appropriate channel width for countering bed degradation

At the Upper Drau River, systematic river training in the late 19th century and in the 1960s, together with torrent control in tributaries, land use changes and gravel dredging, caused channel incision and exhibited negative economic and ecological consequences (Habersack and Nachtnebel, 1998). Next to historic maps (Figure 9), a numerical sediment transport model helped in the planning stages of restoration measures. The one-dimensional sediment transport model HEC2SR was used to test the effect of different channel widths on sediment transport (Spanzel, 1997). If no measures would have been implemented, the bed degradation would have continued (Figure 8a). In contrast, an increase of the channel width by 20 m (50% of the channel width) exhibited an approximately constant bed level (Figure 8b).

a)

b)

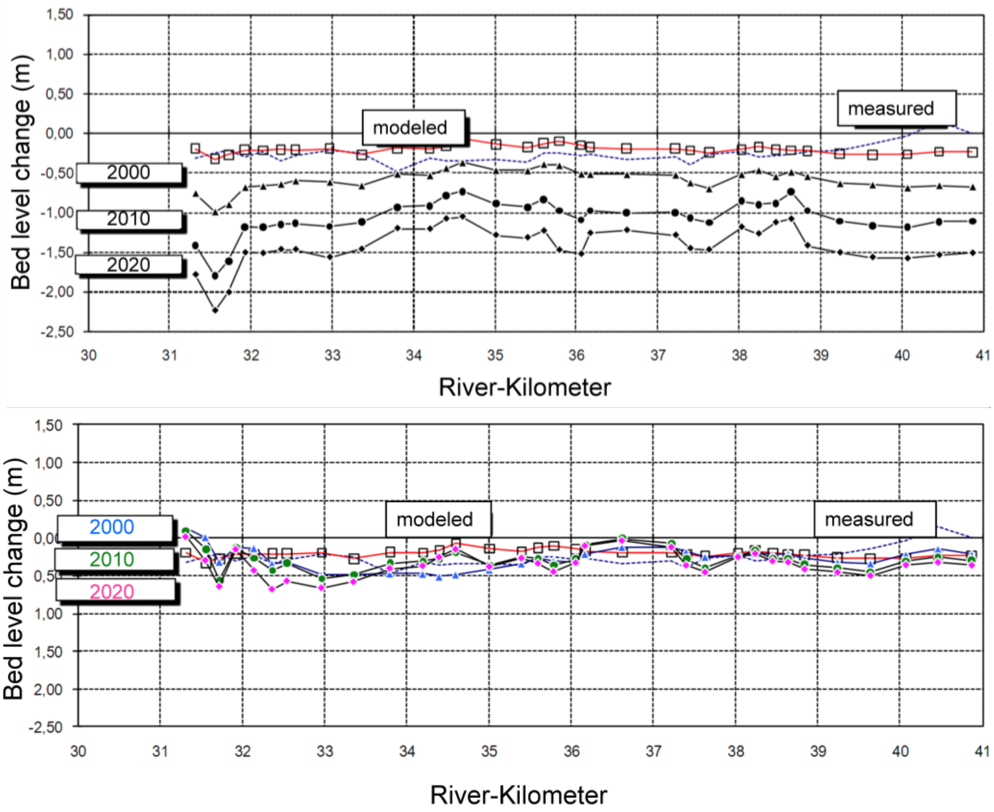


Figure 13: Simulation of bed level changes a) without measure implementation, b) after widening of the bed by 50% over the entire length

The evolution of the widened channel in the municipality of Kleblach-Lind (completion in 2003) confirmed the stabilizing effect of the widening on the bed levels. Bars developed, 24,000 m3 of sediment deposited in the restored section, and the bed levels were lifted on average by 0.35 m (Figure 14).

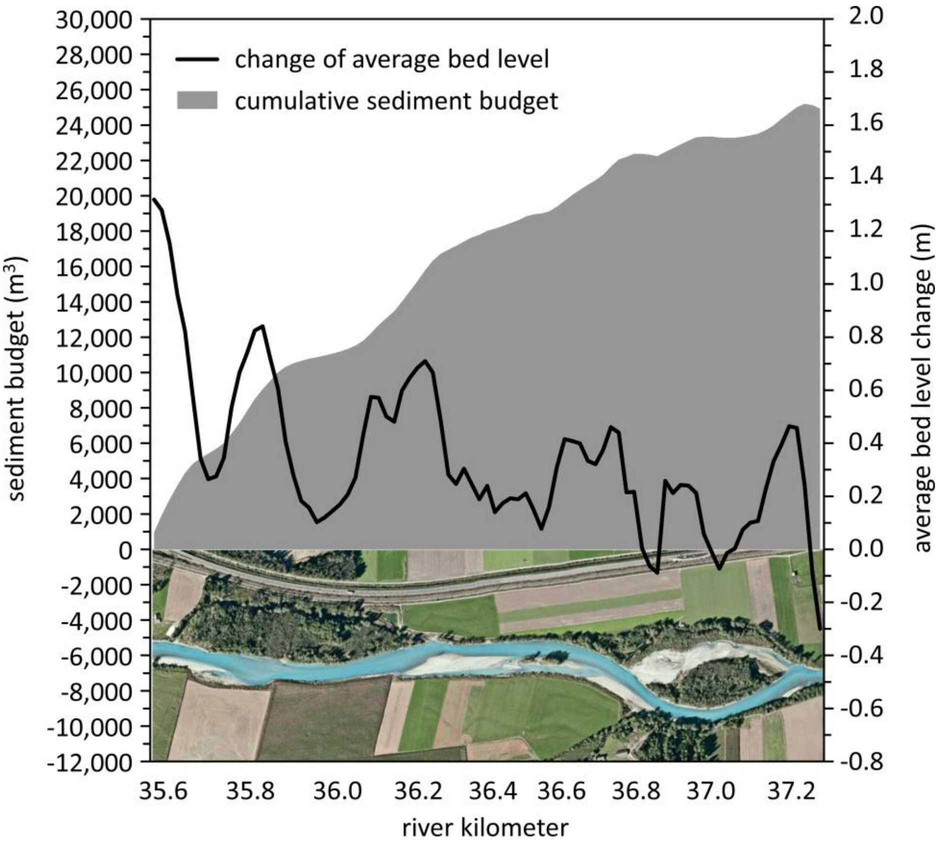


Figure 14: Morphology of the Drau River which developed in the new channel width (modified after Habersack et al., 2013)

3.4.5.1.2 Considering bed level changes for flood water levels

Widening produces a larger channel width, which at first glance would lead to lower water levels. However, widening reduces Rh in Eq. 1 and hence – in case of bedload supply from upstream – causes bedload to deposit, increasing the bed levels. Higher water levels at low flow correspond to the aims of restoring degraded rivers; there terrestrial and aquatic organisms often suffer from lowered groundwater levels, decreased flooding frequencies or disconnected side-channels. In contrast, increased water levels during floods may cause problems for flood protection. While the widened channel may still yield lower flood water levels after moderate aggradation given the larger width, large deposits may become a problem. It is therefore important to test the effect of virtual bed aggradation on flood water levels.

One widening of approximately 1.15 km length was completed at the Drau River in 1999 close to settlements of the villages Greifenburg and Bruggen. Shortly after measure completion the aggradation of the riverbed was measured. One-dimensional flow modelling using HEC-RAS was performed prior and after measure implementation to monitor the effect of deposits on flood water levels (Habersack et al., 2000). Modelling the exact same discharge (a one-year-flood: 320 m3s-1) over different channel geometries allowed direct comparison of the water surfaces.

The results showed that the flood water levels remained below the values from the state before restoration, despite the observed aggradation (Figure 15). Once established, a hydrodynamic model may serve for re-modelling the flow after repeated surveys and hence serve as a tool for flood risk management.

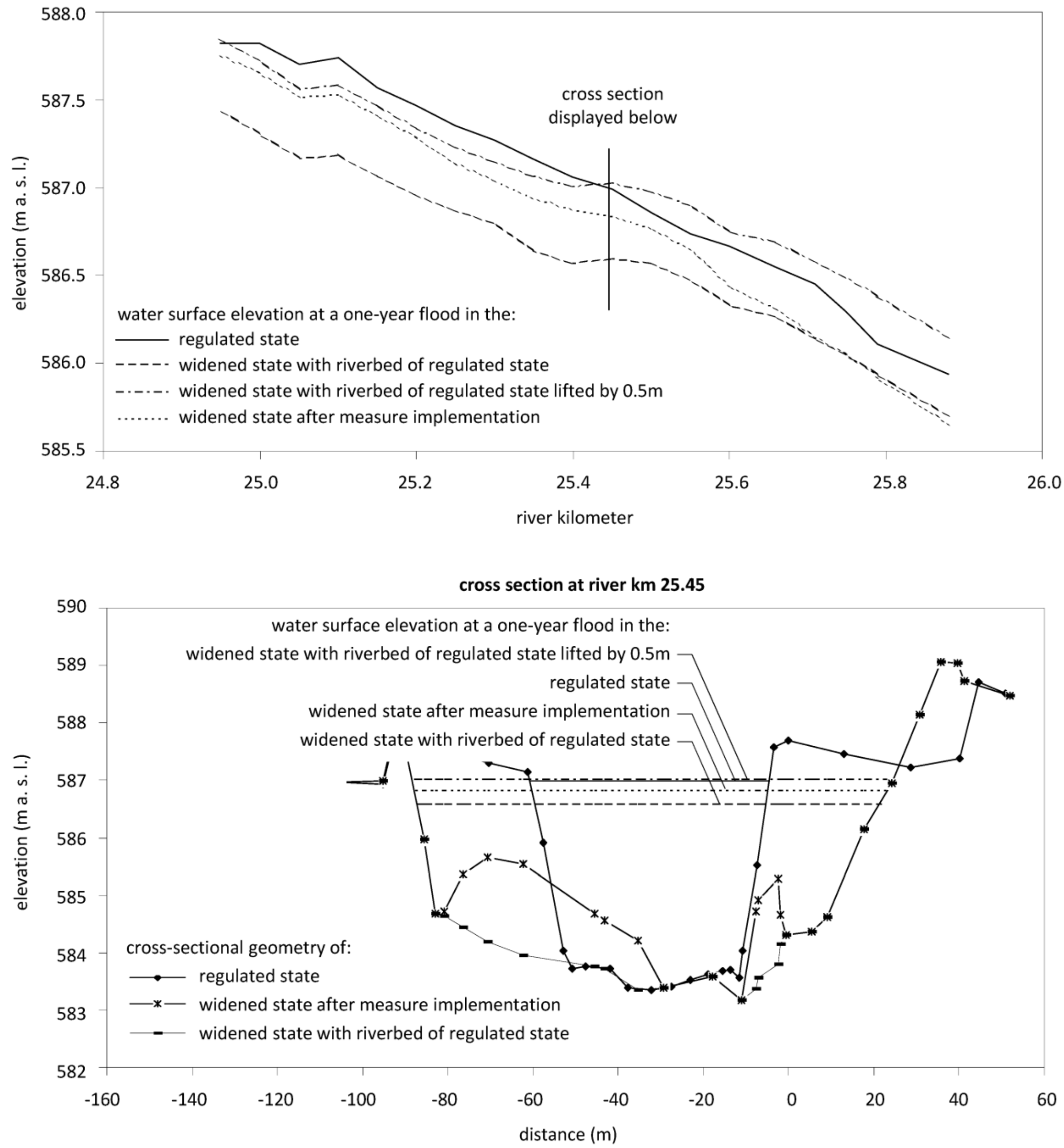


Figure 15: Modelled water surface elevations of a one-year-flood in a river section at Greifenburg-Bruggen, Austria, before and after bed widening, including a scenario of an aggraded bed (Habersack et al., 2000)

3.4.5.2 <u>Mitigating Channel Incision at the Mur River, Austria</u>

At the border reach of the Mur River between Austria and Slovenia, a historically braided river section, systematic river training and deficits in bedload supply led to continuous bed incision and to considerable ecological consequences. In a Basic Water Management Concept (Austrian-Slovenian Standing Committee for the Mur River, 2001) a series of countermeasures was proposed, based on findings outlined below.

3.4.5.2.1 Selecting the appropriate measure for mitigating channel incision

If space for river restoration is available, the shear stresses may be reduced in two ecologically-oriented ways: (1) decreasing the slope I in Eq. 1 by increasing the channel curvature, or (2) decreasing R_h in Eq. 1 by increasing the channel width. Applying the one-dimensional hydrodynamic flow model HEC-RAS to a schematic channel representing the Mur River geometry allowed determining the bedload transport capacity for different channel slopes and channel widths. The model results showed that – within the spatial constraints along the Mur River – bed widening was more effective in reducing the bedload transport capacity (Figure 16).

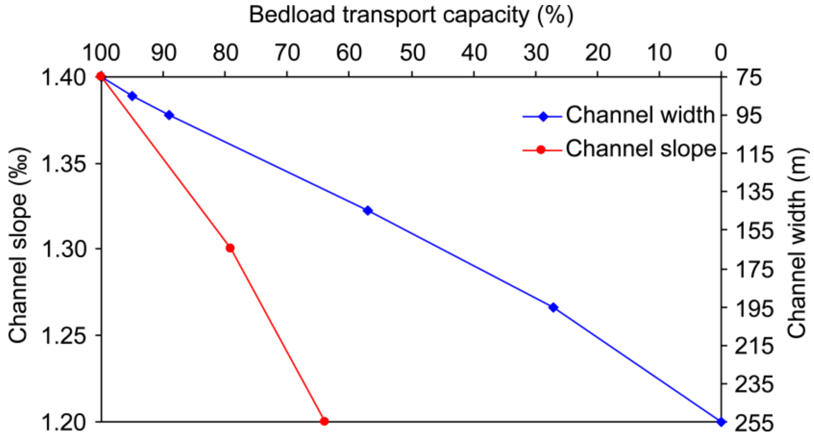


Figure 16: Bedload transport capacity in relation to channel slope and channel width (based on Habersack and Schneider, 2000)

3.4.5.2.2 Positioning of measures

The floodplain across the whole river length of the border reach of the Mur River was investigated for stretches suitable for river-bed widenings. The migration and high bedload transport of the historical river system stored high amounts of Quaternary deposits in the floodplain. The whole river length was evaluated to determine the amount of gravel in the adjacent floodplains and the relative elevation of the gravel layer compared to the elevation of the river-bed. The suitability for river-bed widenings across the river length was assessed by also considering natural and infrastructural constraints to the channel (e.g., only 86 m river width in town Bad Radkersburg). By coupling the suitability with the historical and the predicted degradation, the sections suitable for river-bed widenings were localized (Figure 17). High priority was given to reaches with extreme degradation. Sections with a gravel bed thickness < 0.5 m above the Tertiary were excluded because bed break-through due to scouring processes remains a threat even if widening takes place (e.g., during bed form migration) (Habersack and Piégay, 2008). Finally, five types of measures were identified: A: river-bed widening to about 200 m and artificial bedload supply; B: self-forming side erosion and increase of river-bed width; C: initial river-bed widening, followed by side erosion; D: activation of gravel deposits without changing the effective bed width in combination with side arm reconnections; E: alternative bed stabilization such as by ramps or local grain size increases. A step-wise realization of the measures was therefore suggested to optimize gravel availability and extend the lifetime of the measures, recognizing that long-term gravel input from outside the reach is essential (Austrian-Slovenian Standing Committee for the Mur River, 2001; Habersack and Piégay, 2008).

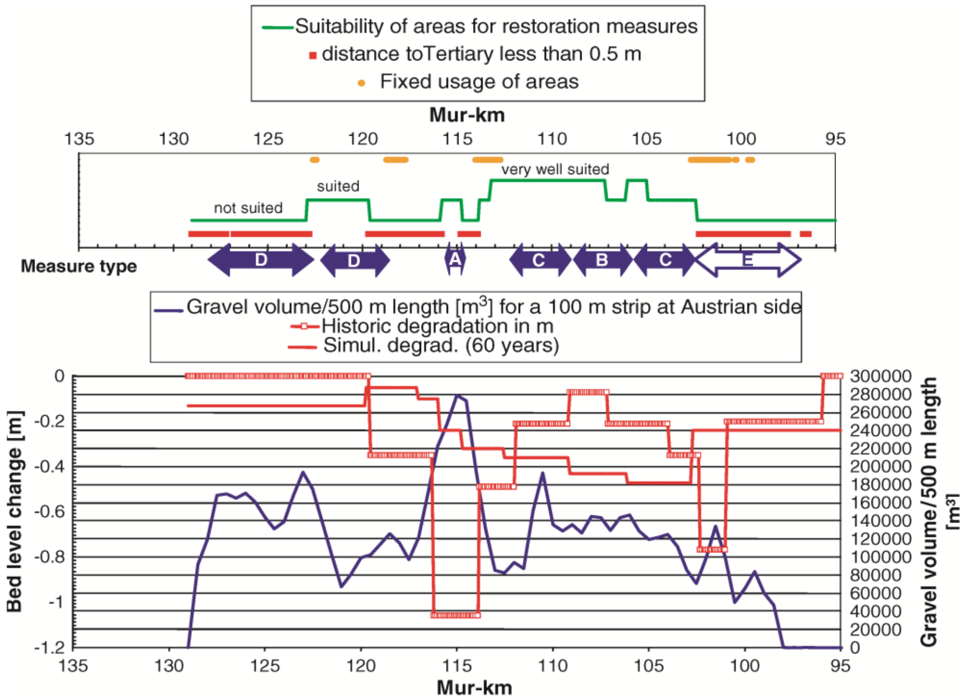
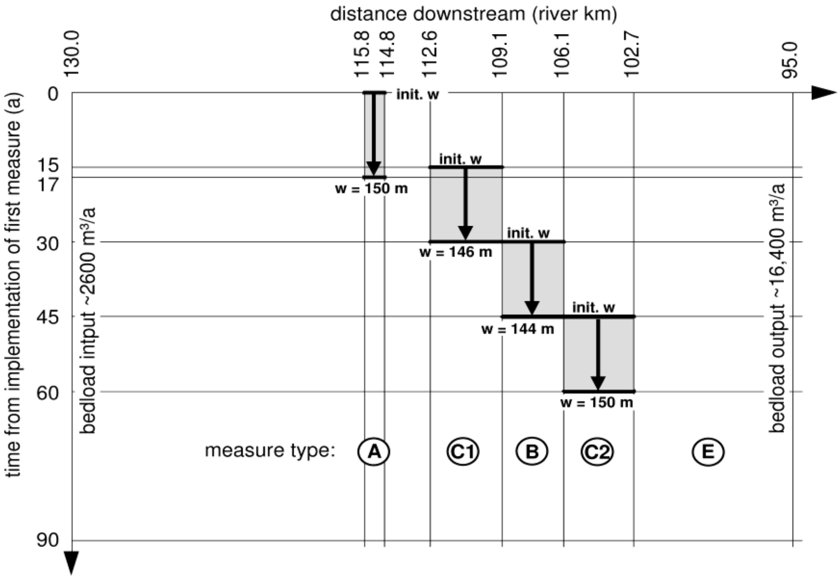


Figure 17: Recommended positioning and types of restoration measures according to the section suitability (determined according to gravel availability in the floodplain, thickness of remaining gravel layer and constraints) and to the historical and predicted bed degradation. A: river-bed widening to about 200 m and artificial bedload supply; B: self-forming side erosion and increase of river-bed width; C: initial river-bed widening, followed by side erosion; D: activation of gravel deposits without changing the effective bed width in combination with side arm reconnections; E: alternative bed stabilization by ramps or local grain size increases); arrows show the length of the various measure types (modified after Habersack and Piégay, 2008). Copyright Elsevier 2008. Reprinted with permission

3.4.5.2.3 Temporal sequence of measure implementation

A one-dimensional, quasi-steady state model was used to calculate sediment-transport rates and bed changes of the Mur River (MORMO, ETH Zuerich). Repeated surveys of cross sections served for model calibration. Bank retreat and the resulting widening were assumed to increase linearly with discharge above 300 m3s-1 (mean discharge: 150 m3s-1). Bank retreat rates had to be estimated, as experiences as well as a representation of bank erosion processes in the model were lacking. The numerical simulations showed overall positive effects of the measures. A step-wise instead of a simultaneous realization of the measures extended the lifetime of the measure combination. Several successions of measure implementation were tested. The succession that yielded the best result is shown in Figure 18.

a)



b)

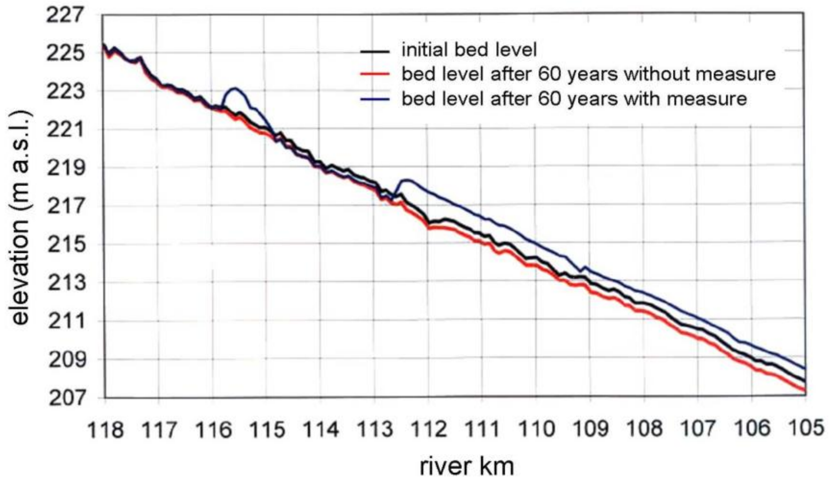


Figure 18: a) Temporal sequence of measure implementation that, according to the sediment transport model, best stabilized the river bed level, b) corresponding model result. (Klösch et al., 2011, modified after Hengl et al., 2001). Copyright © 2013, John Wiley and Sons. Reprinted with permission

3.4.5.2.4 Measure implementation

As recommended in the Basic Water Management Concept, the first major measure was implemented between river km 115 and 116 at Gosdorf, upstream of a reach suffering from severe bed degradation. There, the Concept proposed a river-bed widening to about 200 m and artificial bedload supply. Widening due to bank erosion was enabled by removing the bank protection structures along the left bank over a length of 1 km. A new side arm was excavated and the dredged material was introduced into the main channel as an immediate artificial bedload supply (approx. 150,000 m³; Figure 19).

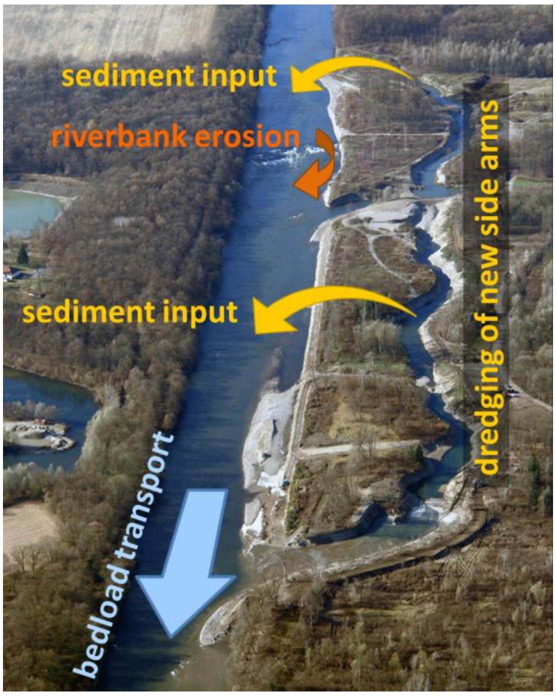


Figure 19: Schematic drawing of the functionality of the measures at Gosdorf (measure type A in Figure and Figure, Klösch et al. 2011). Copyright © 2013, John Wiley and Sons. Reprinted with permission

3.4.6 Conclusions and recommendations

River engineering structures for flood protection and river training exhibited severe impacts on the sediment continuity of Alpine Rivers, causing a variety of ecological, economic and technical problems as well as effects on flood risk, possibly endangering human life. It was therefore one aim of the SedAlp project to establish a guideline for "planning and designing of effective flood protection systems, river training and restoration projects that have lower impact on sediment continuity". Subsequent to the problem identification and an analysis of involved processes, the guideline proposed procedures for improved planning in river engineering. Finally, some of the procedures were exemplified by practice examples. Based on the insights gained in establishing the presented guideline, the following recommendations were derived for policy makers, practitioners and researchers:

3.4.6.1 Recommendations for Policy makers

When assessing the environmental impact of planned river engineering structures, the sediment connectivity should be accounted for not only at the local scale of the structure, but regarding the overall downstream effect on sediment transport. Every engineering measure exerts an impact on sediment transport to some extent. As Alpine rivers are opposed to multiple pressures and as the impacts on sediment transport accumulate with distance downstream, environmental impact assessments should precisely determine the magnitude of disturbance and lead to a detailed prescription of compensation measures rather than assessing whether the impact remains within an acceptable range. Monitoring programs should be prescribed and used for repeated adjustment of compensation measures to the structure's impact.

When assessing the ecological integrity of a river reach, sediment continuity between sediment production in the catchment and the reach to be evaluated has to be considered as a major precondition for the ecological functioning of a river reach.

3.4.6.2 Recommendations for practitioners

For practitioners, the presented guideline provides (1) an understanding of processes of sediment transport and relations to river engineering, making them aware of possible consequences of river engineering measures, and (2) suggestions for improved planning of river engineering measures. Practitioners following the guideline consider sediment transport already in planning stages of not only restoration projects. River engineering in general should be performed with the aim to maintain sediment transport dynamics, or to minimize negative effects on sediment transport while being aware of the consequences. Repeated consultation of the state of the art derived from research outputs would improve and optimize the applied engineering methods and may lead to better and/or more economic solutions.

3.4.6.3 Recommendations for Researchers/Academics

The field of sediment transport and its interaction with engineering measures is widespread and there are many knowledge gaps that need to be explored. Increasing computational power allows to numerically solve problems with increasing complexity. However, there is a discrepancy between the number of theoretical, numerical or laboratory investigations and the number of investigations in the field, where factors may appear that otherwise would remain undetected. Future research should find a balance with field verification, implying a close collaboration with policy makers and practitioners.

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4 Conclusions and recommendations

Manmade structures in river system and torrents have various purposes, i.e. from power production to torrent control, flood protection and other natural hazard mitigation. Sediment transport is a natural process, while sediment continuity should be one of the priorities when planning river and torrent structures.

Such planning and design is one of the biggest professional challenges in the regulation of torrents and rivers, because when dealing with the threat from the negative effects of sediment transport, water and sediment regime in the whole river basin should be considered to keep the positive effects of dynamic sediment transport. In selecting the best solution, the knowledge of all ongoing geomorphic processes and their possible interaction with the mitigation measures is needed. This means that a multidisciplinary approach has to be applied, including specialized skills in applied geomorphology, fluid dynamics, forestry and structural engineering. One of the SedAlp project aims is to establish guidelines for planning river and torrent structures with low impact on sediment continuity. Torrent structures are closely linked to downstream reaches due to insufficient sediment feeding from upstream stream systems. A stream network perspective must be adopted to expose the sediment continuity problem of a river system.

In a river system, the presence of dams for hydropower production alters the natural tendency to the morphological quasi-equilibrium which maximizes the flow resistance giving stability to the system itself, due to the sediment connectivity alteration in space and time. So, problem identification and solutions focused on sediment management in artificial reservoirs should involve concerted actions and strategies.

River engineering structures for flood protection and river training have severely affected the sediment continuity of Alpine rivers, causing a variety of ecological, economic and technical problems as well as effects on flood risk, possibly endangering human life. Therefore an improvement in the approach is necessary to ensure flood protection without impacting the sediment continuity of the river system.

The Guidelines in this Report are divided into three groups, with an additional section on Improved Concepts:

- Improved concepts of responses of torrent/river control structures to floods and debris flow impacts (including wood)
- Guidelines for planning/designing of efficient torrent control structures with low impact on sediment continuity between upstream torrential headwaters and downstream river reaches
- Guidelines for improved planning of hydropower plants aimed to improve the longitudinal sediment continuity between upstream torrential headwaters and downstream river reaches
- Guidelines for planning and designing of effective flood protection systems, river training and restoration projects that have lower impact on sediment continuity

Each Guideline provide recommendations for policy makers, practitioners and researchers. General recommendations from all Chapters (Guidelines) are summarized below, while detailed recommendations can be found in the respective Chapters (3.1, 3.2, 3.3 and 3.4) of this report.

4.1 Policy makers

- Adequate risk-based land use planning
- Holistic (whole river system) approach when planning flood protection and control measures
- Timely and adequate monitoring and maintenance of the existing water infrastructure (sufficient financing)
- Awareness of vulnerability of control structures for events with a longer return period than the designed one – evacuation plans, risk management, additional measures
- Sediment continuity problem solving might lead to strong modifications of existing protection systems
- Restoring sediment dynamics involves "giving space"
- When planning structures, measures and hydropower structures the morphological point of view must be taken into account, not only the hydrological/hydraulic and ecological points of view
- Environmental impact assessment should precisely determine the magnitude of disturbance and lead to a detailed prescription of compensation measures

4.2 Practitioners

- The prevailing extreme sediment transport process should be determined for each reach of the torrent (floods, fluvial solid transport, debris flood and debris flow)
- Functions of torrential barriers can be divided into the following functional process control types: stabilization/consolidation, retention, dosing and filtering, energy dissipation
- Torrent control measures should be scenario-oriented
- In the case of building open barriers it is recommended to plan two or three barriers with complementary functionality in a chain, rather than only one open "large barrier"
- Practitioners should be open to consider deriving knowledge for the planning process from backward-oriented indication, mathematical modelling and physical lab experiments
- Planning or designing efficient torrent control structures involves providing verifications of the obtained solutions with respect to the system performance at different scales

- Sediment continuum and the impact of dams on channel morphology must be considered in the Management Plans of HP managers
- Sediment transport process should be considered already in the planning phase, not only in restoration. River engineering in general should be performed with the aim to maintain sediment transport dynamics

4.3 Researchers

- Long-term data collection, analysis and survey of sediment retention basins – also surveying during filling and self-cleaning (self-cleaning optimization) and after disaster (focus on sediments and driftwood)
- Further development of management of sediment connectivity
- Interdisciplinary research at the interface between processes, risk consequences and resilience
- Applied research targeted at improving the quality of protection system design
- Specific research to better understand river morphology, ecohydraulics, system functions and the related, monetarily quantified, system services
- Research activities supporting the effectiveness of the decision, communication and participation process
- Studies have to be carried out through field and flume surveys, and monitoring analyses. They should be made at different spatial (catchment, hydrographic network, channel reach) and time (short- and long-term variations of hydromorphological and ecological parameters) scales in order to better understand the response of the various river system aspects to human impacts (hydropower exploitation)
- There is a discrepancy between the number of theoretical, numerical or laboratory investigations and the number of investigations in the field, where factors may appear that would remain undetected otherwise. Future research should find a balance with field verification, implying a close collaboration with policy makers and practitioners

5 Annex