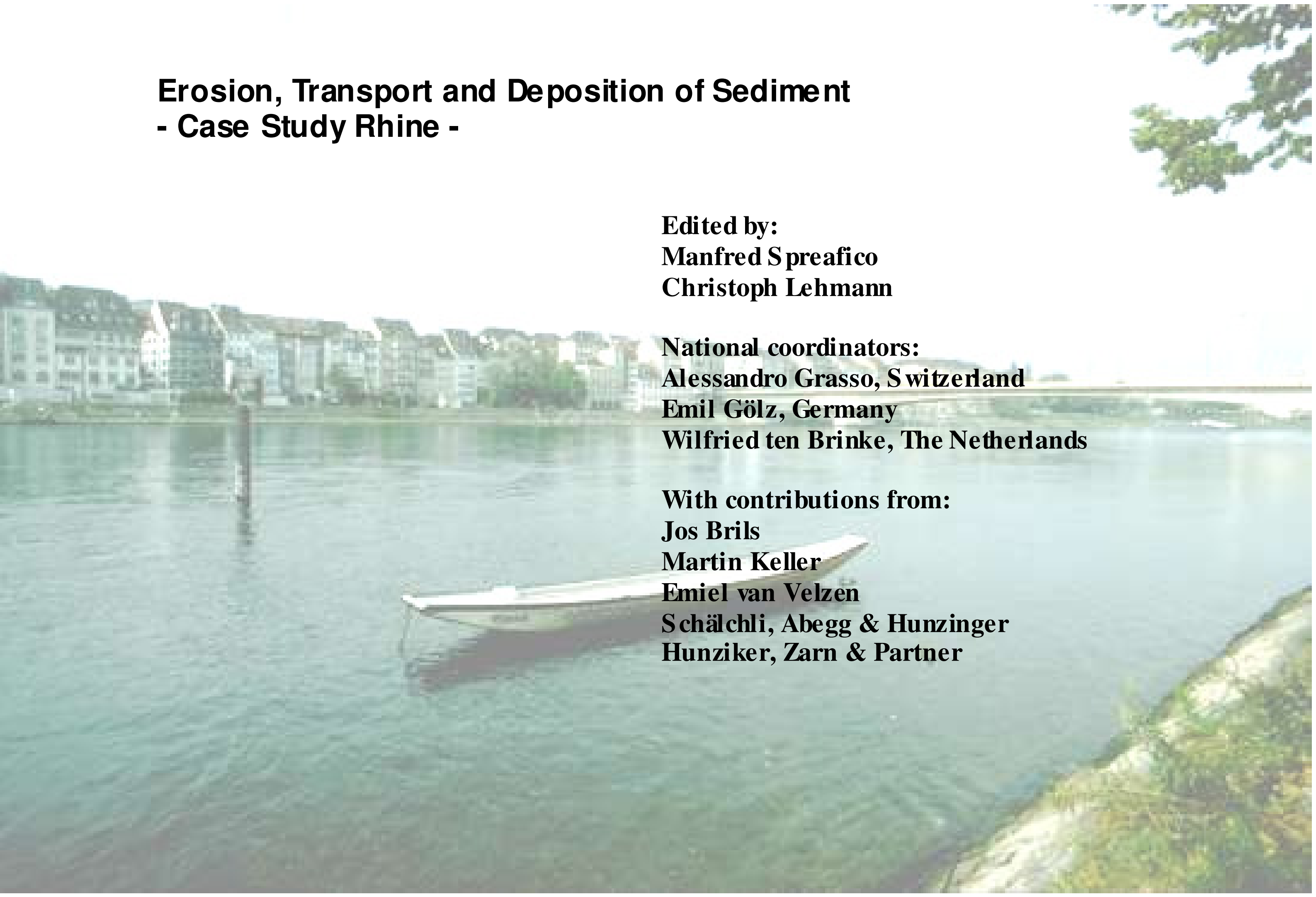
International Commission for the Hydrology of the Rhine Basin



Erosion, Transport and Deposition of Sediment
- Case Study Rhine -

Edited by:
Manfred Spreafico
Christoph Lehmann

National coordinators:
Alessandro Grasso, Switzerland
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With contributions from:
Jos Brils
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Contribution to the International Sediment Initiative of UNESCO/IHP

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Confederation

bfg Bundesanstalt für Gewässerkunde

Deltares

Report no II-20 of the CHR

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Preface

„Erosion, transport and deposition of sediment"
Case Study Rhine

Erosion, transport and deposition of sediment have significant economic, environmental and social impacts in large river basins.

The International Sediment Initiative (ISI) of UNESCO provides with its projects an important contribution to sustainable sediment and water management in river basins. With the processing of exemplary case studies from large river basins good examples of sediment management practices have been prepared and successful strategies and procedures will be made accessible to experts from other river basins.

The CHR produced the "Case Study Rhine" in the framework of ISI. Sediment experts of the Rhine riparian states of Switzerland, Austria, Germany and The Netherlands have implemented their experiences in this publication. Prof. Emil Gölz and Dr. Martin Keller of the German Federal Institute of Hydrology, Dr. Wilfried ten Brinke and ir. Emiel van Velzen of the former National Institute for Inland Water Management and Waste Water Treatment in The Netherlands, Dr. Jos Brils from the Dutch research institute Deltares and Dr. Alessandro Grasso from the Division of Hydrology of the Swiss Federal Office for Environment have provided valuable contributions for the publication, based on studies carried-out in the respective countries. The CHR secretariat under the guidance of ing. Eric Sprokkereef has prepared the printing of the publication.

On behalf of the CHR coordinators I thank the institutions and experts involved in the preparation for the provided excellent contributions.

Prof. Dr. Manfred Spreafico
President of the International Commission
for the Hydrology of the Rhine basin

Content

Introduction

The case study Rhine is a contribution to the International Sedimentation Initiative of UNESCO. The International Sedimentation Initiative (ISI) has been launched by the United Nations Educational, Scientific, and Cultural Organization (UNESCO), as a major activity of the Sixth Phase (2002-2006) of the International Hydrological Programme (IHP)[1]. In justifying the resolution, the Intergovernmental Council considered that:

- *i) Erosion and sedimentation processes and management in catchments, river systems and reservoirs are increasingly important in all parts of the world*
- *ii) Erosion and sedimentation processes have significant socio-economic and environmental impacts in river basin management*
- *iii) Sediment production processes are not sufficiently understood for practical use, while various sediment transport models are available*
- *iv) Within the next few decades more than 50% of the world's reservoir storage capacity may be lost due to sedimentation, and realizing that appropriate storage sites of water are limited,*
- *v) Sediment management practices should be improved.*

The mission of ISI:
The International Sedimentation Initiative is expected to add a new dimension to ongoing efforts aiming at sustainable sediment management, in the context of sustainable water resources development at a global scale. Hence, its mission directly relates to the commitments of the international community expressed in major documents such as the Millennium Development Goals, the Rio Declaration of Sustainable Development, the World Water Assessment Programme, World Water Development Reports, etc. By its activity, the International Sedimentation Initiative aims to uphold the importance of sustainable sediment management within the context of the two United Nations decades that will start in 2005: the "Water for Life Decade" and the "Decade for Education for Sustainable Development".

With direct access to stakeholders represented in the IHP National Committees and the Intergovernmental Council, ISI should be viewed as a vehicle to advance sediment management at a global scale.

The vision of ISI:
Sediment management is viewed as an important component of sustainable water resources management, and hence of the all-important enterprise of sustainable existence and development of the planet Earth. It seems therefore to be appropriate to include into this review a short message addressed to researchers and professionals dealing with erosion and sedimentation, stakeholders interested in sediment management, decision and policy makers upon whom the planning and execution of the management depends.

Researchers and professionals should appreciate that each and every case of sediment management is site-specific and requires originality in its approach and methodology. The complexity of issues must be looked at from different angles and addressed through concerted collaboration of natural and social sciences.

[1] Resolution XV-8 of the Intergovernmental Council, Paris, 17-22 June 2002

Stakeholders should resist being influenced by lobbies that often act on ill-founded impulses based on incomplete information, motivated sometimes by conflicting private interests. They should rather rely on unbiased advice from the scientific and professional community. Decision-makers should mistrust apparently attractive solutions that often result from the oversimplification of complex erosion and sedimentation processes.

Policy makers should respond to the views and wishes of actual stakeholders, but must not forget that the majority of water users have no voice and no vote, simply because they were not born yet. In view of the inherent imprecision of long-term planning, they should ensure that sediment management continues to be adaptive to the inevitable yet vaguely predictable natural and social changes in the future.

What are the objectives?
The overall objective of the International Sedimentation Initiative is to promote and interact with activities that will result in:

- Increased awareness of sedimentation and erosion issues;
- Improved and sustainable management of soil and sediment resources;
- Better advice for policy development and implementation.

The specific objectives are in short recapitulated below:
Global Evaluation of Sedment Transport (GEST-Project): The project will entail the development of a global repository for data, information and documentation on soil erosion and sediment transport, which can serve as a basis for global assessment of erosion and sedimentation problems and their social and economic implications. The data and information base will be developed in existing competent international institutions, such as the IRTCES in Beijing, China, GEMS-Water in Canada, ISIDE Observatory, in Italy, etc.

Initiation of case studies for river basins as demonstration projects: Case studies are seen as efficient means of raising awareness in different regions about erosion and sedimentation problems. They will offer examples of monitoring and data processing techniques, procedures and methodologies for analysis of environmental, economic and social impacts, and evaluation of management practices. It is decided to start with pilot river basins, such as the Nile, Zambezi, Rio Parana, Yellow River, Danube River and Rhine River. Other case studies will be included depending upon the circumstances.

Review of erosion and sedimentation related research: Information of ongoing research is an important contribution to the operation of the databases and information systems, bearing in mind the inadequacy of knowledge about various aspects of erosion and sediment phenomena for addressing key sedimentation problems. A substantial role could be assigned to associations such as ICCORES for reservoir sedimentation, as well as to the newly created World Association for Sedimentation and Erosion Research (WASER).

Education and capacity building for sustainable sediment management: Within the medium term, the accent should be placed on identifying the modes of education at all levels, taking also into account regional priorities and interests in different socio-economic and eco-hydrological settings. The formulation of this task should consider the findings of the GEST Project, and the updated survey of sedimentation related research. In line with its educational commitment, ISI will encourage the involvement of young scientists in its activity.

General strategy of the initiative:
In order to achieve such objectives, the International Hydrological Programme set up a Steering Group, which had several meetings and proposed an action plan that was approved by the Intergovernmental Council of IHP, at its 16th session, on 24 September 2004.
The International Sedimentation Initiative should achieve its goals by stimulating other actors in the field. ISI is open to collaboration with all interested institutions, international, regional, or national associations, in the interest of promoting sound and sustainable sediment management policies. ISI is eager to establish close working contacts with international, regional, and national projects, programmes and networks, such as SedNet, all over the world. In the above sense, the ISI is about to develop its strategy, focusing on those aspects of erosion and sedimentation problems where the UNESCO-executed action would be the most effective, filling in gaps that other organizations could execute less efficiently. Apparently, this would concern in the first place the organization and promotion of international information exchange on sediment related matters, ensuring a most direct access to the policy makers in the member states, as well as motivating and activating the scientific and professional communities in the interested regions and countries.

The “GEST” Project
Erosion, transport and sedimentation processes gain increasingly in importance in socio economical and -ecological respect. Problems in the field of sediment transport are subjects of concern for different institutions as well as for private enterprise worldwide. In particular, the question of the origin of sediment as well as sediment transport processes of big river systems down to deposition processes and delta formation into the sea, including sediment quality aspects as well as social, economical and ecological impacts are of major importance.

The individual processes are extremely complex. Therefore, each process is usually examined in an isolated manner. Depending on problem formulation, investigation projects and practical studies are carried out in well defined and specific areas or catchments. No actual coordination of activities or sufficient information about the relevant results exists on a global level. Knowledge of sediment transport is general and theoretical (as a result of e. g. laboratory investigations) or very specific (catchment-, time– scale or event-related). Hence, results from practical studies are not published as a rule, and therefore not generally available.

To gain more information and to improve general awareness about sediment transport on a global scale, the project GEST (Global Evaluation of Sediment Transport) as a program of the ISI has been introduced under the leadership of the UNESCO.

Objectives of the GEST project are:

- Introduction of a list of previous global findings on erosion and transport processes. Inclusion of the available data and of investigations;
- Development of methodical and organizational general conditions for the assessment of erosion and transport processes on a global level. Analysis of case studies in selected river basins as well as a global risk analysis in connection with sediment processes;
- Definition of the results to be expected within the framework of the IHP ISI as well as the denomination of the most important key players.

Study for the development of guidelines of case studies in river basins
The main objective of the study is the elaboration of guidelines for case studies in selected river basins. The respective work includes the following tasks:

- Compilation of essential sediment transport processes which occur from small mountainous catchments all the way down to the sea delta;
- Structuring of a case study for large river basins which aims at statements about erosion, transport and sedimentation processes

The tasks are executed by an international work group. Representatives from The Netherlands, Germany, Argentina and Switzerland elaborated the draft guidelines for the preparation of case studies (Rhine basin and Rio Bermejo as examples).

Note:
It is an important goal of the development of guidelines to support the comparability of the individual case studies.

The study was financed by the Swiss Hydrological Survey of the Federal Office for Water and Geology. As examples, the Rhine River and Bermejo River have been selected (see Fig. 1).

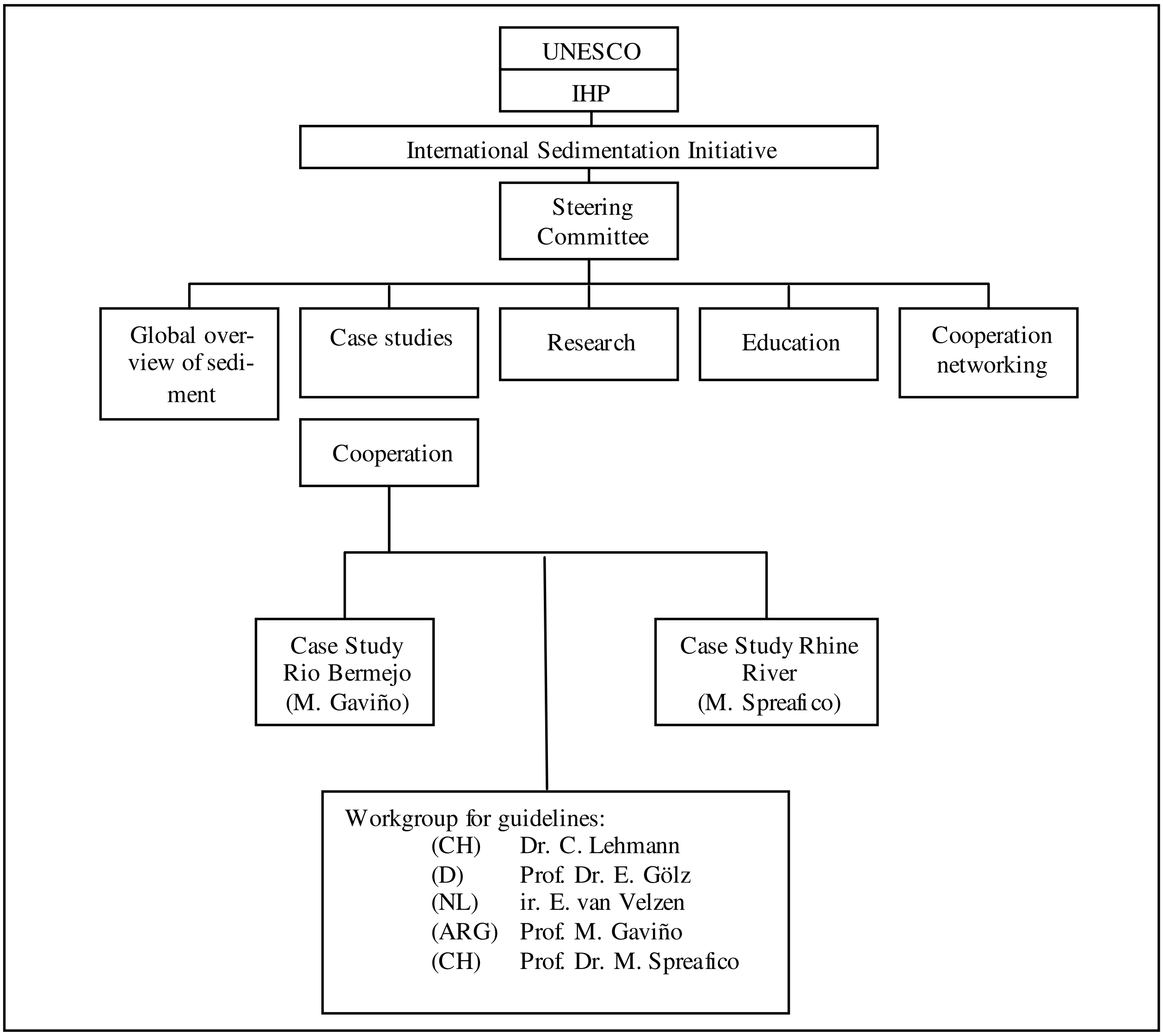


Fig. 1: Organization of the study

The contents of the guidelines include the following:
All sediment-related aspects, as comprehensive as possible, are illuminated: upper, alpine catchment areas, virtually identical with most of the Swiss part of the Rhine basin, catchment areas in the lower mountain range (as mainly found in Germany) as well as the flatlands (The Netherlands). Different elements should be considered, for example:

- Description of catchments, including most relevant sediment-related aspects: land use, soils, tectonic and geological aspects, topography, river channels, climatic issues…
- Mention of the most important stakeholders (see Fig. 2)
- Identification of sediment sources (point sources, diffuse sources) and their importance to sediment budget
- Where applicable for problems with contaminants: Identification of main sources of contaminants and their effects on waters and environment
- Elaboration of a list with description of most important sediment-related processes (e. g. landslides, debris flows, delta formation, suspended sediment transport…)
- Identification of main pathways to deliver sediments to running waters
- Presentation of the available documents / studies and findings in the catchment areas
- Gathering information about available data. However, only data and investigations existing at this stage should be considered, so for example from the following elements:
    - Sediment production and –mobilization
    - Erosion and transport process in running waters
    - Sediment budgets (per event, long-term)
    - Sedimentation processes (reservoirs, natural lakes...) and delta formation
    - Suspended sediment transport
    - Studies about further aspects of sediment management

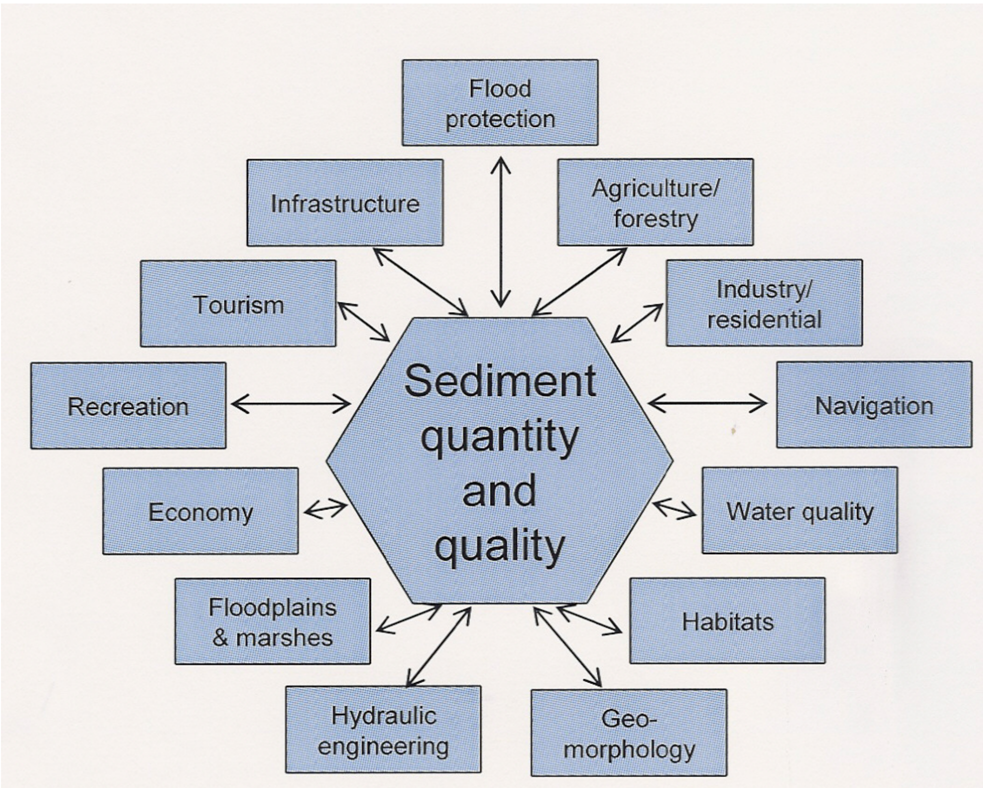


Fig. 2: General users and uses of sediment (after Owens et al. 2004)

Due to existing methodical problems, the global estimates mentioned above are at this time not yet possible in the originally planned sense. Apart from the methodical problems, the state of the art knowledge does not yet meet the requirements for such global assessments.

Therefore, it appeared reasonable for the time being to work out the problems and knowledge by means of case studies. Rhine, Danube, Zambesi River, Nile, Parana and Yangtze Rivers were selected as pilot catchments. The main reason for this selection was the fact that notable investigations have already been carried out in parts of these river systems or should be carried out in the foreseeable future. The river basins mentioned will therefore serve as a model for further activities. Intentions to compile detailed information about sediment transport exist for example in respect of the Danube river basin (SEDAN project). In the Rhine basin, sediment transport observation has a long time tradition, although the majority of sediment-related problems have not yet been sufficiently investigated and understood. An overall sediment transport assessment is not available for large river systems. But some comprehensive information exists on some midsize rivers or defined sections of larger rivers.

Close cooperation is planned and already implemented in first steps between the KHR/CHR[2] and the COBINABE[3]. Under the umbrella of the UNESCO, IHP and ISI, professional cooperation should among other things be supported and institutionalized. Furthermore, the elaboration of comparable case studies, which complement each other professionally and methodically, is planned.

The case studies should occupy a key position within the framework of the ISI. Moreover, case studies should serve as demonstration projects and models for the developing of a higher awareness amongst stakeholders of sediment-relevant problems. Furthermore, the case studies should support communication as well as cooperation between the groups which work in the river basins. Finally, the case studies will also be used as guidelines for dealing with sediment oriented problems.

2 Internationale Kommission für die Hydrologie des Rheingebietes (KHR). The International Commission for the Hydrology of the Rhine basin (CHR) is an organization in which the scientific institutes of the Rhine riparian states formulate joint hydrological measures for sustainable development of the Rhine basin.

3 Commision Binacional para el Desarollo de la Alta Cuenca del Rio Bermejo y el Rio Grande de Tarija (in Argentina and Bolivia)

1 Description of the Rhine River Basin

1.1 Overview

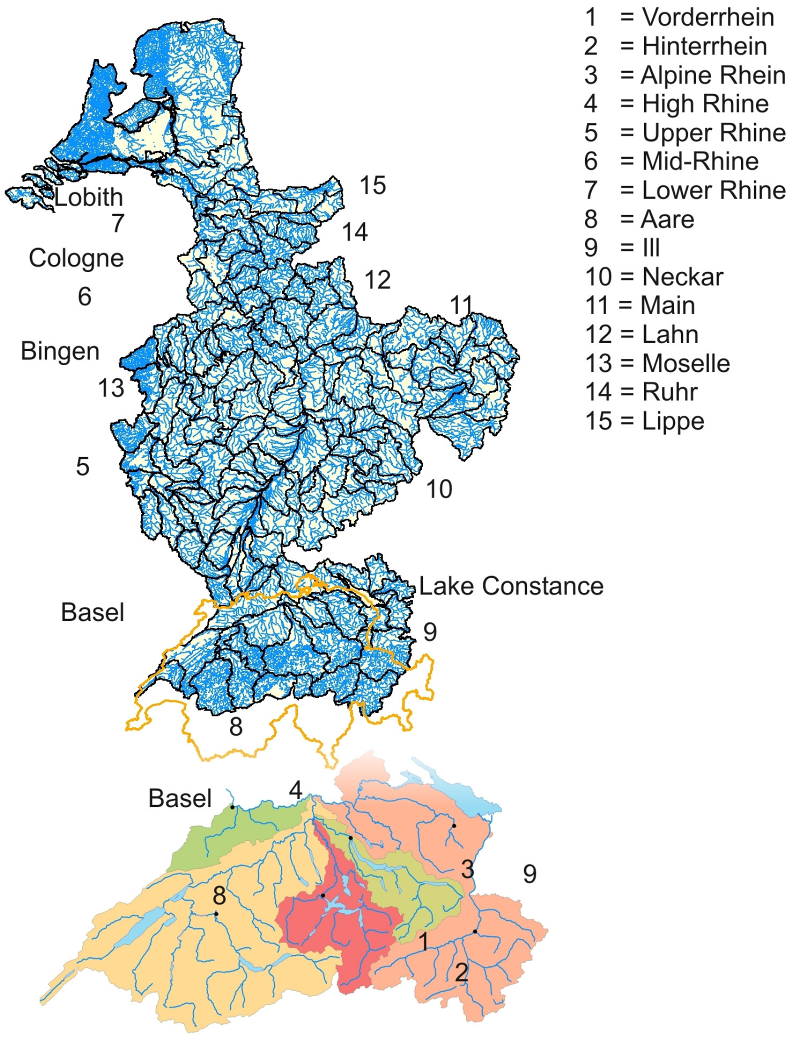


Fig. 3: The Rhine basin with sub basins (BAFU 2006)

With a catchment area of almost 190'000 km^2, the River Rhine ranks high among the European rivers that are most important and transport most water. As a shipping route it is one of the busiest in the world.

The course of the River Rhine, with a length of 1'320 km, can be divided into 6 major parts: The stretch from the main sources, Vorderrhein and Hinterrhein, to the point where the river discharges into Lake Constance is called Alpine Rhine. Between Lake Constance and Basel it is called High Rhine, downstream to Bingen its name is Upper Rhine and the next stretch to Cologne is named Mid-Rhine. From Cologne to Lobith it is called Lower Rhine and a few kilometres downstream the Rhine delta begins. The main tributaries of the Rhine are Aare, Ill, Neckar, Main, Lahn, Moselle, Ruhr and Lippe.

The Rhine catchment area is distributed between 9 countries. More than half of the catchment area belongs to Germany. Switzerland, France and The Netherlands have nearly the same shares in the catchment (Tab.1). The width of the catchment area is strongly varying, from about 300 km in the Alpine region, 70 km on the southern end of the Upper Rhine Graben, to more than 500 km from the Lorrainian upland to the Fichtelgebirge mountains (Fig. 3).

Tab. 1: Areas of the Rhine basin shared by different states (IHP/OHP 1996: 5)

Country	Area (km²)	Percentage (%)
Germany	105'478	55.60
Switzerland	27'963	14.74
The Netherlands	24'500	12.91
France	23'556	12.42
Belgium	3'039	1.60
Luxembourg	2'513	1.32
Austria	2'501	1.32
Liechtenstein	106	0.06
Italy	51	0.03

1.2 Longitudinal and cross-sectional profiles

The River Rhine shows a variety of longitudinal and cross–sectional profiles which are strongly marked by the character of the landscape as the result of human influence.
The geological and morphological conditions cause specific conditions for the gradient of the river bed. Where the High Rhine leaves Lake Constance the slope is 0.8 ‰, which is reduced at the end of the Upper Rhine at Bingen before the entry into the Rhenish slate mountains to 0.1 ‰. On the reach through the mountains the slope again increases to 0.4 ‰ and then approaches zero continuously towards the inflow into the North (see Fig. 4).

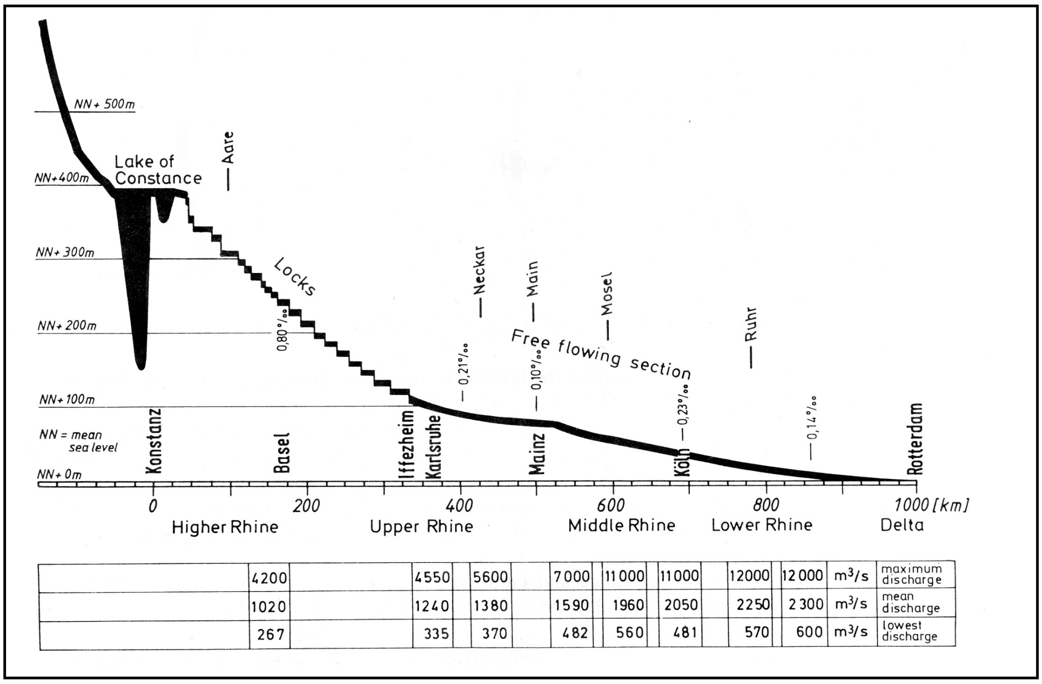


Fig. 4: Longitudinal profile of the Rhine and location of floodplains (after CHR 1987)

a.

b.

c.

d.

e.

f.

Fig. 5: Views of the Rhine in Switzerland (all pictures courtesy of Federal Office for the Environment): a. Vorderrhein – Ilanz; b. Hinterrhein – Fürstenau, c. Alpine Rhine – Domat Ems, d. High Rhine – Neuhausen, e. High Rhine – Rheinfelden; f. High Rhine – Basel.

Fig. 6: The Rhine in Germany and in The Netherlands: a. Upper Rhine at Breisach (KHR 1993: 82), b. Middle Rhine at St. Goar between Bingen and Coblence (KHR 1993: 116), c. Middle Rhine: "The Deutsches Eck" at Coblence, Rhine and Moselle (www.meinestadt.de), d. Lower Rhine at Duisburg (KHR 1993: 168), e. Rhine branch near Arnhem (Ten Brinke 2004: 126), f. Rhine west of Nijmegen (Ten Brinke 2004: 58)

1.3 Human impact

1.3.1 Hydraulic Works

Regulation works were necessary, in order to protect the population from the harmful effects of floods and to come to a water management that enables optimum use of the water. Some of the most important measures have been: bed fixation, river-bend cut-offs to increase the discharge capacity, dyke building against flooding, expansion and stabilizing works in shipping channels (groynes, bank and bed fixations, short-cuts, widening and dredging of the channel) and complex construction works such as weirs, large canals, diversions of water courses and impounding reservoirs.

Vorarlberg, Austria (Alpine Rhine)
The state contract of 1892 with Switzerland concerning the regulation of the Rhine from Lake Constance up to the mouth of the Ill impelled the beginning of protection measures in Vorarlberg. Article 19 of the contract which was renewed in 1924 and 1954 stipulates that all member states of the Rhine catchment area had to carry through defence works in torrents. The implemented structural and forest measures are checked every five years by the international Rhine commission. All pending problems are discussed at these meetings.

The Vorarlberg Rhine torrents include all torrents in the catchment area of the III, which flows in Feldkirch into the Rhine. Defence works of the Rhine torrents were made up to the second world war within the framework of the so called Rhine correction. The first Rhine correction lasted from 1896 to 1908, the second from1909 to 1924 and the third from 1925 to 1937, each of them was done by special funds. After the Second World War a dynamic development took place in Vorarlberg. In the wake of the economical development, since the end of the fifties, the population grew from 150’000 to 330’000 people. That is a unique value for a mountainous country with only 15% of flat lands. Among other things, the construction activities of these decades led to a gigantic demand for gravel. Gravel was removed almost entirely from the torrents in an order of magnitude of several millions of cubic meters. As during the same period no large floods occurred, natural sediment discharge was strongly reduced as well. As a result, large bed erosion took place in the III, in Bludenz for example up to 4 m. In total, these activities led to large bed erosion in the regulation stretches of the Rhine. As a countermove, the dredgings were mostly stopped. The defence work activities also reacted rapidly and have promoted the construction of open check dams. Large hole check dams were built, also slit dams and beam dams. In applying such constructions, mid size floods pass the construction and sediments up to a certain grain size are retained. In the case of a catastrophic event, the orifices are blocked and the check dams will function as conventional retention dams.

The doubling of the population in the last 30 to 40 years led to a big settlement pressure in the valleys and therefore to uncontrolled advance of construction activities into the danger zones of torrents and avalanches. As a result, new needs for defence works surpassed the capacities to finance them. In 1975, as a counter measure in the forest law and within the framework of regional planning, the elaboration of danger zone plans was implemented. Through danger zone mapping, construction activities could be regulated. From a contemporary point of view, the combination of forest and technical measures in the catchment area has proved to produce good results. The law from 1884 that was still effective had been far ahead of its time and has initiated forest environmental control to last for more than 100 years. The generous and extensive defence works in the torrents in the Austrian, the Liechtenstein and the Swiss Rhine catchment areas achieved an important contribution to the success of the Rhine regulation. During the last decades, thanks to the protective effects of the defence works, numerous local floods and debris flows passed the structures without causing any damage. The population in the endangered valleys appreciates this success. They are hardly recorded for the general public; only disasters are media effective.

Canton of Grisons, Switzerland (Alpine Rhine)
During the flood disasters of 1834 and 1868, the local municipalities were helpless and could only watch how local protection works in rivers and torrents were destroyed by the power of water. Immense physical casualties and damage to property of the inhabitants were the result. In 1870, the "Wuhrgesetz" (defence work act) was accepted by Grisons population. Therefore the legal basis for a systematical procedure and financial support for protective measures was introduced. In 1877, the federal law of "Wasserbaupolizei" (water surveillance law) came into effect, enabling the financial support of flood defence works by the federal authorities. Thanks to technical and financial support by the Federation and the canton efficient protective measures could be carried out with respect to the most dangerous torrents at the end of the 19th century. In spite of numerous protection works implemented with considerable financial expenditures, floods and debris flows may still cause great damages in residential areas and to traffic lines. Natural conditions in Grisons do not allow absolute protection. The increasing requirements for settlement and traffic routes make sure that defence works continue to be confronted with problems.

For all rivers and torrents in the Rhine basin area of the canton, which suffered damage by extreme events, protection measures were carried out. Since the middle of the 19th century, a total of 825 defence work projects have been implemented. Among them, there are 593 torrent projects only. The expenditures invested amounted to 214 million Swiss Francs in total during the last more than 100 years. The Federal contributions mounted up to 105 million Swiss Francs (approx. 49%), the canton paid approx. 64 million Francs (approx. 30%). For the municipalities which are mostly financially weak mountain municipalities there resulted another 45 million Francs as remaining costs.

The constructions carried out in the last 100 years show continuous change in the defence technique. Instead of gravity dams made of dry and mortar masonry, slab dams of reinforced concrete are in use today. Open check dams allow sediment discharge regulation in the retention basins. Strong construction machines decrease the laborious manual work even in remote canyons. In former times, defence works were carried out in very urgent cases only. Today, environmental viewpoints play a larger role in conformity with the new water law of 1974.

Canton of St. Gall, Switzerland (Alpine Rhine)
With the law of the 12 August 1869 on the protection against torrents and also the postscript law dated April 3rd, 1877 as well as the corresponding execution arrangement dated November 16th 1877, the corner stone for comprehensive correctionand defence works in the waters of St. Gall was created.

The federal law on water survey which was adopted by the Swiss councils on July 22, 1877 was also of great importance. Apart from this, the state contract between Austria and Switzerland of 30th December 1892 contributed to correctionand defence works in the torrents. Art.19 of this contract obliged the two countries to carry out protection works in the torrents of the Rhine catchment.

Almost 100 years later, on the 23rd March of 1969, the "Grosse Rat" of the canton St. Gall adopted the new law on hydraulic works. Today there are already talks about a further revision of this law. The main purpose of torrent control consists of the prevention of erosion damage in the upper course of torrents and aims therefore at avoiding deposits in the lower course. The overall goal is controlled sediment discharge. Retention basins are an effective measure to protect the valley from uncontrolled accumulation. Almost all torrents in the St. Gall Rhine valley have such a retention basin.

From Bad Ragaz to Thal, there are a great number of torrents. Only two of them, the Tamina in Bad Ragaz and the Trübbach in the municipality Wartau, flow directly into the Rhine. All other torrents drain into the Werdenberger channel, into the Saar channel, or into the Rhine channel.

<u>Principality of Liechtenstein (Alpine Rhine)</u>
From the time before 1835, no documents about defence works are available. It is however probable that already before this time small longitudinal constructions of stones for the diversion of debris flows had been made. The recordings of 1835 consist in the first place of descriptions about origin and effect of debris flows, but without being concerned with direct measures. It is pointed out that good success had been achieved in the neighbouring Tirol with different kinds of measures. The Liechtensteinians however were discouraged to take additional measures against natural powers.

By means of another record of 1860 it can be proven that defence works already began in 1855. In 1855, people had to cope with devastating debris flows. Obviously the first attempts to protect torrent beds from erosion were hesitant and executed with wooden transversal structures that were too weak. Failures occurring again and again led to discouragement.
With the increasing application of heavy building materials, such as large boulders, success in defence works increased. The tasks were correctly recognized. It was a question of stabilization of torrent beds and fixing of landslides and of banks in canyons in order to reduce weathered material as much as possible. As however one still was far from solutions like check dam constructions because of lacking financial means, damage by flowing about the check dams and scouring below check dams often occurred. As a result, the structures were destroyed or became inoperable.

The importance of the forest as optimal protection against erosion was soon also recognized and underlined with a clear cutting prohibition and the creation of avalanche forests.
In 1871 a first legal prescription for debris flow defence works was elaborated, which assigned the defence duty to the municipalities. For special cases, financial contributions were made by the state. In the law of 1899, a Landesrüfenkommission (national debris flow commission) was created as an advisory board of the government, of which the respective head of the government still is the chairman up to now.

Through this, the great importance of the debris flow problem at that time was clearly recognized. In addition, a 50% support to all defence works was ensured. In the following years, countless frictions between the municipalities about thekind and manner of constructions and cost distributions were obstacles for important hydraulic projects. For this reason, in 1937 an own technical authority of the country for debris flows was created and the country contribution was raised to 70%. This would pave the way for an impressive reduction of debris flow damage.

The most important debris flow torrents drain their water to the Rhineside. The catchments are very steep and near the "Three sister" mountain range virtually without vegetation. Furthermore, the catchments mainly consist of weathering prone material. Between 1894 and 1990 almost 56 million Swiss francs were spent for torrent control in Liechtenstein. The State of Liechtenstein has supported the works since 1938 with a 70% contribution.

<u>Correction of Rhine river stretches downstream of Basel</u>
In earlier times, the Upper Rhine did not have a bed as we know it today. The Rhine Plain was swampy, and malaria plagued the population. The river meandered over the whole width of the valley and changed its channels and created or swallowed islands after each flood event (Fig. 7).

Fig. 7: Upper Rhine around 1810 at the 'Isteiner Klotz' north of Basel (KHR 1993: 40)

About 1815, the training of the river began (see Fig. 8). The regulation of the Rhine was planned with a view to the following aims:

- reducing the danger of floods;
- improving agricultural land use by lowering the groundwater table;
- reclaiming additional areas for settlements and agriculture;
- reducing the health hazards (malaria etc.);
- clarifying the position of the border between Germany and France along the River Rhine;
- improving navigation.
- Fig. 8 serves an example for Rhine river correction works.

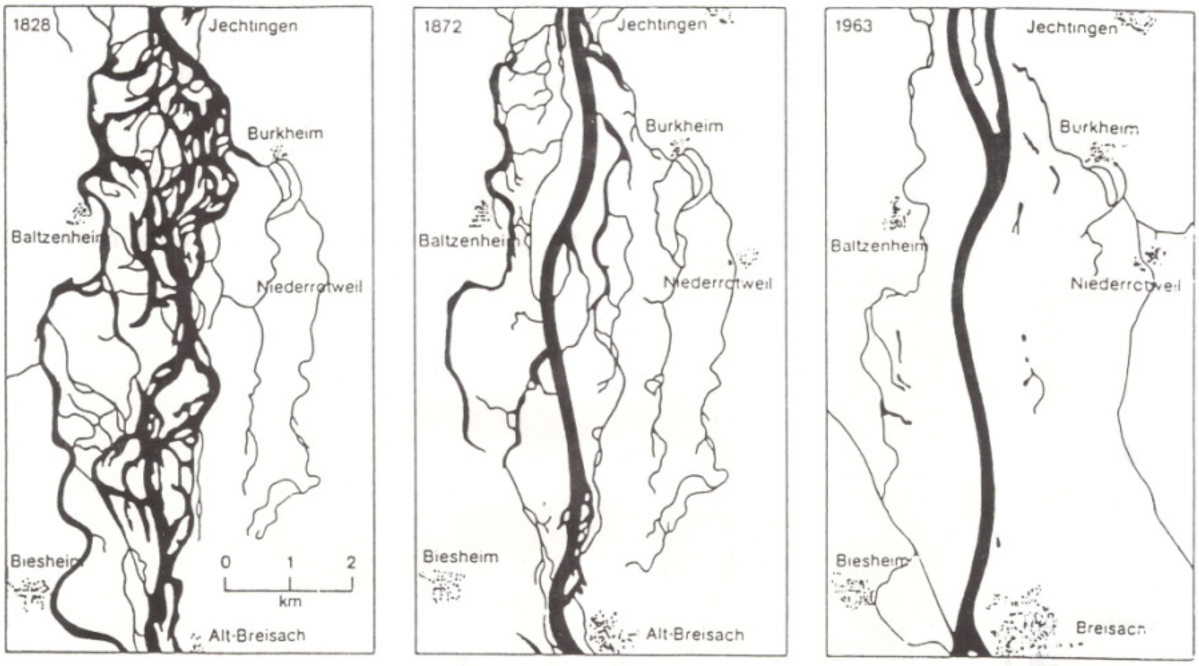


Fig. 8: Upper Rhine River at three stages: 1828 before regulation, 1872 after regulation and 1963 after regulation and canalization (IHP/OHP 1996: 68)

The river training concept was based on the laws governing river discharge, which say that the hydrostatic behaviour of a river is a function of discharge, of the cross section, of the longitudinal gradient, and of the depth of the water. Accordingly, the Rhine was forced into a self-deepening bed by building structures across and along the river. River bends and meanders were cut off. On the whole, the river bed gradient increased, and the river eroded its new bed. In the course of time the river bed cut down seven meters due to the increase in gradient and shortening of its course. The groundwater table dropped in the same order of magnitude.

In a treaty concluded between France and Germany, France was given the right to harness hydropower on the Upper Rhine. France then built a lateral canal which was lined with concrete slabs, so that interactions with groundwater were interrupted. The consequence was a further drop of the groundwater table. At some places, the habitats in the meadows dried up. Further river training projects were developed to mitigate and reverse the damages to landscape and river on the Upper Rhine. The adopted concept was the so called loop solution, which provided for returning the water through cut-offs into the bed of the River Rhine downstream of each impoundment weir with power station, thus restoring the interactions between river and groundwater (Fig 9). However, downstream of the last impoundment, erosion set in again, so that the danger of further lowering of river bed and water table continued. A treaty adopted in 1969 provided for the construction of new impoundments. However, the ecological awareness among the public had increased so much that the implementation of this technical solution encountered severe resistance, although its main purpose was to avert further damages. After long-lasting investigations it was agreed to use artificial bed-load supply instead of building new weirs. This means that gravel of appropriate grain size is dumped into the river in order to prevent further erosion or to reverse the existing one.

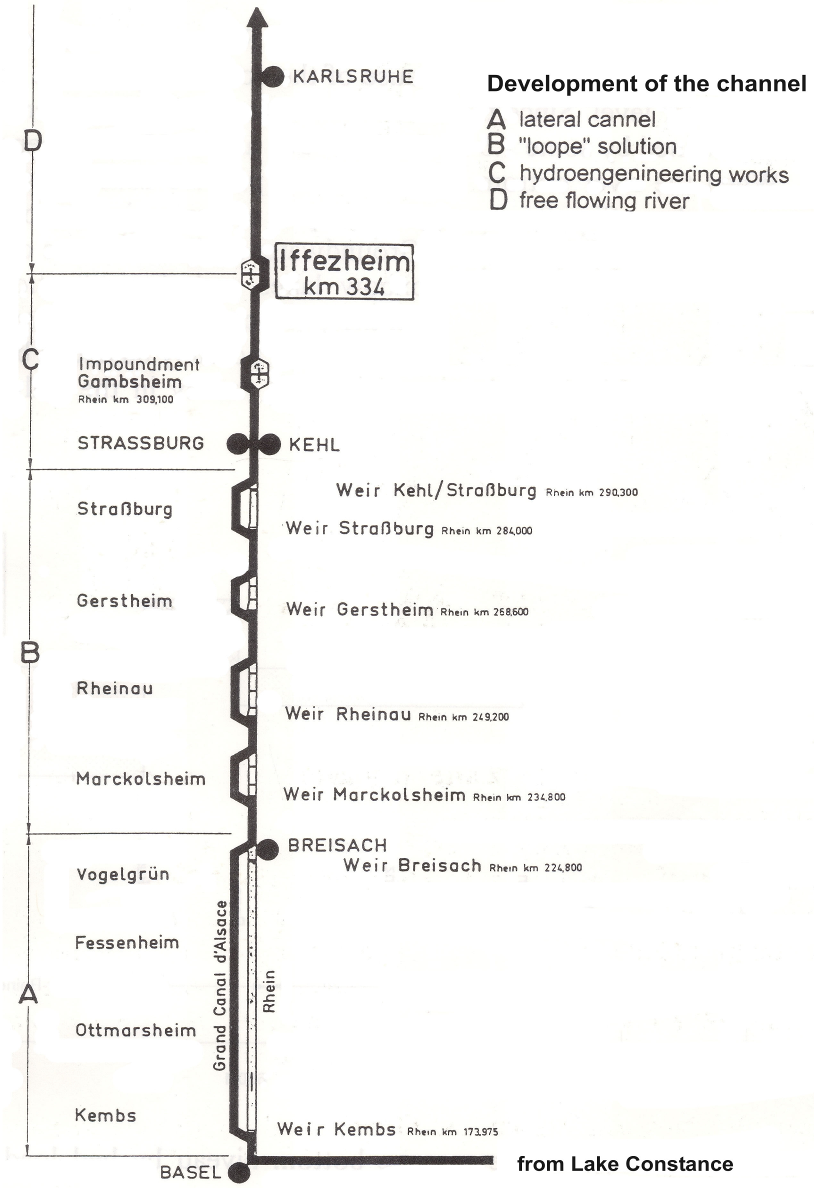


Fig. 9: River development scheme for the Upper Rhine (IHP / OHP 1996: 69)

In the regions of the Middle Rhine and the Lower Rhine the river bed had also repeatedly changed its position in earlier times. The river was braided with many islands and oxbow lakes, and it spread at mean flow over a width of 450 m. In the 18th century the first training works for flood protection were begun. The division of the river into several channels was removed and narrow bends were cut off. From 1880 to 1900, the mean-flow bed was trained according to plan, and the navigation channel was deepened between Bingen and Emmerich. This created the basis for the outstanding importance of the River Rhine as receiving watercourse and navigation channel in Europe.

Since 1900, the river training has been continuously improved. This included the construction of groynes, training walls, dredging in the fairway, and backfilling of scours. The maintenance of the navigation channel in the Lower Rhine, as it resulted from the training works, is becoming increasingly difficult because of the continuing erosion of the riverbed and the lowering of the water level. Since the turn of the century, the equivalent water level at the gauge Ruhrort has declined by some 1.5 m. In the 1950s and 1960s the deepening rate reached 4 cm per year. Simultaneously the depth of water in harbours and waterways without flow-through decreases. Groundwater in riparian areas drops, so that water supplies are impaired and drying up of oxbow lakes and desertification of meadows is threatening. Some minor regulation projects in the 1970 could improve navigation locally, but the aim to establish and maintain a lasting river bed with possibly balanced bed load regime was not reached. The mean annual change of the average bed level is shown in Fig. 10.

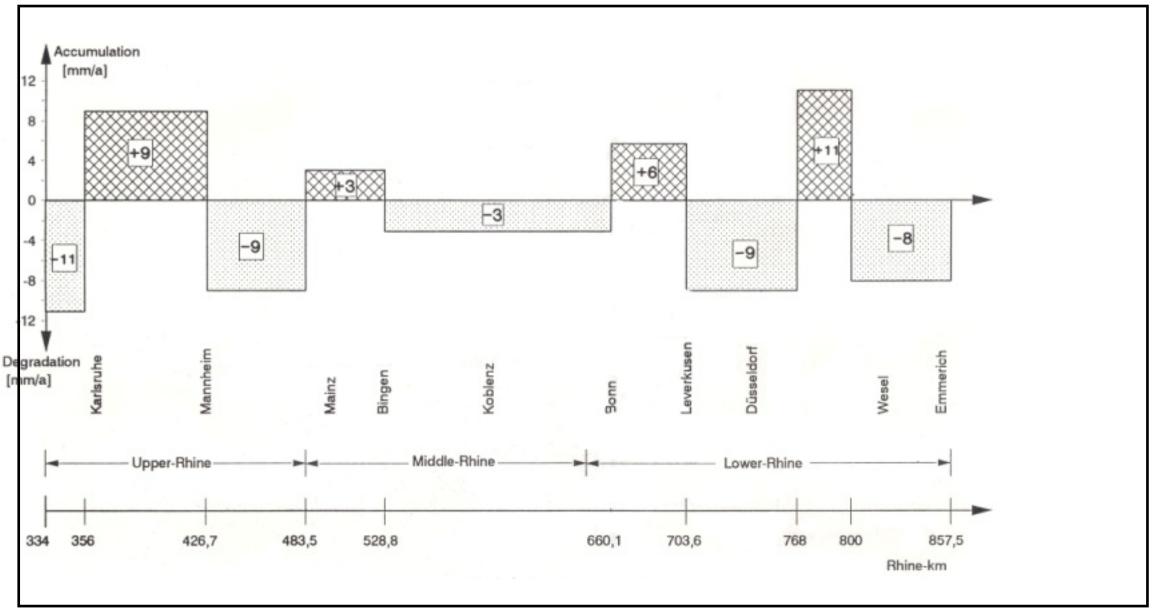


Fig. 10: Mean annual change of the average bottom level by bed load balance between 1981 and 1990 (IHP 7 OHP 1996: 70)

Fig. 11 shows The Netherlands at the beginning of the 20th century. In the central embayment, called Zuyderzee, storm surges caused many inundations. The flood disaster of 1916 was the last impulse to carry out the long-cherished plan to close and partly reclaim the Zuyderzee. There were four main reasons to realize this plan: flood protection, fight against salination, water supply in dry periods and reclamation to increase food production.

The closure dam with sluices was completed in 1932 creating the Lake IJssel. The IJssel, the north flowing branch of the Rhine supplies the lake. The lake was transformed into a fresh water reservoir by the IJssel input. It supplies the northern parts of The Netherlands with fresh water during dry periods and discharges the surplus through sluices into the sea in wet periods. By constructing four polders, parts of Lake IJssel were reclaimed and turned into rich farmland. In the last reclaimed polder (Southern Flevoland) new towns are built for the expanding population on the old land, particularly Amsterdam. The water level in the remaining lake may vary with 20 cm creating a fresh water reservoir of 500 million m^3. Besides the supply to the northern and north-western part of The Netherlands the lake also receives excess water from these areas in wet periods.

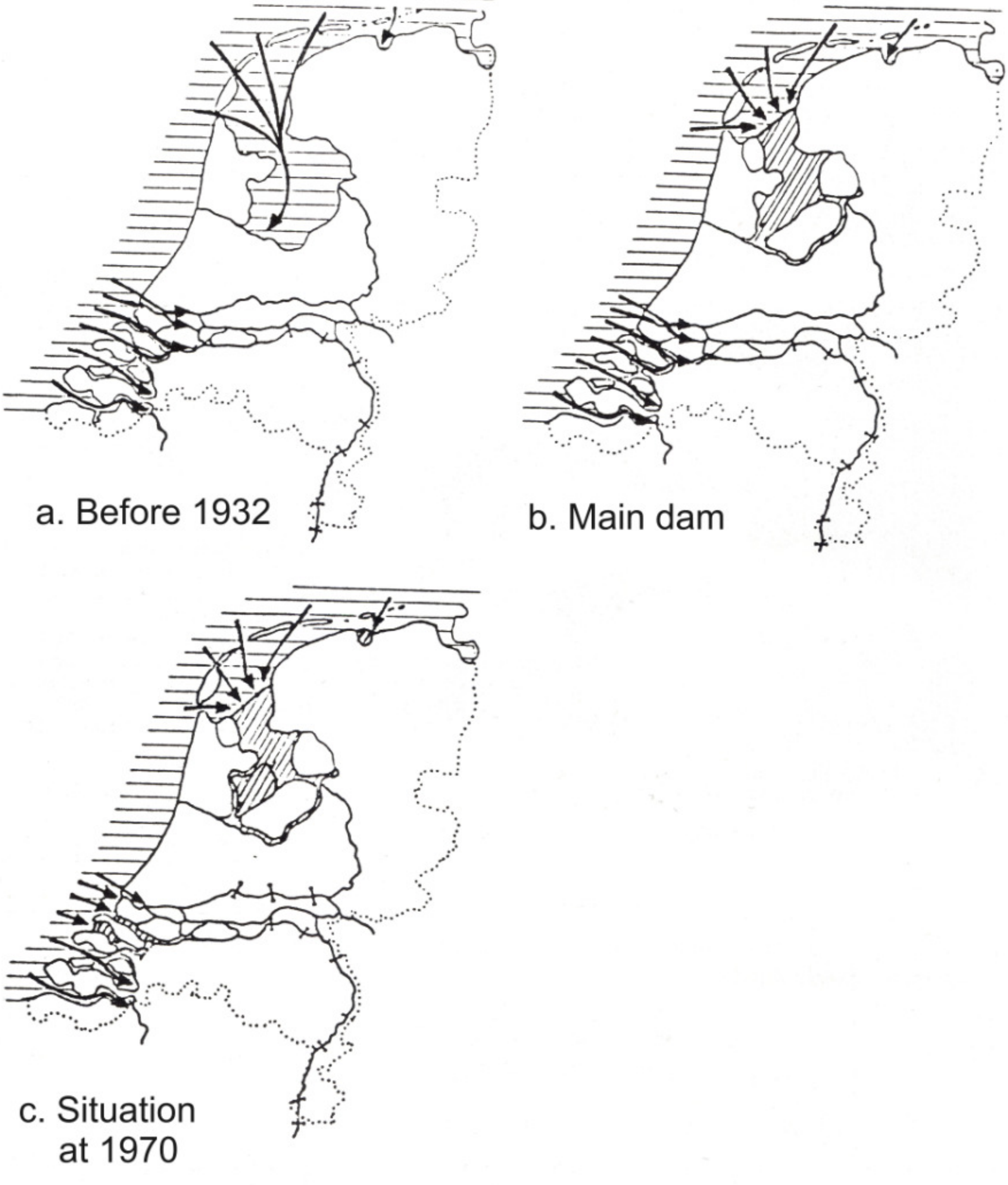


Fig. 11: Protection against storm surges and salinization in the 20th century in the Netherlands (IHP / OHP 1996: 86)

The south-western estuarine area of the country has islands, surrounded by deep tempestuous estuaries, into which the Scheldt, the Meuse and 90% of the Rhine discharge. The storm surge of February 1953 breached the dikes at 900 places, large areas became inundated, many people and livestock drowned. It gave the final impulse to the delta project with the aim of damming the estuaries in the south-west. Originally the Rotterdam Waterway and the Western

Scheldt were excluded from the scheme because of their importance as entrances to the harbours of Rotterdam and Antwerp. Safety along these water courses is achieved by substantial reinforcement of the dikes.

The delta plan has been modified at two major points. According to the original plan the Eastern Scheldt was to be closed by one of the largest dams ever built in The Netherlands. In 1975 environmental considerations led to the decision to build a storm surge barrier dam, that leaves the tidal movement largely unmodified, but can be closed during storm surges. Due to the rapid development of the harbour of Rotterdam it proved to be necessary in 1987 to build a storm surge barrier in the Rotterdam Waterway. In contrast to the measures in the fifties, the deepest harbours of Rotterdam got a separate obstacle free entrance to the sea in 1975.

The main features of the delta project are as follows. There are five primary elements: the Rotterdam Waterway barrier (1998), the Hartel barrier (1997), the Haringvliet dam (1970), the Brouwersdam (1972) and the Eastern Scheldt barrier (1986). The last project was the most expensive enterprise. Its costs amounted to almost 8000 million guilders (some 4500 million US dollars).

Fig. 12: The weir at Driel in the Lower Rhine. The weir directs water to the north or allows it to pass on to the west of the country (IHP / OHP 1996: 94)

Fig. 13: The 32 km long main dam separates the Wadden Sea from the fresh water of Lake IJssel (IHP / OHP 1996: 94)

1.3.2 Reservoirs and hydropower

Hydropower generation in the High Rhine amounts to approximately 9'200 GWh per year (Tab. 2). In the Rhine basin of Switzerland the annual production is about 4'500 GWh (Tab. 2). In the past a high number of hydropower plants have been installed, most of them with large retention basins. Tab. 2 shows an overview of retention basins in the Rhine River basin in Switzerland. The total retention volumes in the tributaries of the Rhine River can be seen in Tab. 3 and Fig. 14.

Tab. 2: Swiss retention basins in the High Rhine (www.lpb.bwue.de/aktuell/bis/2_00/rhein.pdf)

	Power plant	Years of construction	Chronological order of initial operation	Power (MW)*	Mean annual production (GWh)
1	Schaffhausen	1960-1963	10	29	168
2	Rheinau	1951-1956	9	37	237
3	Eglisau	1914-1919	4	34	240
4	Reckingen	1939-1941	7	39	234
5	Albbruck-Dogern	1929-1934	6	85	569
6	Laufenburg	1908-1914	3	110	630
7	Säckingen	1961-1966	11	74	392
8	Ryburg-Schwörstadt	1928-1931	5	120	760
9	Rheinfelden	1894-1898	1	26	185
10	Augst-Whylen	1907-1912	2	73	405
11	Birsfelden	1950-1954	8	100	555
				Total 727	4'475

*) 1 MW = 1'000 kW, 1GWh = 1'000'000 kWh

Tab. 3: Reservoirs in the tributaries of the Rhine River in Switzerland (www.lpb.bwue.de/aktuell/bis/2_00/rhein.pdf)

Hydropower generation	Power plant	Power	Production in GWh			Reservoirs	vol. of reservoir	Height of dam
		MW	(Year)	(Su)	(Wi)		Mio m^3	m
Vorderrhein			761	301	460	Curnera Nalps Sta. Maria Runcahez	40.8 44.5 67 0.44	153 127 117 33
	Sedrun	151						
	Tavanasa	180						
Russein	Russein	12	42	32	10	Barcuns	0.12	29
Brigels	Brigels	12	53	42	11	Brigels	0.25	18
Ilanz			260			Panix	7.3	52
	Ilanz I	34.5						
	Ilanz II	49.5						
Zervreila			570.0	264.5	315.5	Zervreila	100	151
	Zervreila	22.4	23.7	4.7	19.0			
	Safien	90	163.6	62.6	101.0			
	Rothenbrunnen	129	340.7	165.2	175.5			
	Realta	25	42	32	10			
Hinterrhein			1060	460	600	Valle di Lei Sufers Bärenburg	197 18.3 1.0	143 58 64
Hinterrhein	Innerferrera	148						
	Bärenburg	176						
	Sils	192						
Albula-Landw.	Filisur	60	266.2	198.3	67.9			
Mittelbünden			773.9	482.8	291.1	Marmorera (Castiletto) Sils	61 1.46	90 61
	Tinzen	69.5	199.6	113.4	86.2			
	Tiefencastel O	56	145.3	75.1	70.2			
	Tiefencastel W	25	87.9	68.4	19.5			
	Solis	7	30.2	21.7	8.5			
	Sils	26	92.6	69.2	23.4			
	Rothenbrunnen	44	218.3	135.0	83.3			
Rätia Klosters			230.0	144.2	85.8	Davosersee		natural
	Klosters	16.5	27.8	14.0	13.8			
	Schlappin	6.5	31.5	22.0	9.5			
	Küblis	43.9	170.7	108.2	62.5			
Reichenau	Reichenau	18	48.4	31.6	15.8			
Sarganserland			343	230	113	Gigerwald Mapragg	33.2 2.7	147 75
	Mapragg	280	141	86	45			
	Sarelli	90	157	104	53			
Kubel	Kubel	13.4				Gübsensee	0.17	24
Schaffhausen	Schaffhausen	22.9	152.9					
Rheinau	Rheinau	21.2	126.8					
Eglisau	Eglisau	30.2	240.2	130.7	109.5			

Hydropower generation	Power plant	Power	Production in GWh			Reservoirs	vol. of reservoir	Height of dam
		MW	(Year)	(Su)	(Wi)		Mio m³	m
Reckingen	Reckingen	19	111					
Albbruck-D.	Albbruck-D.	45.4	307.3	164.2	143.1			
Laufenburg	Laufenburg	55	315	181.5	133.5			
Säckingen	Säckingen	36.8	137					
Ryburg-Schw.	Ryburg-Schw.	60	252.5					
Augst	Augst	10.5	88					
Rheinfelden	Rheinfelden	43	200					
Birsfelden	Birsfelden	61.5	341.3	194.3	147.0			
Kembs	Kembs	31.3	187.6	106.6	90.0			
Total			9174.6					

Tab. 4: Water retention capacities of reservoirs in the Rhine basin (KHR 1996a: 56)

Tributary	Volume [hm³]	Sum of volumes [hm³]
Vorderrhein	253.14	253.14
Hinterrhein	289.36	542.50
Tamina	38.50	581.00
Ill (A)	183.40	764.40
Bregenzerach	8.40	772.80
Lake Costance	1.40	774.20
Thur	0.60	774.80
High Rhine (CH)	7.26	782.06
Aare	496.95	1279.01
Reuss	153.19	1432.20
Limmat	314.86	1747.06
High Rhine (D)	112.85	1859.91
Upper Rhine	27.63	1887.54
Ill (F)	24.29	1911.83
Neckar	37.99	1949.82
Main	59.64	2009.46
Nahe	14.05	2023.51
Lahn	6.63	2030.14
Moselle	103.58	2133.72
Mosel	50.53	2184.25
Sauer	71.40	2255.65
Wied	4.45	2260.10
Ahr	0.73	2260.83
Sieg	123.10	2383.93
Wupper	140.43	2524.36
Erft	51.00	2575.36
Ruhr	496.06	3071.42
Lippe	50.01	3121.43

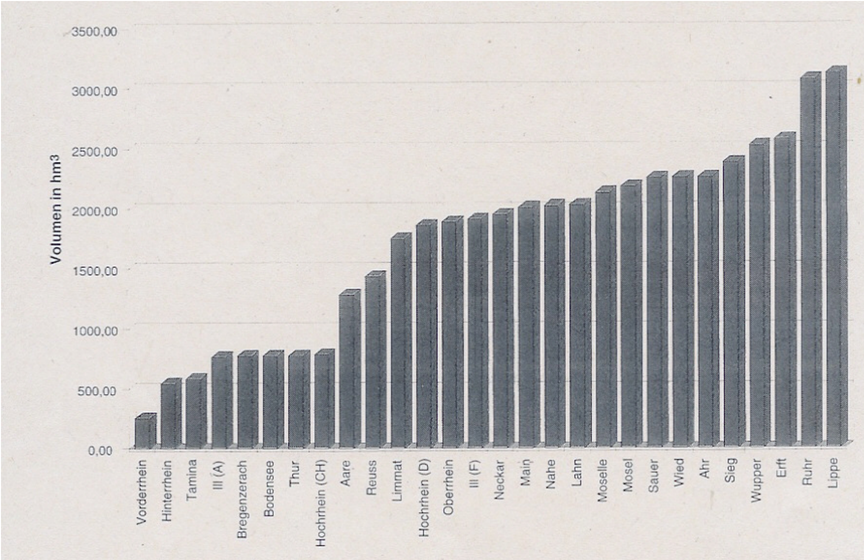


Fig. 14: Cumulative retention volumes in the tributaries of the Rhine River (KHR 1996a: 56)

The High Rhine with its slope of 150 m between Schaffhausen and Basel and its relatively narrow valley offers favourable conditions for hydropower generation. Moreover, stream flow is relatively even because of the upstream lakes and reservoirs. Hydropower has been used on the River Rhine for more than 120 years. Altogether, there are twelve hydropower stations with capacities between 30 and 120 MW, while most stations have an installed capacity between 30 and 50 MW. The mean potential productive capacity of the twelve stations on the High Rhine is around 4'200 MWh.

By 1978, ten hydropower stations had been built on the Upper Rhine, some of them on lateral canals. They have installed capacities between 100 and 200 MW, with about 170 MW being the preferred size. The maximum output of these ten stations amounts to 1.5 million kW, and the mean annual power generation is around 8,500 million kWh.

The power station Iffezheim for example was built in the same axis like the weir, the barrage, and the lock passage (Fig. 15). It has four sets of tubular turbines in horizontal position which have a rotation speed of 100 revolutions per minute and a total throughput of 1100 m^3/s. The fall of water head is 11 m, and the maximum capacity reaches 112 MW. In the case of an emergency stoppage the turbines can be switched into an unloaded mode which ensures the passage of 60 % of their normal throughput. The remaining water is diverted over the weir by the automatic control system.

In former times, the impoundments on the High Rhine and the Upper Rhine were built exclusively for the purpose of hydropower generation. When mineral oil became a major source of energy and when nuclear power was utilized, the construction of hydropower stations on the Rhine and its tributaries only for energy production was stopped. However, whenever impoundments were built for other purposes like landscape protection or improvement of navigation, they were always combined with power generation.

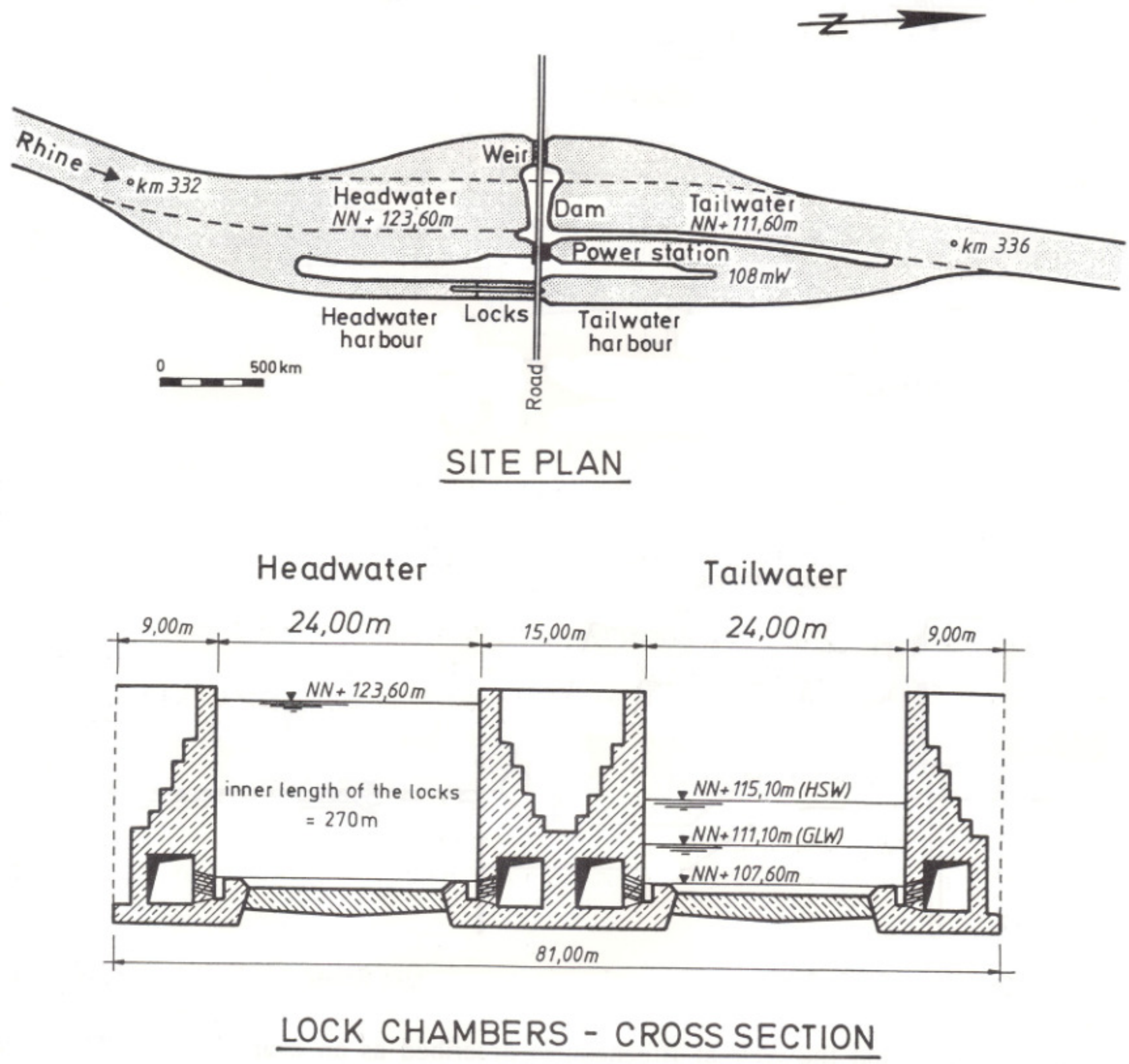


Fig. 15: Impoundment weir Iffezheim (IHP / OHP 1996: 75)

1.3.3 Water supply

The Rhine has also great importance for water supply: However, the Rhine River catchment area is a conglomeration of high population density, accumulated high-tech industry and at the same time an area which is most intensively used for agricultural purposes. 104 chemical plants like BASF, Bayer, Ciba Geigy and Hoechst, and some 50 million people use the Rhine as the final recipient for their treated sewage. Fig. 16 indicates regions of concentration of waterworks and chemical industry.

But where do cities like Zürich, Basel, Strasbourg, Stuttgart, Frankfurt, Mainz, Cologne, Düsseldorf and Amsterdam get their drinking water from? Water withdrawal from ground water resources is restricted to the annual average natural recharge. This recharge does not meet the demand in areas that have high population density. The available ground water resource has to be increased for example by bank filtration. Therefore some 20 million people depend on the water of the Rhine, its tributaries and the lakes within the Rhine basin as sources for their drinking water supply. Several measures have to be taken by the waterworks in order to ensure a safe supply (Fig. 16).

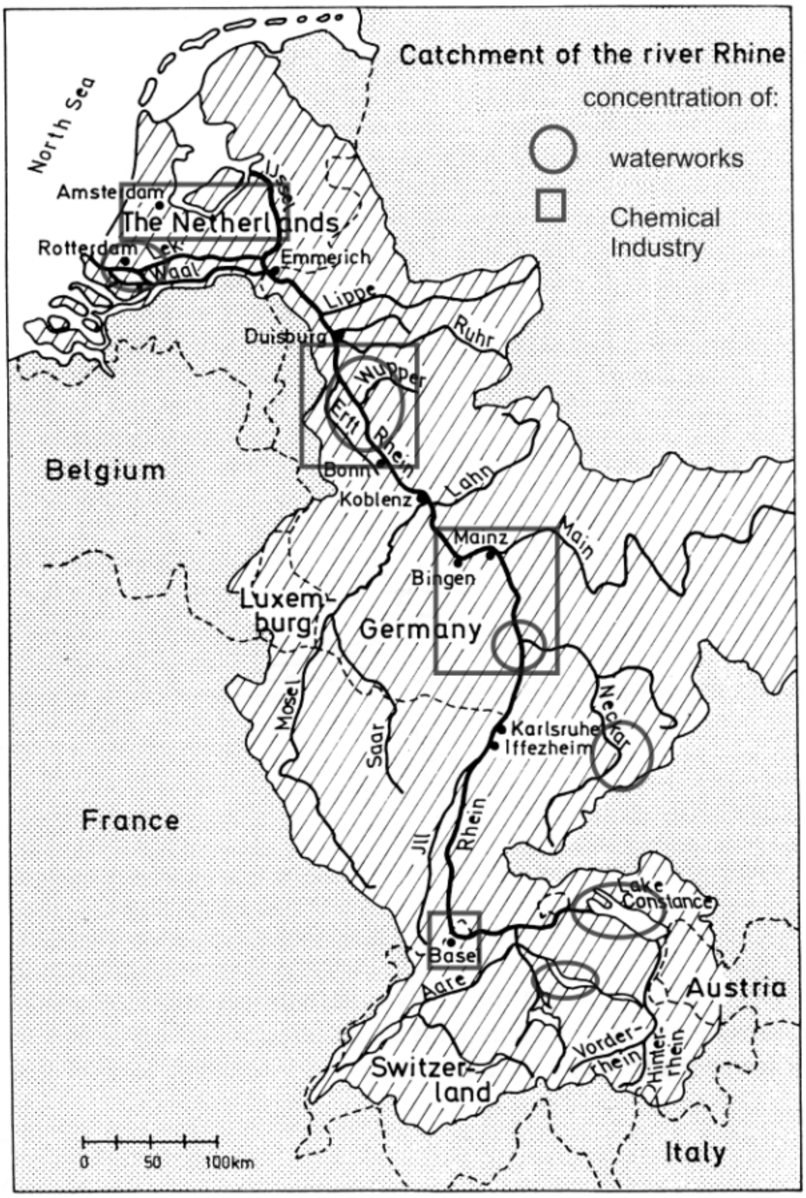


Fig. 16: Regions with high concentration of waterworks and chemical industry in the Rhine area (after IHP / OHP 1996: 48)

119 waterworks in seven European countries: The Netherlands, Germany, Belgium, France, Switzerland, Liechtenstein and Austria are represented by the International Association of Waterworks in the Rhine Basin (IA WR). This association was established in 1970 by three regional associations: RIWA (Samenwerkende Rijn en Maaswaterleidingbedrijven), ARW (Arbeitsgemeinschaft RheinWasserwerke) and AWBR (Arbeitsgemeinschaft Wasserwerke Bodensee-Rhein). The waterworks realized that only international cooperation could eventually fight the deterioration of the Rhine water quality. They demand the preventive protection of water resources and the sanitation of the Rhine to the point that natural treatment like bank filtration is sufficient to produce drinking water in sufficient amount and quality.

Bank filtration can be achieved due to ground water pumping. The depression cone in ground water table builds a gradient that allows surface water to infiltrate into the underground. Such a well will gain both bank filtered water from the river and natural ground water. The portions of the two vary with the difference between the ground water table and the actual water level in the river, the pumping rate and the distance between well and river.

In places where geology or other factors do not allow gaining bank filtered water, treatment plants with several purification steps are needed to withdraw water directly out of the river. The purified water is infiltrated into the aquifer to allow natural purification within the underground before the water is extracted again and processed in filtration plants to produce drinking water (Fig. 17). AI measures mentioned are sufficient to guarantee a safe yield in terms of quantity, provided that the quality of the river water allows its use for the production of drinking water.

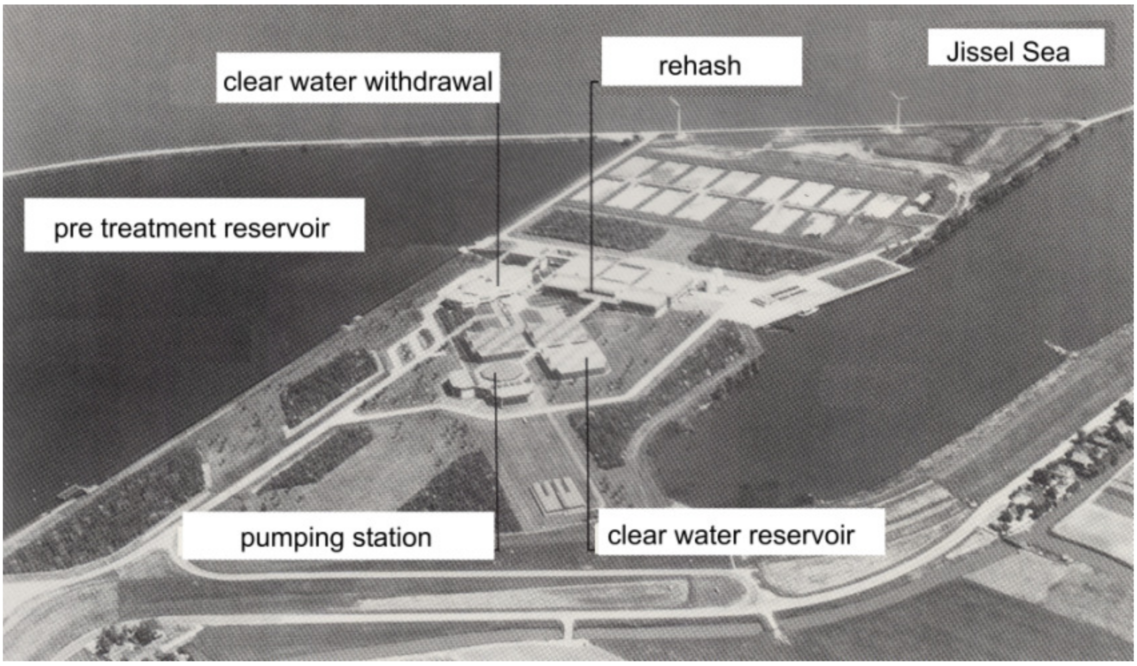


Fig. 17: Water supply in The Netherlands (KHR 1993: 31)

The average drinking water consumption in Germany does not follow any of the prognoses in the past. Meanwhile one person needs 139 litres per day. This amounts to one billion m^3 each year for 20 million people and is negligible compared to the annual water flow of the Rhine of about 70 billion m^3. This volume though may arrive in different portions, causing flood in the city centre of Köln as it occurred in January 1995. Even at low water in the Rhine there was never a shortage problem but problems were caused by declining water quality.

1.3.4 Water quality

Corresponding to the multiple functions and uses of the Rhine waters since the 19th century, water quality decreased, especially during the reconstruction of towns and Industries after World War II. Until the early seventies the ecological measures could not follow the economic development and the Rhine was called "the cloacae of Europe" in order to enforce protection measures. Since then a lot of international activities have been directed at sustainable water protection and they have now resulted in a successful experiment for the rehabilitation of a river ecosystem (Irmer 1996).

To control the effectiveness and success of water protection measures a net of monitory stations was built up along the River Rhine and its tributaries. Today there are nine international stations between Switzerland and the North Sea (Fig.18).

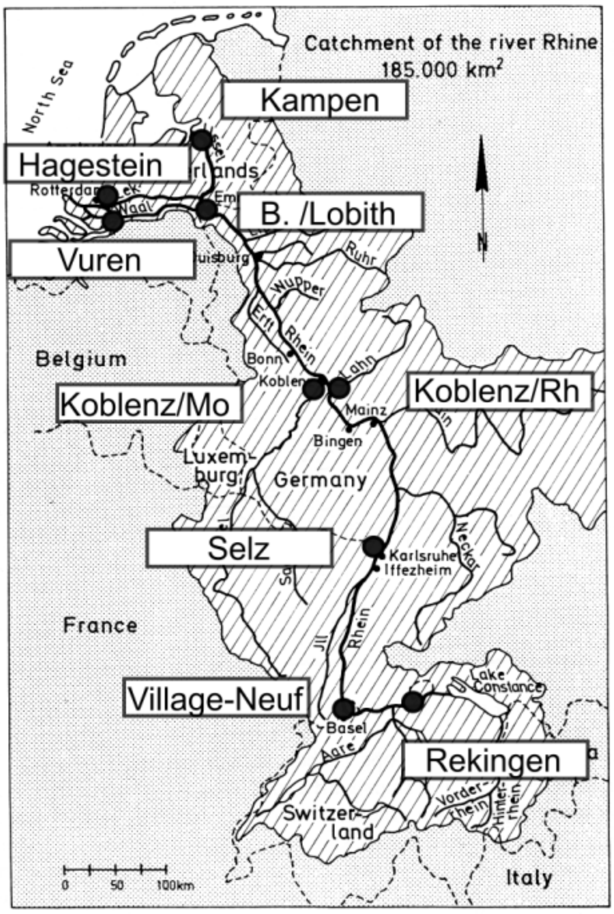


Fig. 18: International monitoring stations for water quality in the Rhine (after Irmer 1996)

Here the river is investigated and intensively monitored with highly sophisticated techniques. In the beginning monitoring stressed measurements in the water body; more and more chemical investigations in the suspended matter, in sediments and biota, and biological surveys have supplemented the monitoring. Today an effective early warning system with continuous bio monitoring and chemical online techniques in the stations can deal with short and sudden contaminations, as in the case of accidents or trouble in wastewater treatment plants (Irmer 1996).

The internationally coordinated monitoring activities are accompanied by those of the member states and there according to their responsibility by Institutes of the particular states. Other non-governmental institutions, like the International Working Group for the Water Works of the Rhine Catchment Area (IAWR), focus on special problems and cooperate with the institutions mentioned (Irmer 1996).

Today, the implementation of the EU directives on water quality in all ICPR Member States belongs to the most important measures. Administrative and in-house surveillance systems are continuously refined, ecological material cycling is enhanced in industry and trade, environmentally compatible agriculture, biological farming and extensification of agriculture are furthered with a view to contributing to a sustainable improvement of water quality.

The implementation of the Rhine Action Programme has considerably improved Rhine water quality. Point source pollution has been significantly reduced so that, today, efforts to further improve the water quality are directed towards reducing pollution of diffuse origin.

In future, Rhine water quality is supposed to be such that the target values for substances relevant to the Rhine traced in water, suspended matter, sediments and organisms will be sustainably respected. This is the only means of granting the protection of aquatic biocoenosis, the drinking-water supply, the aptitude of fish for human consumption and the use of Rhine sediments (www.iksr.org).

In Switzerland, the national programme (NADUF) for the long-term analytical investigation of Swiss rivers started in 1972. The goal is to provide continuous, complete records of the concentrations and loads of different substances. The data collected in the major Swiss rivers are presented graphically as timecourses over 22 years, and comments on the data are provided. Detailed descriptions are given of the network of stations with at present 17 measuring points, the measuring program (with 30 parameters), automatic flow-proportional sample collection for weekly or fortnightly sampling, and the chemical analyses performed (BUWAL 2000, Fig. 19).

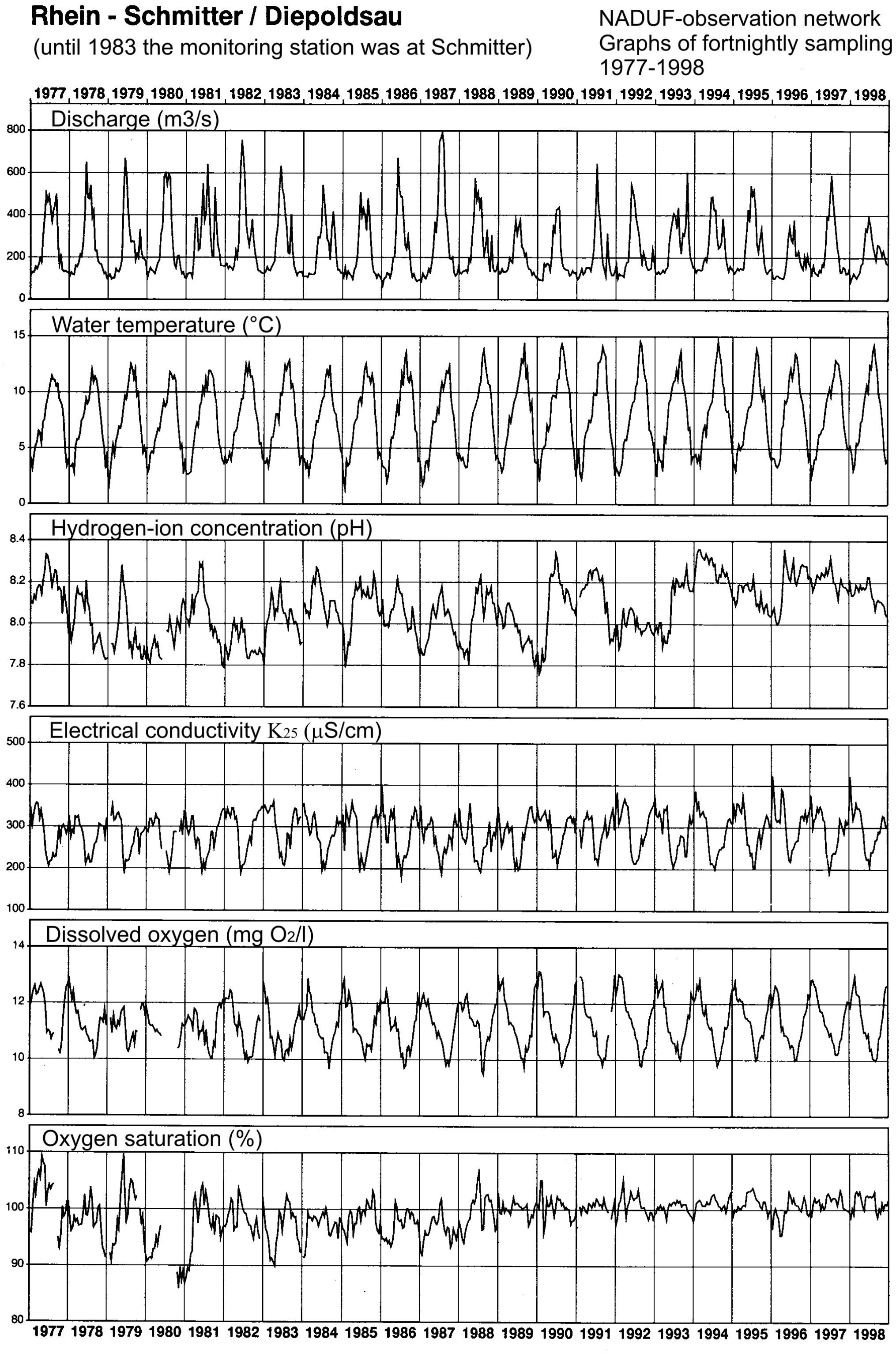


Fig. 19: Example of a result-sheet of fortnightly sampling of discharge, water temperature, hydrogenion concentration, electrical conductivity, dissolved oxygen and oxygen saturation at the monitoring station Rhine-Diepoldsau (BUWAL 2000: 48)

1.4 Population

In antiquity and in the Middle Ages the Rhine basin was much less populated than it is today. However, on the rivers Rhine, Mosel and in the Main river basin agglomeration areas developed early. In the modern era, the "Thirty Years War" (1618 – 1648) caused a considerable decline in population in Germany. Afterwards, the increase was steady, reaching about five million inhabitants by 1800 in the German Rhine basin. On the whole the population figure increased to six times the original population over 160 years. Today, about 50 million people live in the whole Rhine River basin. Their distribution among the riparian countries is shown in Tab. 5.

Tab. 5: Population among the Rhine countries in the 20th century

	population	
	(million)	percent (%)
Germany	30	60
The Netherlands	10	20
Switzerland	5	10
France	5	10
Other countries	0.5	<1

The population trend in the modem era is characterized by increasing urbanization. In some parts of the Rhine basin agglomeration regions emerged. Nearly one third of the entire population is concentrated there. These agglomerations are located on River Rhine or are connected to it by channelized rivers and canals. As the Rhine basin is very intensely used by commerce, industry and agriculture and because of its good infrastructure, its total population amounts to more than 50 million people. Some areas are very densely populated.

In the Swiss part of the basin they are the regions of Basel, Zurich and Bern; in the French territory the areas round Mulhouse, Strasbourg, Nancy and Metz. In Germany in the Upper Rhine basin the regions of Freiburg, Karlsruhe, Ludwigshafen and Mannheim stand out; in the Neckar basin the area round Stuttgart should be mentioned; in the Main basin the region of Nürnberg-Erlangen, Würzburg and particularly the lower Main basin from Frankfurt to Wiesbaden; on the left bank the area between Mainz and Bingen, as well as the Bonn-Cologne-Düsseldorf region may be distinguished. In the Moselle basin Saarland should be mentioned. The Ruhr area between Duisburg and Dortmund stands out as a purely urban and industrial region. The part of the Rhine basin in The Netherlands is very densely populated. Especially Arnhem and Nijmegen in the east, as well as the ports of Amsterdam and Rotterdam should be mentioned in this respect.

1.5 Land use

Far into the modern era land use in the Rhine basin was dominated by agriculture and forestry. Since the Middle Ages forests, which were the natural vegetation, have been widely cleared, especially in areas allowing easy cultivation. Timber was a major product, also in the trade with the sparsely wooded but economically active coastal areas to which it was brought by rafting. The wood was used there for ship building, housing construction, and as fuel. In the 18th and 19th centuries the clearing of forest became excessive and resulted in erosion damage and floods. The counteraction was reforestation. Today, about one third of the Rhine basin is forested.

The transition from barter economy to money economy, the increasingly intensive and more rational cultivation practices, and the application of artificial fertilizers have multiplied the yields of major crops over the past 100 years. Agriculture had already early advanced into the riparian plains. There, it had to face recurring floods and was impaired by waterlogged soils which were caused by swamps and changing flow conditions. Thus, improvements in the soil water balance through flood protection and drainage have also played a role in the increase of agricultural yields.

The Rhine basin from Lake Constance to Bonn and the valleys of the tributaries have been winegrowing areas since ancient times. Through the high quality of the wines viniculture has gained great importance. The chemical industry arising since the middle the 19th century managed its greatest European factory groups near Basel, Ludwigshafen, at the Lower-Main, at the Lower Rhine and in the Delta of the Rhine in The Netherlands (see also Fig. 16). Processing industries such as glass factories, paper and cellulose factories as well as textile industry, sugar works and breweries, settled or merged from older manufactories. Metal processing and machine building experienced a strong evolution. They gained world importance in the last hundred years, so at sites in Switzerland, the Upper Rhine, Neckar, Regnitz, Lower-Main, Upper Moselle and above all in the Ruhr District and in The Netherlands. In the latter country, an important electric industry arose just like in other parts of the Rhine basin. Industry concentrated in and nearby large cities.

In order to cover the increasing demand for energy, numerous big thermal power plants were built almost exclusively next to the Rhine and its tributaries because of the cooling water requirement. Later a number of nuclear power plants were constructed in the Rhine basin.
The expansion of traffic went along with the intensification of the economy. The old road network in the Rhine basin was corrected and more and more extended. Already before Second World War it started to be complemented by highways.

The railroads also form important traffic routes on both sides of the Rhine. The Rhine itself was enlarged to be a large waterway. It shows the greatest shipping traffic of all European waterways. The extension of traffic routes, settlements and industrial plants took mainly place in areas with former agricultural and forestry use. As a result, their roles decreased considerably in the last 100 years, while the settlement and economy became more extensive. The settlement area increased in the Upper Rhine from 1950 to 1985 from 6.7 to 12.9% of the total area. This might lead to locally more rapid drain of the precipitation and higher discharge peaks. In the Rhine, this can be noticed in the case of small and medium size floods.

1.6 Hydrometeorology

1.6.1 Climate and Meteorology

The annual amount of precipitation in the Rhine basin varies in the case of Kolmar of approx. 450 mm in the Alsace and also less than 500 mm in the triangle Mainz-Alzey-Worms up to almost 4'000 mm in higher parts of the Bernese Oberland. In the first case, the boundary from deciduous forest to the steppe is achieved, in the last case in some spots to the rainforest of middle latitudes. The second fundamental climate parameter, the annual mean temperature, drops from about 10°, which is valid for almost the entire navigable Rhine, to below 0°C in the source areas of the Alps.

During the 20th century, the climatic conditions changed in all parts of the Rhine basin. The area averages of the precipitation and of the air temperature increased to a considerable extent in spite of regional differentiation. During winter season, precipitation increased significantly, while temperature increased in both half-years (Belz 2006). Fig. 20 and 21 illustrate this, representing generalized decade to decade averages for the whole Rhine area.

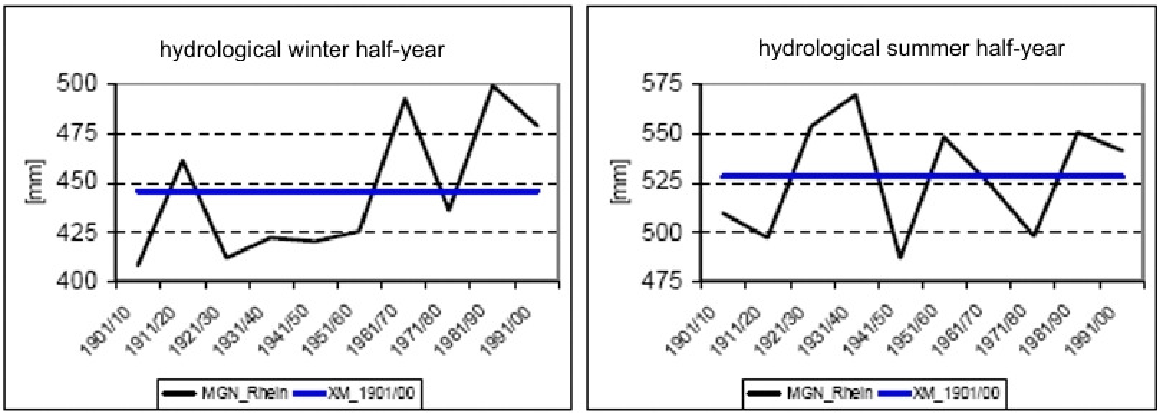


Fig. 20: Evolution of the decade averages of the areal precipitation (=MGN_Rhein) compared to the total average of the areal precipitation (=XM_1901/00) in the Rhine basin in the 20th century (Belz 2006)

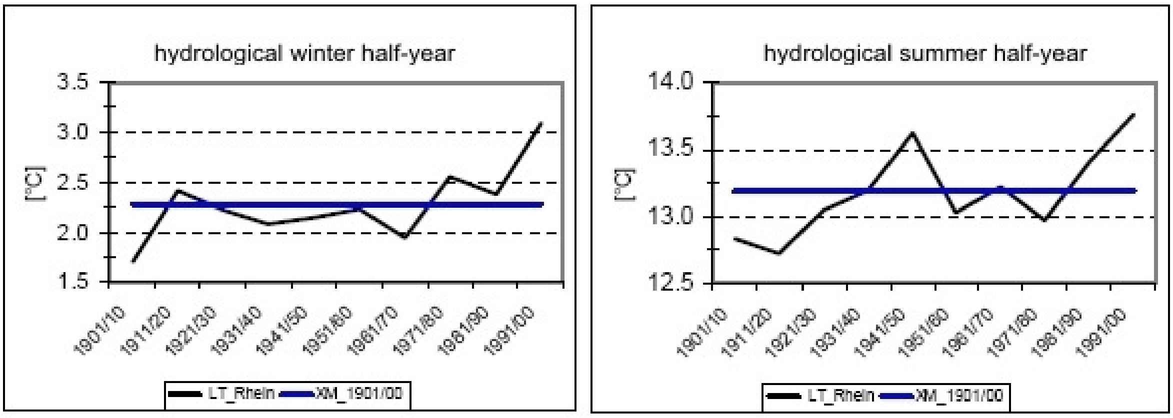


Fig. 21: Evolution of the decade averages of the air temperature (=MGN_Rhein) compared to the total average of the air temperature (=XM_1901/00) in the Rhine basin in the 20th century (Belz 2006)

Especially in wintertime the increase of the areal precipitation is detectable as a trend with a significance level of 95% for many partial catchment areas. The increase in areal precipitation in the winter half-years corresponds with large "humid" weather situations.

1.6.2 Hydrology

1.6.2.1 Runoff regime of the River Rhine

The Rhine basin with an area of 185’000 km^2 and a mean annual discharge of 2’200 m^3/s is one of the most important river basins in Europe. The Rhine has its source in the snow and glaciers of the Swiss mountains and flows through Austria, Germany, France and Luxembourg to the flat lands of The Netherlands. On average, the Swiss Alps contribute 50 % of the total runoff of the Rhine. In summer, owing to snow and glacier melt, this contribution rises to 70%. The components of the water balance in the Rhine basin are: precipitation 1100 mm, runoff 520 mm and evaporation 580 mm.

The runoff regime of the Rhine in the mountainous region is characterized by a large difference between low flow and high flow. The ratio between the lowest and the highest flow in the Swiss Alps is 1:68. Downstream the difference decreases noticeably, mainly owing to the storage capacity of larger natural lakes and anthropogenic factors such as artificial reservoirs.

At the border between Germany and The Netherlands the ratio is only 1:21. At Rheinfelden in Switzerland the Rhine has low flows during the winter months and high flows in June and July. In Germany and France the Neckar, Main, Mosel and Lippe tributaries to the Rhine contribute low flows in the summer months and high flows during winter. The runoff regime at Rhine-Rees at the border between Germany and The Netherlands therefore shows high flows in January to March and low flows in August to October (Fig. 22). There is a great variety of runoff regimes within the Rhine basin. In Switzerland alone, 16 different natural regime types are recognized (Fig. 23).

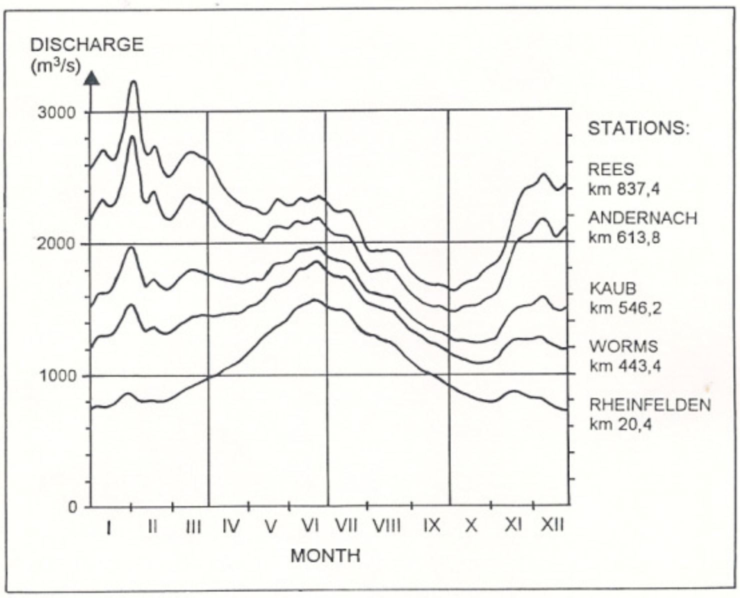


Fig. 22: Runoff regimes of the Rhine at selected monitoring stations (KHR 1993: 17)

Fig. 22 shows a hydrological profile of the Rhine from the Lake Constance to The Netherlands. It shows mean flood discharge MHQ, mean flow MQ and mean low flow MNQ for the sections of the Rhine between major tributaries. The pattern of mean specific flood discharge MHq is also shown (Fig. 24). The mean specific discharge varies between 29 l/km^2 in the Swiss mountains and 14 l/ km^2 in The Netherlands. These values are based on monitoring between 1951 and 1990.

In recent years the Rhine basin has seen more heavy floods than before, which have caused enormous damage. In 1987 a flood devastated large parts of Switzerland, causing damage in the amount of US$ 1'000 million. In 1990 and 1993/94 the countries along the Rhine suffered flood damage amounting to US$ 900 million. In January 1995 many towns along the Rhine and the Mosel were flooded. In The Netherlands, dykes were on the verge of breaking and several hundred thousand people had to be evacuated. The damage incurred amounted to several billion US$. The reasons for these floods were:

- a long period of at times very heavy rainfall in many parts of the catchment area, insufficient retention of rainwater in the soil, which already held large quantities of water
- from earlier rainfall and/or, in the case of the winter floods, the fact that the soil was frozen and therefore impermeable,
- erosion, transport and deposit of sediments.

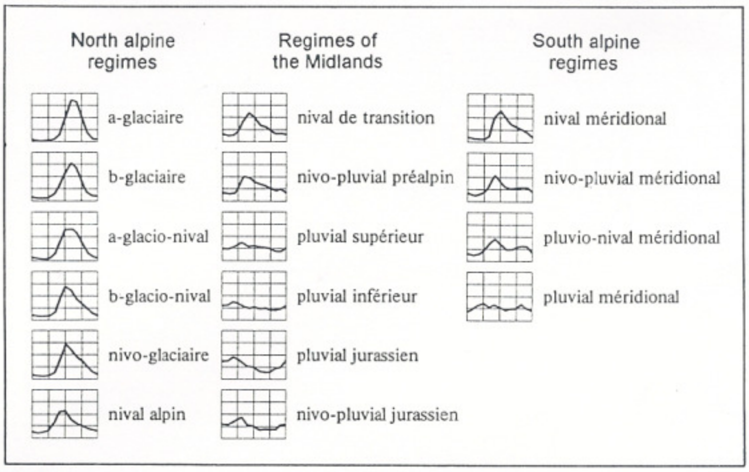


Fig. 23: Natural regime types in Switzerland (IHP / OHP 1996: 15)

Apart from natural causes, floods are also influenced by man-made factors. The water balance can be upset by any changes made to the natural water retention of vegetation, soil and hydrographic systems, such as:

- sealing the surface through residential and industrial buildings and roads,
- educing forested areas through clearance and damage to trees,
- damaging the ground water through agricultural practice which is unsuitable to local conditions,
- reducing water retention alongside rivers by canalizing them for the principal purpose of rapid drainage,
- reducing the area naturally flooded by building dykes.

On the other hand, flooding has been affected in a positive way in some areas through the construction of flood retention basins and the regulation of the water Ievel in lakes. The effects of these individual human-made factors on flooding vary for each section of the Rhine. They depend in particular on the size and characteristics of each local catchment area. Physical-deterministically reliable estimations of the effects of human intervention are only available in a few cases because of the complex correlations involved.

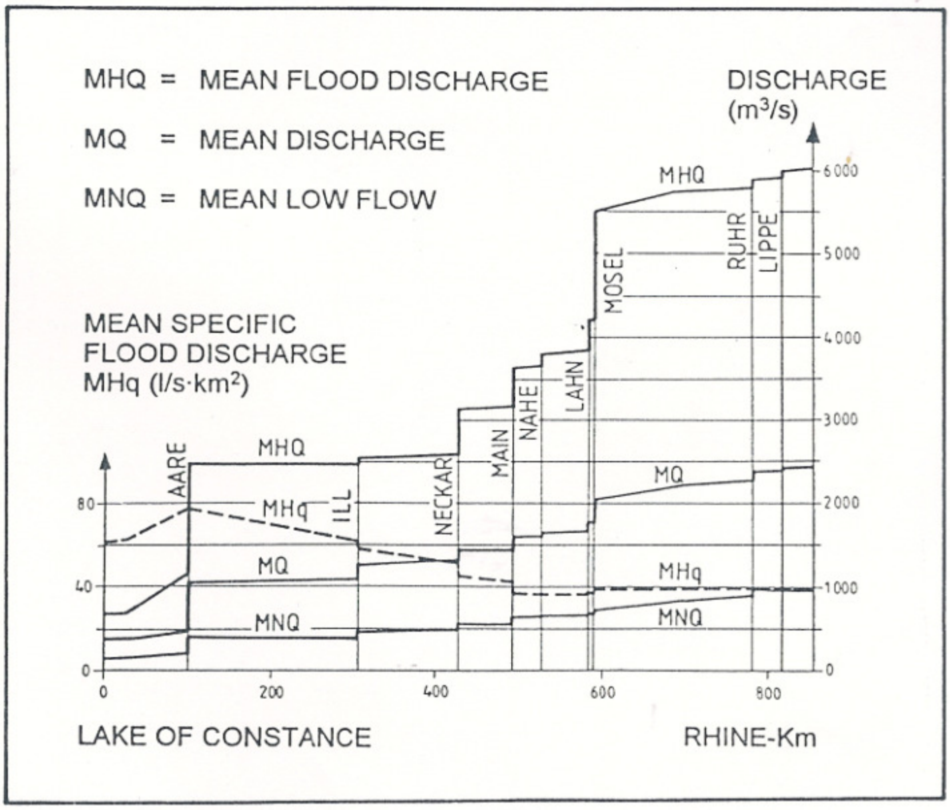


Fig. 24: Discharge of the River Rhine (IHP / OHP 1996: 15)

Tab. 6: Water-balance components of the extreme flood of 24th/25th August 1987 in the basin of the River Reuss (IHP / OHP 1996: 16)

Component	Amount		
	mm	$10^6 m^3$	%
Precipitation	182	151	100
Discharge			
total	94	78	52
direct runoff	49	41	
from roads	0.6	0.5	
Evaporation			
total	7	6	4
interception by forest	0.6	0.5	
Storage			
total	81	67	44
snow	8	7	
soil	60	50	
flooded areas	4	3	
reservoirs	9	7.5	

The causes and effects of the flood that occurred between 23rd and 25th August 1987 in the 832 km^2 Alpine catchment area of the River Reuss down to Seedorf have been examined in detail (LHG 1988; LHG 1991). The water balance at the time can be described as follows:

From the rain that fell, 27% flowed directly and 25% indirectly, through soil transfer. The roads (sealed surfaces) in the catchment area contributed about 1% of the direct runoff. The degree of interception by forest and, in particular, any possible modification of this effect owing to damage to the forest is not significant in relation to the water balance and in comparison with the mistakes incurred in measuring rainfall and runoff. The retention capacity of the soil was the most important regulating parameter for measuring the volume of the flood (see Tab. 6). The following conclusions can be drawn:

- earlier rain, snow melt and temperature pattern all led to high runoff rates;
- total rainfall of 170 mm in 60 hours is rare in areas of over 800 km^2 in this region; the pattern of rainfall intensity played a decisive role;
- in comparison with previous weather patterns and the capacity of soil storage, which depend on the geological substratum, the influence of vegetation was negligible;
- the flood build-up was hardly influenced at all by human modification of the landscape;
- the rainfall levels and distribution created such unfavourable conditions that human-made factors could not alter the situation. Human intervention which reduces the retention capacity in the catchment area (deforestation, sealing the surface) can, however, drastically increase the frequency of average floods in the same catchment area. The storage of water in reservoirs helped to reduce peak discharge levels;
- debris flows and sediment brought down by the mountain rivers caused a large part of the damage.

1.6.2.2 Influence of climate change on the runoff regime

Many investigations have been carried out in the Rhine catchment area to determine the medium and long-term changes in runoff in the area and to gain more knowledge concerning their causes. An example is given in Fig. 25 which shows the changes in water-balance components at Basle between 1901 and 1995. Average air temperature rose during the observation period by around 1.4 ac. Precipitation rose by approximately 120 mm, which constitutes around 8 % of the annual precipitation. A noticeable increase was observed in the 1hour maximum precipitation levels since the 1970's. Runoff increased on I y slightly (5 mm), while evaporation rose considerably (107 mm). An average annual rise of 1.5 per mill was seen in flood peaks at Basle. Similar trends have also been seen in long measurement series in Germany, where the rise in runoff was somewhat higher. As far as runoff is concerned, it must be added that it has risen at low and mean flow as well as flood flow.

The causes of these trends are changes in the river regime, climatic changes and human intervention. For example, it was observed that wind patterns have changed. A west wind is more common, which brings longer and more intensive precipitation. The increase in air temperature has led to a change in volume and temporal distribution of rainfall. It can also be seen that winter precipitation has risen and at the same time the frequency of snowfalls has decreased. The increase in air temperature has also caused a considerable reduction in water reserves of glaciers and snow in the Alpine regions. The degree of frequency of flooding can of course also be considerably influenced, in a positive or negative way, by water management. For example, mountain reservoirs can reduce peak floods by retaining water.

If one considers the most important parameter besides the temperature, the precipitation, it is obvious that it has increased in the entire catchment area of the Rhine mainly in wintertime (see above Fig. 20). As there is the same time an increase of mean temperatures as well (Fig. 21), especially in the winter half-year, a tendency towards higher discharges in winter could result.

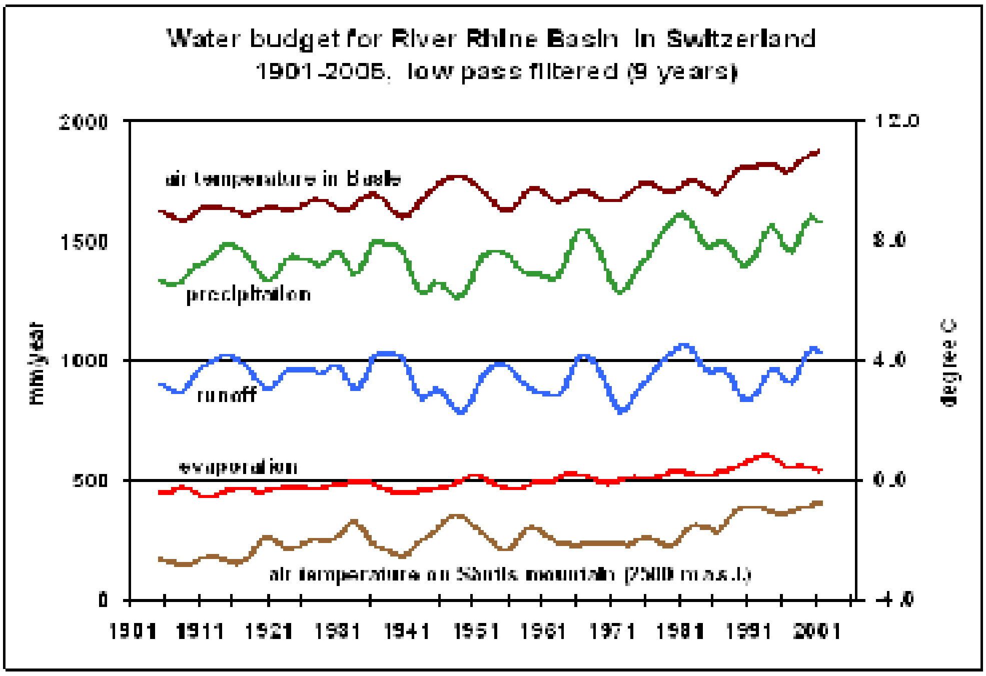


Fig. 25: Time series of air temperature and water balance components at Basle from 1901 – 1995 (Schädler, 1985 and Schädler and Bigler, 1992)

For several years, the International Commission of the Hydrology of the Rhine Basin in co-operation with other hydrological institutions in Europe has been investigating the impact of possible climate change or land-use change on mean flow, flood and low flow occurrence. These projects should provide a basis for developing counteract strategies to the effects of global warming. Catchment models and a model for the entire Rhine basin have been developed or adapted for the studies.

In several catchments in Switzerland the repercussions of a CO_2 doubling on the water balance have been studied using the IRMB model (Bultot 1992). This model is a daily conceptual hydrological model, developed by the Hydrology Section of the Royal Meteorological Institute of Belgium. It is able to simulate the components of the water cycle in medium-sized catchments with surfaces from 200 km² to 1'500 km². It is not distributed, i.e. the input data must be considered as uniform over the whole area. The IRMB model is based on a sequence of sub-reservoirs representing the different main water storage of the catchments and transfer between them. The parameters of the model have been determined by fitting the daily values of the total flow at the outlet of the catchment. As input variables climate data (precipitation, net radiation, air temperature, air humidity, soil temperature at various depths, wind) and physiographical data (soil cover, albedo, leaf index, soil types, urban areas, maximum possible water content of the aeration zone) are needed. The calculation of the daily increases in precipitation, temperature, radiation, water vapour pressure and cloud cover due to CO_2 doubling were calculated according to a method described in Bultot (1988).

The water balance components of the Ergolz catchment between CO_2 disturbed conditions and present climatic conditions for the years 1983 to 1990 are shown in Tab. 7. The main conclusions are:

- Increased potential and effective evapotranspiration; consequential impact: a slight increase in biomass and agricultural production.
- Despite rising infiltration, decreased annual deep percolation water flow, the infiltration surplus being consumed by evapotranspiration.
- Increased seasonal runoff with no effect on the annual total flow at the outlet. Total flow is higher from December to February and lower from May to September.
- Increased daily maximum flow.
- Greater frequency of soil moisture content below 60% of the saturation capacity in the aeration zone.
- Shorter spells with snow cover; consequently lower cost of snow-clearing operations but negative economical consequences for winter recreation areas.

The additional waters from melting glaciers in connection with the temperature rise are from marginal importance in the Rhine basin (Belz 2006). This statement refers to a study about glacier retreat in the Vorderrhein basin in the canton of Grisons, Switzerland (Fig. 26). The basin area is 776 km^2 and outflow of the basin is measured at Ilanz. The total glacier volume decreased about 76% since 1850 in that area (Fig. 27), resulting in a water equivalent of approx. 1.16 km^2. The average increase of discharge due to glacier retreat resulted to be less than 1% for the last 150 years, which is believed to be a small influence compared to other parameters in the Rhine basin.

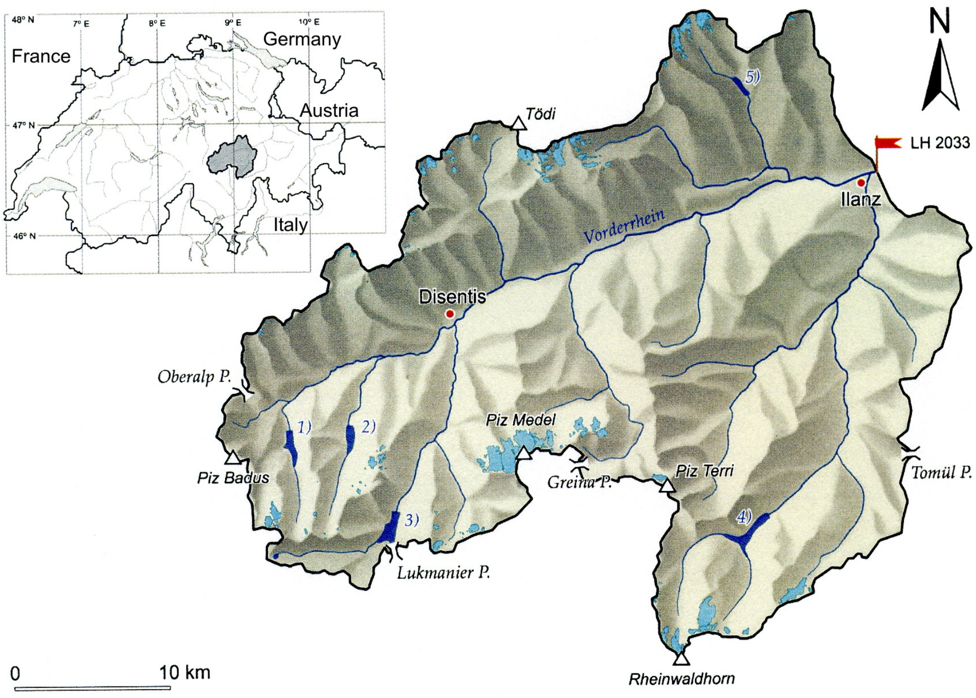


Fig. 26: Study area with hydrometric station at Ilanz, glaciers (in blue) and reservoirs (numbers 1 to 5; Frauenfelder-Kääb 2005: 5)

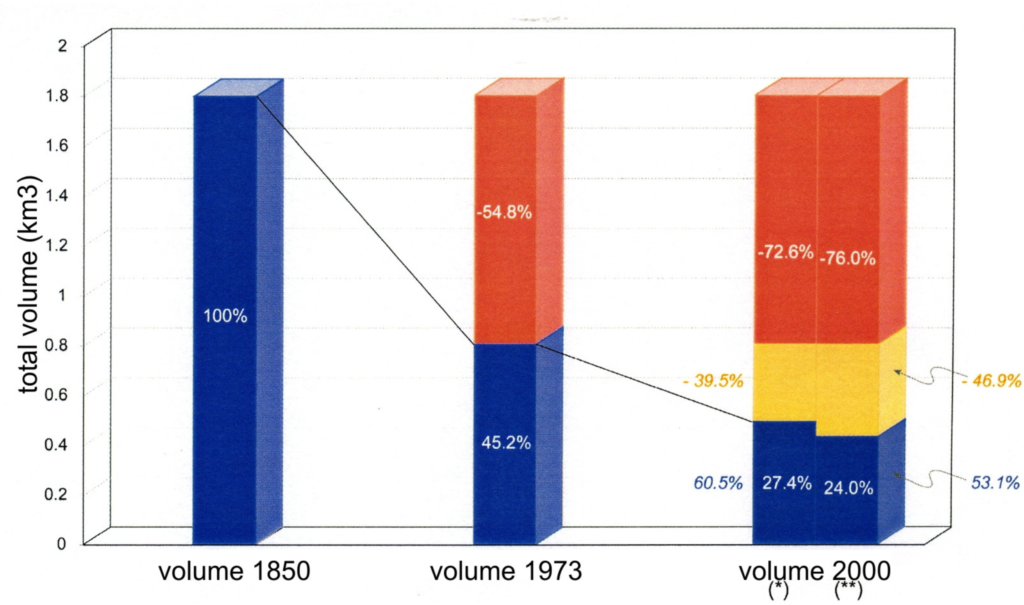


Fig. 27: Estimated loss of glacier volumes in the Vorderrhein basin (Frauenfelder-Kääb 2005: 21). The difference of the volumes in 2000 is the result of two distinguish methods of calculation.

Tab. 7: Water balance of the Ergolz catchment. Increases between scenario 1 (CO_2 doubling) and scenario 0 (present) (IHP / OHP 1996: 19)

Ergolz at Liestal scenario 1 - scenario 0	Annual mean water balance (mm)								Mean
	1983	1984	1985	1986	1987	1988	1989	1990	
Precipitation	51.3	49.8	43.2	66.0	44.9	70.2	50.7	58.1	54.3
Potential evaporation	67.5	82.8	68.0	73.8	71.6	71.6	68.4	64.1	71.0
Effective evaporation	51.5	58.4	47.8	63.2	66.9	61.4	47.3	48.4	55.6
Direct evaporation	10.9	12.1	4.0	11.4	16.1	18.3	7.1	9.2	11.2
Evap. upper aer.zone	25.3	27.9	27.7	37.1	38.2	27.9	23.4	26.2	29.3
Evap.lower aer.zone	15.3	18.2	16.1	14.6	12.6	15.2	16.8	12.9	15.2
Interception	10.9	11.5	4.6	10.4	16.6	17.9	7.1	9.2	11.0
Throughfall	40.3	44.2	33.5	54.5	28.0	52.1	43.5	48.8	43.1
Infiltration	14.5	26.7	21.7	35.9	27.7	3.8	32.1	17.7	22.5
Runoff water supply	26.0	26.6	11.8	20.1	-1.1	48.8	11.7	30.2	20.7
Deep percolation	-21.0	-22.0	-22.8	-13.7	-27.5	-36.2	-5.2	-23.0	-21.4
Simulated total flow	-5.0	-5.4	-8.8	6.4	-27.8	-13.2	8.2	17.8	-0.2
Direct surface flow	20.6	13.0	8.2	15.0	-2.2	36.9	9.0	20.9	15.2
Delayed surface flow	10.8	3.5	4.8	4.4	1.5	11.8	4.2	3.3	5.6
Percolated water flow	-36.4	-21.9	-21.8	-13.1	-27.0	-35.5	-5.1	.-6.4	-20.9
External flow	-0.9	-0.5	-0.6	-0.3	-0.6	-0.8	-0.1	-0.2	-0.5

The impact of human-induced global climate change on the Rhine discharge is simulated by the RHINEFLOW model. Changes in regional annual water availability and seasonal Rhine discharge have been estimated using climate scenarios. The climate scenarios are based on greenhouse gases emission scenarios. Two scenarios are used, which have been developed for the Intergovernmental Panel on Climate Change: the Business-as-Usual (BaU) scenario in which current trends continue and a considerable growth in the use of fossil fuels is forecasted, and the Accelerated Policies scenario (AP), which represents adequate environmental policies and stricter international protocols. For both emission scenarios, three runs were carried out with the RHINEFLOW model. One uses the change fields for precipitation and temperature from the "Best Guess". Best Guess uses the average expected change for temperature and the average precipitation from the weighed results for precipitation from the 7 GCM experiments. In the two other runs the lower and higher 90% confidence limit were used.

The RHINEFLOW model has been developed to investigate month to month changes in the water balance compartments in the Rhine basin. RHINEFLOW uses the standard meteorological input variables of temperature and precipitation and the geographical data on topography, land use, soil type and ground-water flow characteristics. These parameters are stored in a raster GIS with spatial resolution of 3x3 km. Calculations of evapotranspiration, runoff and snowmelt are based on the Thornthwaite-Mather method for actual and potential evapotranspiration and a temperature-index method for snowfall and snowmelt. The model separates monthly water surplus into direct runoff, which is discharged in the same month, and delayed runoff. Stream flow calculations are corrected by using data on lake water-storage changes and changes of water storage of glacier ice. The model produces time series for the river discharge. It also produces maps showing the temporal and spatial distribution of a number of hydrological variables such as potential and actual evapotranspiration, snowfall percentage and snow cover duration.

1.7 Travel times

The travel time of a solute cloud in the river Rhine may be determined by different methods and models, all depending on the knowledge of mean velocities in the river. The more the information about velocities is known, the more accurate travel times are. By means of a hydrodynamic model travel times in the river Rhine between the Lake of Constance and Bale were computed. These calculations were carried out for different steady flow conditions from low water to high water (Fig. 28). Diagrams allow the estimation of travel times between two river places (cross-sections). If there are unsteady flow conditions in the river, the travel time of a solute cloud is strongly influenced by the flow variations (Fig. 29).

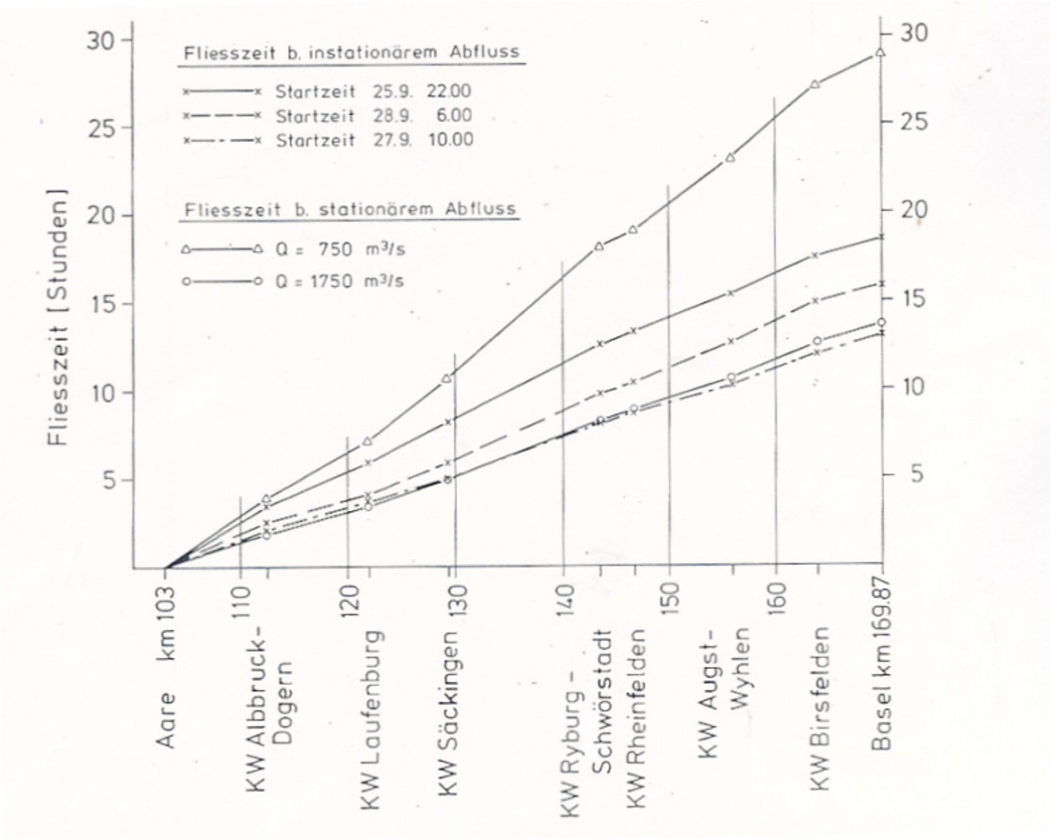


Fig. 28: Travel time comparison calculations between the River Aare inflow to the Rhine and Basel (LHB 47)

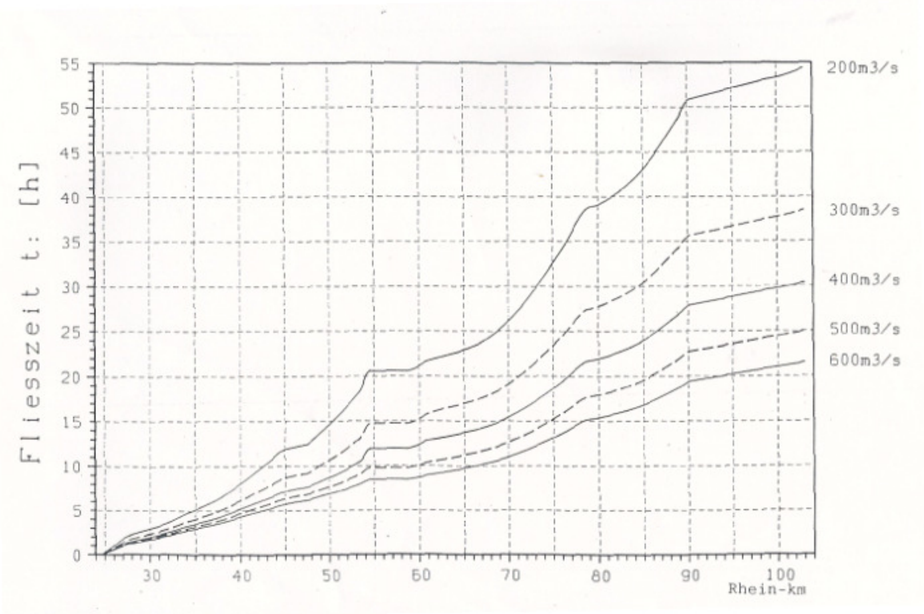


Fig. 29: Mean travel times of the Rhine between Stein am Rhein and Aare inflow (LHB 56)

1.8 Hydrogeology

The morphological structure of the basin is somehow reflected in the structure of the groundwater provinces. Changing rock conditions cause also great local differences in groundwater flow. OnIy those groundwater provinces which play an important role in drinking water supplies are mentioned here.

In the Alpine region and partially also in the uplands, the long-stretched gravel-filled troughs in the valleys are exploited for water supplies. Almost 80% of the drinking water in Switzerland comes out of groundwater. The Upper Rhine Graben consists of Mesozoic strata with an overlying cover of marine, sandy-clayey Tertiary material of more than 2'000 m depth. The top cover in the central basin is formed by 200-400 m thick Quaternary deposits. These deposits contain extensive and productive aquifers.

A particularly groundwater-rich landscape in the Rhine basin is the Lower Rhine Embayment and the area of the eastern Netherlands. In the series of several groundwater storeys it is in the first Line the upper one in the sands and gravels of the Pleistocene Rhine terraces that has the highest hydro geological importance. By far the richest in water is the lower terrace on both banks of the present course of River Rhine between Bonn and The Netherlands consisting of 20-30 m thick sands and gravel that show good to very good water permeability. The lower terrace is in direct connection with the surface runoff in River Rhine so that besides groundwater abstraction from the 10-30 km wide terrace increasing use is made of bank ion in the vicinity of the river.

The drinking water of Switzerland originates for up to approximately 40% from very productive ground-water supplies originating of gravels of the extensive valleys (Fig. 30). 40% originates from karts formations and fractioned solid rock formations (springs). Since gravels show a high cleaning effect compared to many contaminations, the ground-water supplies fed by flow infiltration form to a large extent the most important drinking water resources of Switzerland. Regions with carbonate rocks are moulded by important subterranean drain and are highly sensitive to contaminations and precipitation.

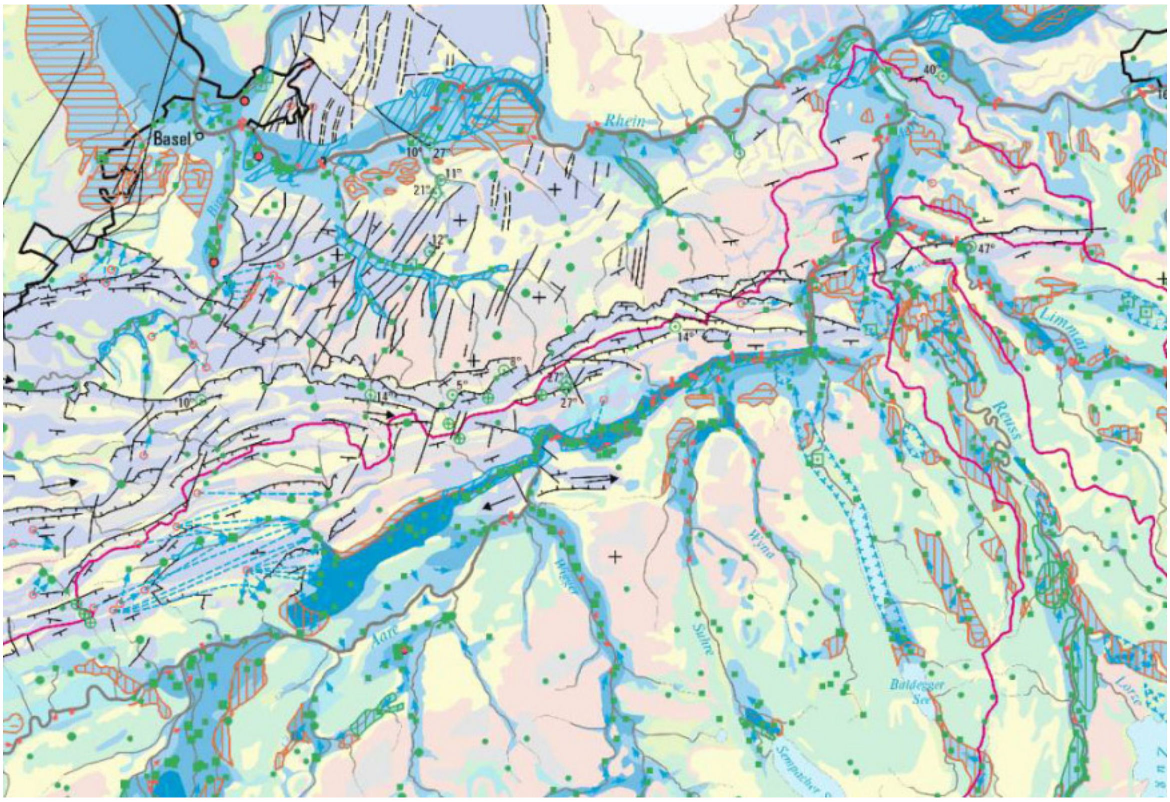


Fig. 30: Detail from the Groundwater Resources Map of Switzerland, 1:500'000 (Bitterli et al. 2004), High yields are represented in blue colours.

1.9 Morphological landscape structure

In terms of elevation and morphological structure the Rhine basin can be divided into the high mountain area (Alps), the Alpine foothills, uplands consisting of separate blocks of the Vatican pen plain and overlying Mesozoic strata, and the lowland. The mean elevation of the Rhine basin was calculated to be 483 m and the mean terrain slope 5°44'. The share of the Alpine high mountains amounts to more than 16’000 km^2. The highest peaks exceed 4’500 m above sea level. Several hundred km^2 are covered by glaciers, although glaciation is presently strongly receding.

Northwest of the high mountains the Swiss Midland stretches over some 220 km with an average width of 45 km and an area of about 10’000 km^2. The Swiss Midland consists mainly of Miocene molasses. In the north of the high mountains there is the basin of Lake Constance which is of glacial origin. Its centre is covered by Lake Constance. With an elevation of the water surface of 396 m above sea level the lake has a maximum depth of 276 m, so that the bottom of the lake at its deepest point is merely 120 m above sea level.

The Alps, the Alpine foothills, the Midland and the Swiss Jura are the major landscapes of the Rhine basin upstream of Basel. Their share in the entire river basin amounts to some 20%. At Basel, River Rhine enters with a sharp bend the Upper Rhine Plain which extends from south to north. With an overall length of 300 km the Upper Rhine Graben has a mean width of 40 km. In the west and in the east along the Upper Rhine Graben, uplands extend which show above the foundation rock the complete series of Mesozoic strata such as Bunter Sandstone, Muschelkalk, Keuper, Lias, Dogger and Malm of the Jurassic system. North of a line Main-Rhine-Nahe, the Rhenish Slate Mountains cover an area of about 26'000 km^2 which drain nearly exclusively into River Rhine. In a 113 km long antecedent valley the Rhine breaks through the Rhenish Slate Mountains between the towns of Bingen and Bonn. Simultaneously with River Rhine its tributaries Mosel, Lahn and Sieg cut their antecedent valleys into the Rhenish Slate Mountains.

From north-west the Lower Rhine Embayment stretches into the Rhenish Slate Mountains. The landscape along the Lower Rhine is characterized by wide aggradation areas, remnants of the northern glaciation and sometimes thick loessial covers. According to its aggradation character the Lower Rhine Embayment is structured in the main terrace, the middle terrace and the lower terrace of River Rhine. On Dutch territory, parts of the river basin lie below the level of the sea.

1.10 Soils

The formation of a soil type depends on a number of factors: parent rock, climate, groundwater conditions, soil humidity, land use and relief affect the development of a soil type. These factors vary widely in the Rhine basin, so that a variety of soil types occurs. Nevertheless, in the Alps, in the uplands, in valleys, and on the Lower Rhine larger areas of similar soils can be found. In the Alps soil covers are mostly shallow, in the uplands braunerde soils prevail, and podzolic soils are frequent in the plains. How intensively the climatic conditions determine the formation of a certain soil is shown by the occurrence of chernozem soils in the area of Worms: here favourable temperatures and relatively low precipitation have produced this soil type which usually occurs only in much more continental regions. Fig. 31 shows, as an example, the soil map of Switzerland.

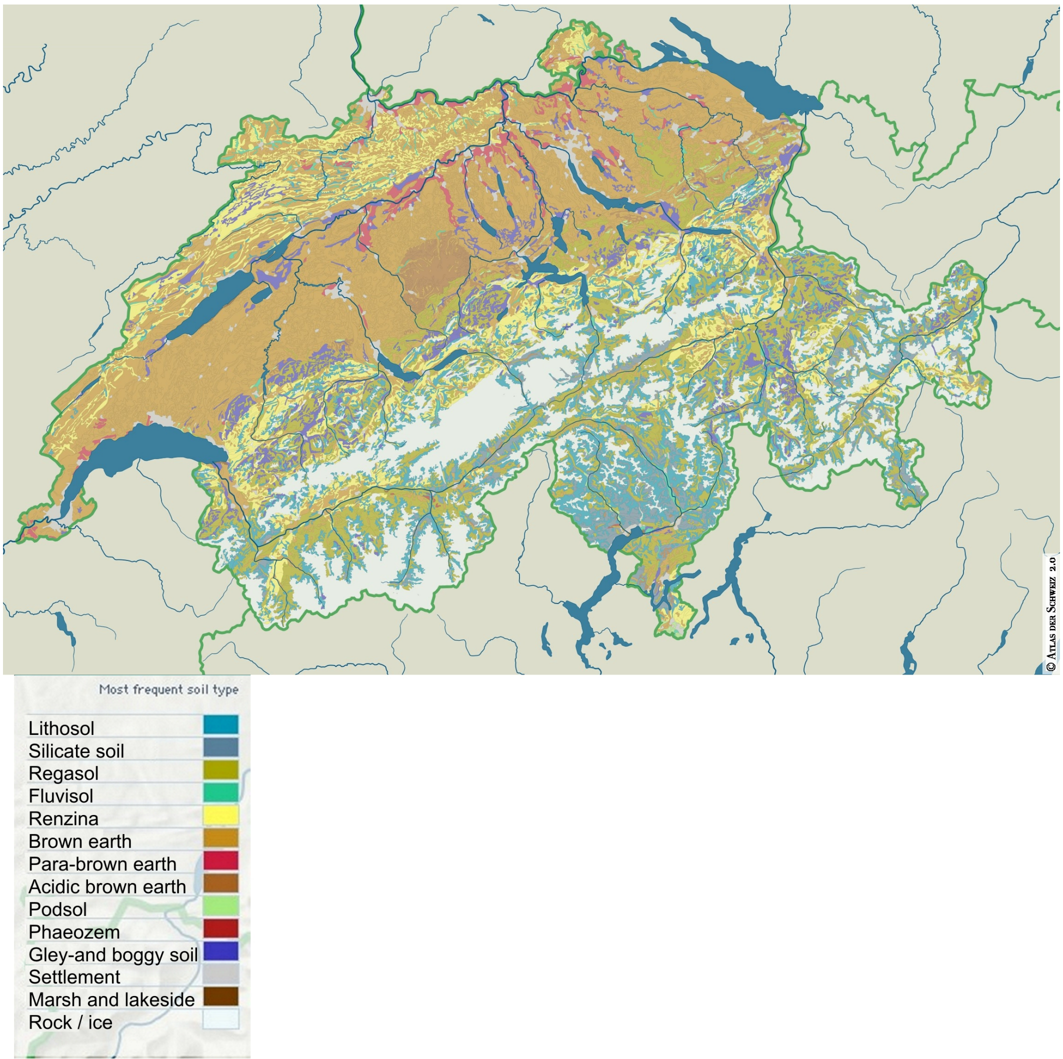


Fig. 31: Soil map of Switzerland (Atlas der Schweiz)

2 Users

In a larger basin, a large number of users have different needs and requirements. In small alpine catchments, uses and users of sediment related affairs might be different than those of larger lowland catchments. In the following, stakeholders and their needs are presented for the two examples of small alpine and, and as a contrary example, large lowland catchments.

2.1 Stakeholders of small alpine catchments

In small and steep Alpine catchments, interactions between uses and users and sediment related problems are mainly governed by the needs of protection against loss and damage (land, forests, settlements, traffic lines etc.), power and water supply and construction. Other uses are conservation of nature like habitat protection and recreation (Fig. 32).

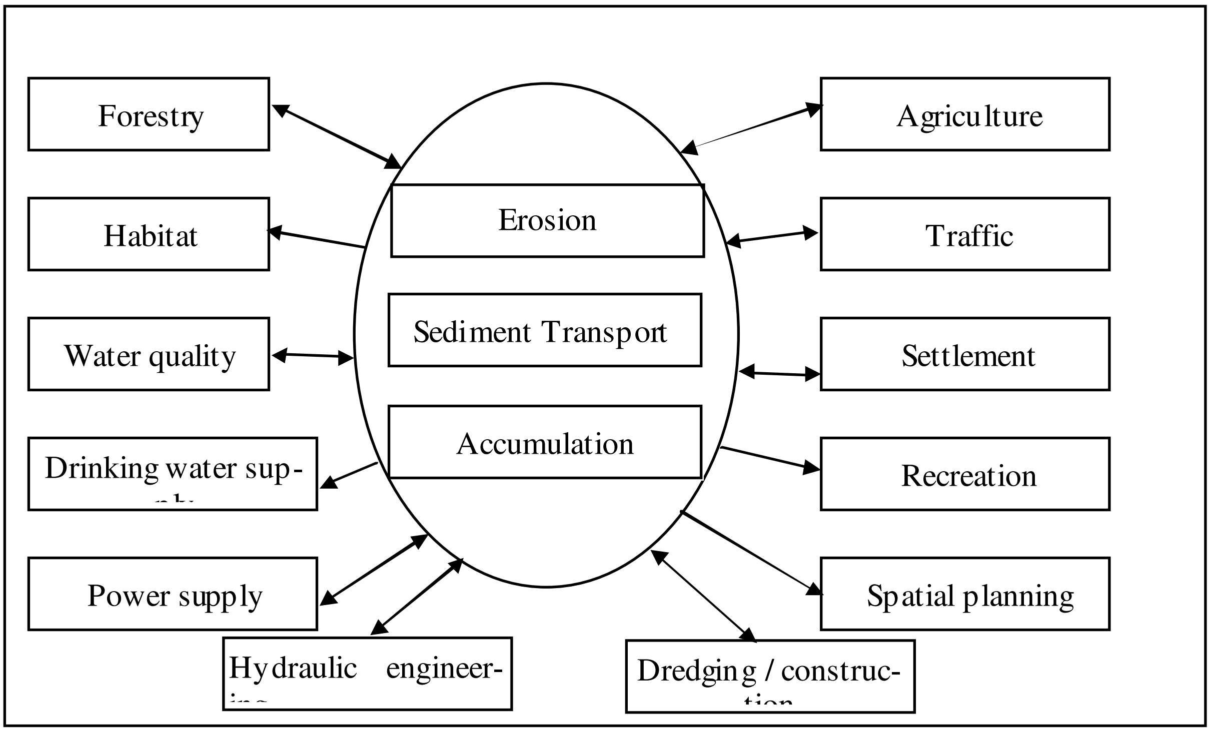


Fig. 32: Some of possible stakeholders in an Alpine catchment; note that some relations are mainly one way relations (indicated by single arrow)

2.1.1 Needs for protection (mainly natural hazards, soil loss)

Sediment management because of protection requirements includes all stabilization and hydraulic works for erosion control, sediment retention and deviation and canalization. Also soft measures like reforestation and bio–engineering are part of sediment management. Protection against natural hazards does also include measures like spatial planning (construction recommendations and restrictions, recently as a result of hazard mapping). All these measures except spatial planning have their influence on the sediment flow and are also influenced by it (double arrow in Fig. 32): size and design of a sediment retention basin for example are a function of sediment properties and inflow volumes (the construction of a basin is therefore influenced by the factor sediment). On the other hand, the basin interrupts sediment flow and might cause increased bed erosion downstream due to unsaturated sediment transport capacity (basin influences the factor sediment: erosion volume, accumulation and transport). Compared to natural hazard protection, soil loss as an agricultural damage is of minor importance, but needs special attention at places with relatively intensive agricultural production.

2.1.2 Power and drinking water supply (reservoir sedimentation, abrasion of turbines etc.)

In alpine regions, electricity is highly generated by waterpower. Therefore, users of water power learned the following during the last decades:

- Increased awareness of sedimentation and erosion issues;
- Improved and sustainable management of soil and sediment resources;
- Better advice for policy development and implementation.

But they still face the following sediment related issues:

- Planning, construction and operation of water intakes (sedimentation, wood retention)
- Construction and operation of water power installations (choice of location, problems of accretion, wash out and erosion, bank protection measures)
- Infiltration and exfiltration.

Turbines work properly only when they are driven by clean water. Sand and finer material result in abrasion and damage.

2.1.3 Construction (use of sediments, dredging)

Since times immemorial river sediments have been used for construction purposes. Dredging sediments out of river beds is a common practice to gain this popular raw material. Dredging is done where apparently enough sediment is available. Disadvantages of dredging are lack of sediment downstream, which often results in increased bed erosion with damage of hydraulic works, walls, bridge foundation etc. In the Rhine basin, dredging permissions have been treated restrictively in recent times. In addition, construction of infrastructural works is also essential:

- Planning of road and railroad construction (culverts, river crossings);
- Planning, construction and operation of waterways for navigation and its infrastructure.

2.1.4 Other uses (habitat protection, recreation, environmental protection)

Natural river behaviour with altering river banks and rich variety of sediment transport favours the development of diverse fauna and flora. Natural river stretches are also popular recreation spots for locals. Therefore, some specific uses might require:

- Nature and landscape protection within the areas of influence of water;
- Treatment of accretion problems in shallow waters (fishery);

- Watershed management (reforestation, stabilization of slopes).

2.2 Stakeholders of large lowland catchments

Stakeholders of large lowland river systems have mainly the same interests and problems with sediment related issues as the population in alpine catchments. A supplementary function is navigation for example (Fig. 33), influenced by bed level alteration by erosion or accumulation of sediments.

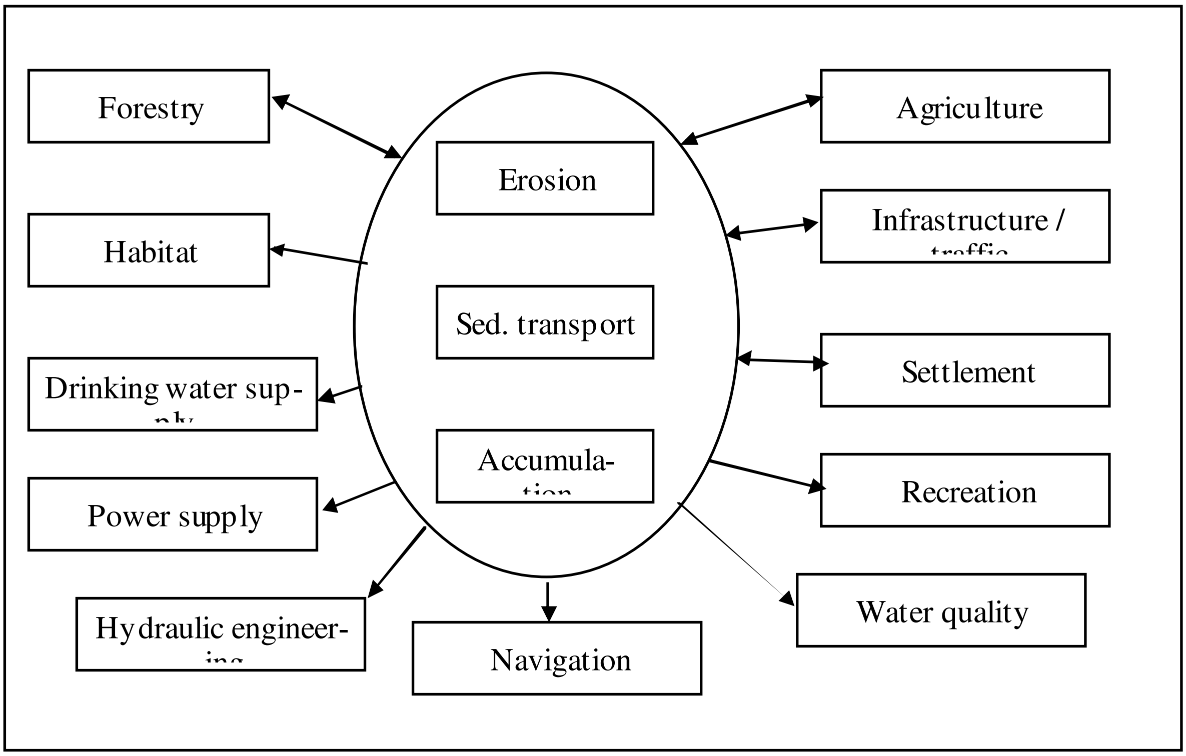


Fig. 33: Some of possible stakeholders in a lowland catchment; note that some relations are mainly one way relations (indicated by single arrow; altered after Owens et. al. 2004)

3 Problems related to sediment management

Problems that are faced by an efficient sediment management are described below. As sediment management varies depending on specific question formulations, the following differentiation is made:

- Torrents and small alpine watersheds;
- Large rivers at medium mountain range and lowlands;
- Lakes and reservoirs.

3.1 Torrents and small Alpine watersheds

Problem	Uses and solutions
1. Protection against damage • Risk detection and -evaluation • Flood protection by constructive measures • Protection of receiving waters • Assessment of sediment budget 2. Water conservation 3. Human impact • Intakes • Roads, paths • Watershed management • Dredging • Deposits 4. Research • Basic research • Applied research	Basic information to solve problems of planning, construction and operation in the following fields: Hydraulic engineering: • Stabilization works • Retention • Effects of torrents on their receiving waters Traffic routes • River crossings • Narrowings • Bridges Sanitary engineering • Intakes • Crossings • Water protection Hydropower utilization • Intakes • Sediment and wood retention Watershed management • Conservation and improvement of the capacity of the watershed by measurements of agriculture and forestry • Drainage, afforestation Landscape protection, planning of use and protection • Risk detection • Hazard mapping • Warning systems

3.2 Large river systems

3.2.1 Switzerland

Problems	Uses and solutions
1. Protection against damage • Risk detection and -evaluation • Flood protection by constructive measures • Protection of receiving waters • Assessment of sediment budget 2. Water conservation • Clogging 3. Human impact • Watershed use (e. g. road construction, bridges, power plants, infrastructure for navigation) 4. Research • Basic research • Applied research	Basic information to solve problems of planning, construction and operation in the following fields: River control Stabilization of river bed and banks regarding tributaries and dredgings Traffic • Roads and railways (river crossings, parallel tracks to rivers) • Structures for navigation (waterways and ports) Sanitary engineering • Intakes, crossings • Water protection • Water purification • Water infiltration and exfiltration (groundwater) Power plants • Sedimentation and flushing, and erosion problems • Bank protection Fishery Passive flood protection • Flood warning (incl. flood wave warning) • Evaluation of danger zones (risk evaluation, risk mapping)

3.2.2 Germany

Like other large European rivers the Rhine has been developed into an efficient inland waterway during the last two centuries. Training works and impounding by weirs have changed both flow and sediment transport. Due to impounding of the upper course and of the large tributaries, the sediment budget of the main river changed drastically. Today the free-flowing section of the river is characterised by a severe bed load deficit leading to bed degradation and falling water levels, whereas in the impounded section further upstream deposition of fine grained sediments occurs.

The economic and ecologic consequences of continuous bed degradation have been described by Gölz (1994). Outgrowing bedrock-sills at the river bed hamper navigation and falling water levels in the inland harbours force both lowering of the harbour bed by dredging and subsequent enhancing of the vertical harbour walls.

Water level lowering in the mainstream causes lowering of the water levels of the adjacent groundwater bodies in the flood plain such endangering the semi-terrestric fauna and flora of the flood plain. In addition, agriculture, forestry and groundwater management in the flood plain may be negatively concerned (Fig. 34).

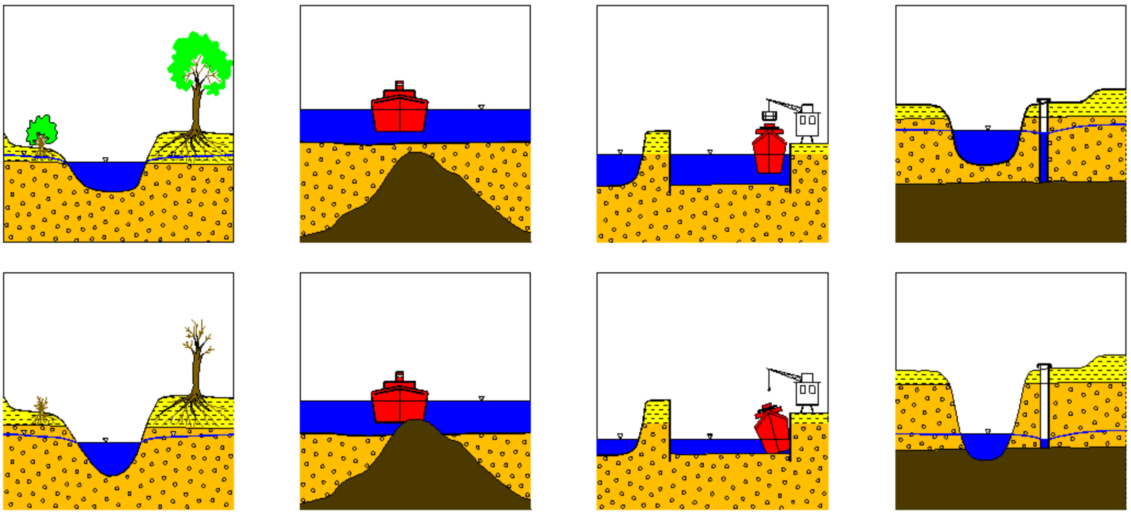


Fig. 34: Economic and ecologic consequences of bed degradation (BfG, 2008)

To stop bed degradation and to improve navigation, a strategy has been developed combining sediment management measures with conventional river training measures (Gölz 1994). Besides local dredging and re-dumping activities six major bed-load management measures primarily artificial bedload supply provide the base for achieving a dynamic equilibrium over a length of 530 km (BMV 1997). More details of this overall concept are described in the chapter Examples and in Gölz (2004).

In the impounded section of the Upper Rhine fine-grained sediments are deposited causing rising of bed and water levels (Gölz 1990; Vollmer and Gölz 2006). To ensure high flood discharge and the security of the dykes, the sediments have to be removed from time to time (Huber et al., 2004). Dredging and disposal, however, are a major problem as the sediments are in parts contaminated by hexachlorobenzene (Koethe et al. 2004). As has been shown by Witt et al. (2003), there is also the risk of remobilization of highly contaminated sediments during high floods.

In the future, due to climate change, the frequency and magnitude of high floods could increase (Asselman 1997; Kempe and Krahe 2005) and might influence sedimentation in the impounded section. Thus the development of strategies both to reduce dredging of sediments and to dispose them in an ecologically friendly and economically acceptable manner is one of the important tasks of sediment management at the Rhine waterway.

3.2.3 The Netherlands

Until the beginning of the 1990s, dredged sand taken from the river was sold for construction applications. Over a period of decades so much sand was eventually removed from the river that it exceeded the quantities supplied from upstream. Dredging was therefore the single biggest cause of falling riverbed levels in the upper reaches of the Dutch Rhine branches in the last century. At the end of the last century, falling riverbed levels caused increasingly more adverse consequences and the need steadily grew to slow down this process. Accordingly, the river manager decided that sand should no longer be removed from the river but should be dumped at deeper locations where it could do no harm. Naturally, it doesn't stay in one place. Deep-water locations do not arise by accident: the depth is caused by the flow present. Dumped sand is also eroded, therefore, and deposited in a sedimentation area somewhere else. Dredging and natural processes interlock and ensure that sand is continually circulated. This appears inefficient, but proves effective. Sand must remain in the system otherwise the riverbed level will continue falling. Moreover, shallows will continue to form, as they are a direct result of the river's flow pattern. It does not matter much, therefore, that the river manager must continually dredge the same sand. By skilfully choosing dump locations in relation to dredge locations, the river manager can keep dredging operations very limited.

3.3 Lakes

Problems	Uses and solutions
1. Protection against damage • Loss of volumes • Sedimentation 2. Water conservation • Clogging 3. Human impacts • Construction • Intakes of canals • Dredgings, earth deposits 4. Research • Basic research • Applied research	Basic information to solve problems of planning, construction and operation in the following fields: Hydraulic works • Planning of structures (weirs, channel design) Hydropower • Sedimentation • Sand deposits and abrasion of technical structures • Control of structures Fishery, traffic • Sedimentation of ports and water ways Water supply • Intakes • Sediment and wood retention Sanitay engineering • Supply of drinking water • Wear of pumps • Water intakes • Clogging of filters Energy supply • producing heat by heat pumps Recreation, sport Landscape and environmental protection

4 Necessary sediment observation

4.1 Switzerland

Sediment observations depend on the formulation of the question. The most common elements of sediment observation are lined out in the tables below. The tables include a list of most relevant processes, the influence on them by other factors, as well as considerations of human impact. A short outline of methods to qualify and quantify the processes is also included. Apart from the description of natural processes, methods to evaluate the processes are important as well.
Apart from methods, tools and devices enabling to qualify and quantify sediment processes and their effects, human interventions in sediment processes are an important component. Several categories of methods, tools and devices are therefore available, as there are among others (listing not complete):

Methods and tools:

- Assessment of sediment potential and sediment budget
- Sediment transport equations / programs
- Soil erosion assessment / calculation
- Mathematical / empirical models (rock fall, debris flows…)
- Risk assessment
- Remote sensing
- Chemical methods to prove pesticides, metals etc.
- Decision supporting systems (dss), such as GIS, excel programming etc.

The following sediment observations are again divided in torrent, river and lake observation.

4.1.1 Torrents

Sediment observations	Supplements
• Bed load • Bed load potential • Transportcapacity, (maximum bed load discharge) • Bed load discharge during floods • Bed load discharge graph • Grain size distribution during flood events • Bed load discharge of floods of different size (recurrence intervals) • Suspended sediment • Suspended sediment concentration • Relation between water discharge and suspended sediment concentration • Suspended sediment discharge • Sediment features • Grain size distribution • Grain shape and petrography	• Cross sections Longitudinal profiles of torrents and their changes with time • Flood traces • Accumulation volumes in and out of river bed • Volumes of landslides and bank erosion • Volumes of erosion in torrents • Waterquality • Channel roughness

Sediment observations	Supplements
• Specific weight • Bulk density of accumulations • Composition of material of debris flows • Wash load • Transported wood volume per flood event	

4.1.2 Rivers

Sediment observations	Supplements
• Bed load • Bed load potential • Transportcapacity, (maximum bed load discharge) • Bed load discharge during floods • Bed load discharge graph • Grain size distribution at flood events • Bed load discharge of floods of different size (recurrence intervals) • Suspended sediment • Suspended sediment concentration • Relation between water discharge and suspended sediment concentration • Suspended sediment discharge • Sediment features • Grain size distribution (as function of place, time and water discharge) of moving and laying bed load and suspended sediment • Grain shape and petrography • Specific weight • Bulk density of accumulations • Wash load • Transported wood volume per flood event	• River morphology • River shape (outlines) • Cross section • Bed shape (banks, Thalweg, etc.) and the changes by time including the features derived (Slope, accumulation and erosion volumes etc.) • River bed roughness • Water quality

Rhein – Diepoldsau, Rietbrücke

percentage (%)	granulometry (µm)
11,50	< 2
46,43	< 20
57,66	< 32
77,82	< 63
96,41	< 100

percentage of particles smaller than the particle size fraction indicated above

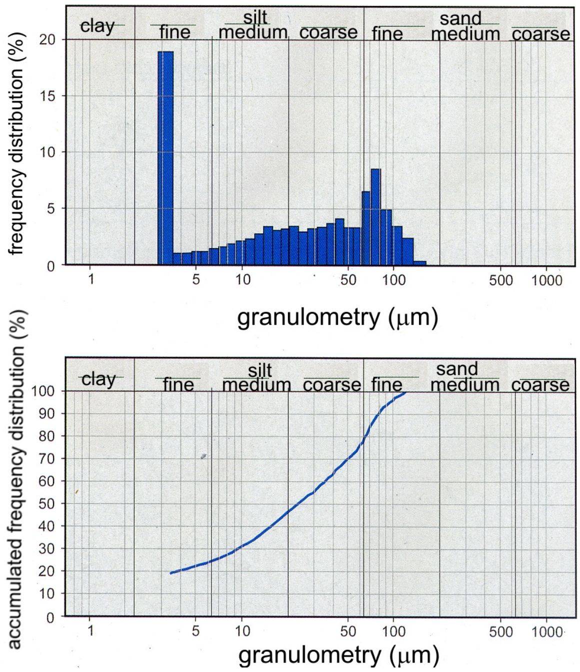


Fig. 35: Example of analysis of granulometry at the Rhine-Diepoldsau monitoring station in Switzerland (Spreafico et al. 2005, 92)

Tab. 8: Suspended sediment yield in Switzerland (Spreafico et al. 2005, 62)

Station	Average annual sediment yield (1000 t)	Variability from … to (1000 t)	Maximum	Factor max/min	Observation period
Aare - Brienzwiler	136	46-574	1991	12	1979-1999
Arve – Geneva	816	292-3056	1992	10	1979-1999
Emme – Wiler	52	8-122	1988	15	1985-1999
Lanquart - Felsenbach	935	215-3450	1999	16	1979-1999
Linth – Mollis	146	55-304	1993	6	1979-1999
Lonza – Blatten	26	5-74	1979	15	1979-1999
Lütschine – Gsteig	130	56-204	1999	4	1979-1999
Reuss – Mühlau	148	50-385	1980	8	1979-1999
Reuss – Seedorf	86	29-205	1988	7	1979-1999
Rhein – Diepoldsau	2809	798-8691	1999	11	1979-1999
Rhône – Porte du Scex	1923	992-3125	1994	3	1979-1999
Thur – Halden	151	19-316	1999	17	1979-1999
Ticino - Bellinzona	241	10-1651	1987	165	1979-1999

Fig. 35 shows an example of granulometry analysis of samples taken in July 1993 at the Rhein-Diepoldsau monitoring station. It shows a high percentage of fine silt material, which mounts up to 20% of the entire sample. Tab. 8 indicates values of average annual sediment yield at 13 Swiss monitoring stations. Variability of sediment yield is as expected quite high and corresponds besides other parameters of influence also with uncertainties in monitoring methods and interpretation.

4.2 The Netherlands

By far the greater part of the measurements of the Dutch Rhine's physical characteristics can be divided into three clusters: measurements of the riverbed level, measurements of the water movement and measurements of sediment transport. These measurements are elucidated in the book "The Dutch Rhine – a restrained river" by Ten Brinke (2005). The text below is taken from this book.

Measurements of the water movement are related to the water level, discharge and flow rate. To measure the water levels, water level recorders at various places along the river have been used for several centuries. These used to be read by people, but nowadays this happens automatically. Daily, in principle, or even several times a day. The discharge is also measured automatically at several locations. Moreover, in particular during floods, measuring campaigns are organised to determine the discharge in the various Rhine branches simultaneously. In this way, field information is obtained about the distribution of water among the Dutch Rhine branches during floods. By determining the relationship between the measured discharge and water levels at these gauging stations, it is possible to calculate the discharge based on the water level, thanks to these ratios, even at times when no discharge is measured.

In order to calculate the total discharge throughout a cross section of the river (a measuring cross line) the discharge must be monitored at various places in this cross section. In the past, this was done with instruments, with which the number of revolutions per time unit of a propeller would indicate how fast the water flowed and therefore how high the discharge was. A ship would have to drop anchor at various positions in the cross section of the river and measure the flow with the instrument at various depths. Nowadays, this is done much more quickly thanks to the invention of an instrument that measures the flow rate by means of sound waves (the Acoustic Doppler Current Profiler ADCP). The velocity of the water, and therefore the discharge at various positions in the cross section, can now be monitored while sailing. One only needs to sail across the river up and down a few times to know the discharge at that place. Sometimes the discharge is not as interesting as the details about the flow, such as close to the bottom of the river. In that case, other instruments are selected, specially developed for this type of detailed studies.

4.2.1 Lakes

Sediment observations	Supplements
• Sediment in- and output	• Soil mechanic parameters
• Sediment load (to be determined in in- and outflowing rivers)	• Origin of sediments:
	• Rivers
• Bed load	• Bank erosion
• Delta survey	• Rockfall
	• Landslides
	• Avalanches
• Suspended sediments	• Dust fall
• Suspended sediment concentration (as function of time and space)	• Artificial earth deposits and intakes
• Turbidity profiles	• Chemical and biogenic production
• Composition of suspended sediments (grain size distribution, organic / inorganic, chemical / mineralogical, clastic)	• Dredgings
	• Survey of extraordinary events
	• Bathymetric surveys, delta formation
• Features of adsorption	• Sediment budget of catchment area
	• Water quality
• Sediments	• Turbidity measurements
• Sedimentation rate	• Flow measurements
• Volume change by redeposition and diagenesis of sediments	
• Grain shape and petrography	
• Composition of suspended sediments (grain size distribution, organic / inorganic, chemical / mineralogical, clastic)	
• Wash load	
• Transported wood volume per time	

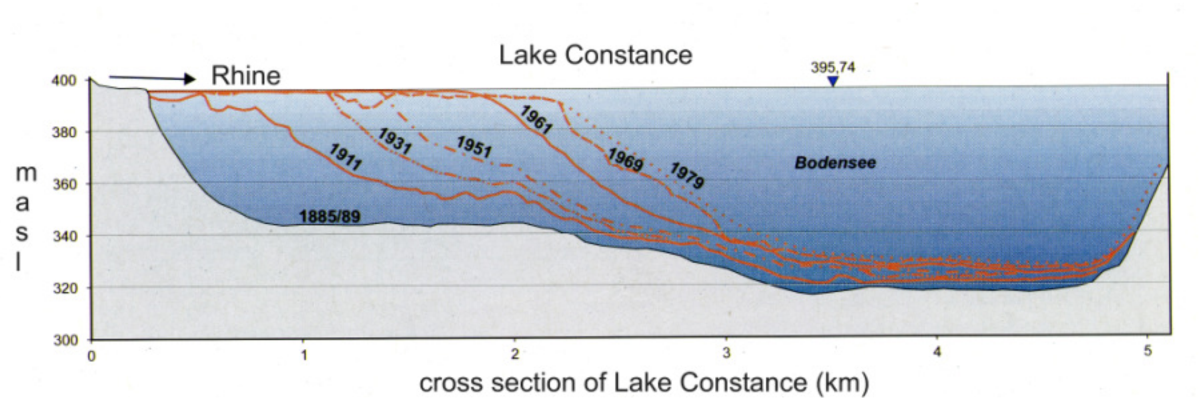


Fig. 36: Development of the Rhine delta into Lake Constance 1885 – 1979 (Spreafico et al. 2005, 66, after Lambert 1989)

Fig. 36 shows an example of delta survey in Lake Constance. Regarding delta growth, the average annual sediment volume transported by the Rhine is 3 Mio. m^3 from 1911 to 1979. Since 1979, unfortunately no survey has been executed any more.

In The Netherlands there is no regular sediment observation program. Only the level of the (summer) riverbed is measured each year with a multibeam loding system. Occasionally, research projects have been organized to understand the sediment phenomena better. For instance, to understand the morphological behaviour of the bifurcations and the morphological response of bed stabilization works.

4.3 Reservoir Sedimentation

4.3.1 The Problem of Reservoir Sedimentation

All lakes created on natural rivers are subjected to reservoir sedimentation. The construction of a dam significantly modifies the flow conditions of natural streams inside and downstream of an artificial lake. Sediments are generally considered an undesirable but unavoidable consequence of water storage. A modern approach to the design of reservoirs should consider rivers as sources not only of water but also of solid elements in the form of bed-load and suspended matter. The natural water-sediment equilibrium is substantially modified by the creation of a reservoir. Sediment deposition in reservoirs reduces storage capacity, and poses risks of blockage of intake structures as well as sediment entrainment in hydropower schemes. Lack of sediment, in that case mainly bed-load, affect the downstream river and its banks and accelerated erosions may occur, especially during larger floods with high sediment input into the reservoir, but only high water output (after flood routing) from the reservoir.

Although the aim behind the efforts to create reservoirs is storing water, other substances are carried along by the water and are usually deposited there. This is a result of dam construction, dramatically altering the flow behaviour and leading to transformations in the fluvial process with deposition of solid particles transported by the flow (Chella et al. 2003). Each reservoir created on natural rivers, independent of its use (water supply, irrigation, energy or flood control), can have its capacity decreased due to deposition over the years. In an extreme case, this may result in the reservoir becoming filled up with sediments, and the river flows over land again.

A reservoir, like a natural lake, silts up more or less rapidly. In actual fact, reservoirs may completely fill with sediments even within just a few years, whereas natural lakes e.g. in Alpine foreland, may remain as stable features of the landscape for as much as 10'000 or 20'000 years after they were formed during the last Ice Age. Reservoir sedimentation reduces the value of or even nullifies the dam construction investment. The use for which a reservoir was built can be sustainable or represent a renewable source of energy only where sedimentation is controlled by adequate management, for which suitable measures should be devised. Lasting use of reservoirs in terms of water resources management involves the need for desedimentation.

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

4.3.2 Consequences of reservoir sedimentation

Declining storage volume reduces and eventually eliminates the capacity for flow regulation and with it all water supply, energy and flood control benefits, International Committee on Large Dams (ICOLD 1989). Reservoir sedimentation can even lead to a perturbation of the operating intake and to sediment entrainment in waterway systems and hydropower schemes (Boillat et al. 1994, Schleiss et al. 1996, De Cesare 1998).

Depending on the degree of sediment accumulation, the outlet works may be clogged by the sediments. Blockage of intake and bottom outlet structures or damage to gates that are not designed for sediment passage is also a severe security problem (Boillat and Delley 1992, Schleiss et al. 1996). Other consequences are sediments reaching intakes and greatly accelerating abrasion of hydraulic machinery, decreasing their efficiency and increasing maintenance costs (Boillat and Delley 1992).

4.3.3 Sedimentation rate

There are no accurate data on the rates of reservoir sedimentation worldwide, but it is commonly accepted that about 1 – 2% of the worldwide storage capacity is lost annually (Jacobsen, 1998). A detailed collection of sedimentation rates in regions all over the world can be found in Batuca and Jordaan (2000). The evolution over the last century and the predicted future development of the volumes of water-storage capacity lost due to reservoir sedimentation and the volumes of installed water storage capacity in the world are presented in Fig. 37. Bearing in mind that the annual increase of storage volume due to the construction of new reservoirs is close to 1%, the problem of sustainability becomes apparent (Oehy et al. 2000). If there are no effective measures taken before the end of the 21st century, the major part of the worldwide useful volume will be lost.

The sedimentation rate of each particular reservoir is very variable. It depends more particularly on the climatic situation, the geomorphology and the conception of the reservoir including its outlet works. Based on an analysis of data of 14 reservoirs, Beyer Portner (1998) showed that on average in Switzerland only about 0.2% of the storage capacity is lost annually due to sedimentation (Fig. 37). The lower sedimentation rate in the Alps is due to the geologic characteristics, mainly rocky mountains, of the catchment areas at high altitudes (Oehy 2003).

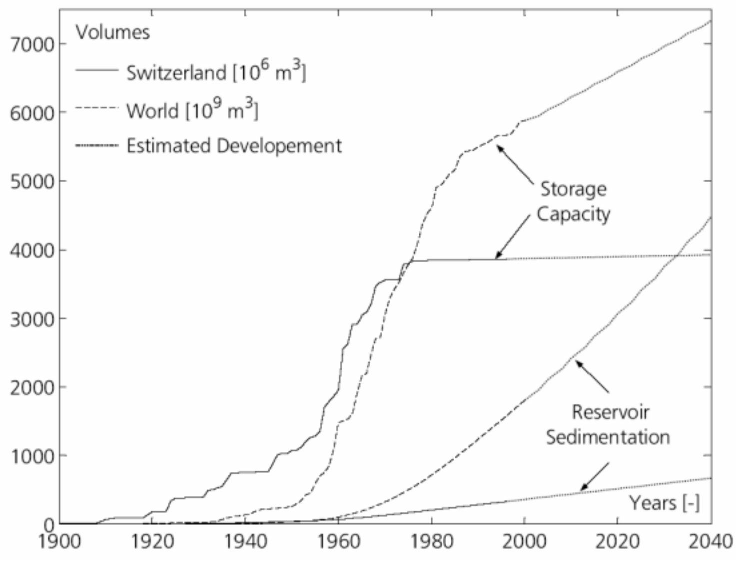


Fig. 37: Increase of the reservoir capacity by the construction of new dams and storage volume loss by sedimentation worldwide and in Switzerland, after Oehy (2003)

4.3.4 Reservoir sedimentation by turbidity currents

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

4.3.5 Measures against reservoir sedimentation

There is a strong need to limit sediment accumulation in reservoirs in order to ensure their sustainable use. Management of sedimentation in Alpine reservoirs cannot be apprehended by a standard generalized rule or procedure. Furthermore, sediment management is not limited to the reservoir itself, it begins in the catchment areas and extends to the downstream river. Every situation has to be analysed for itself in order to determine the best combination of solutions to be applied. The possible measures are summarized in Fig. 38 and grouped according to the areas where they can be applied:

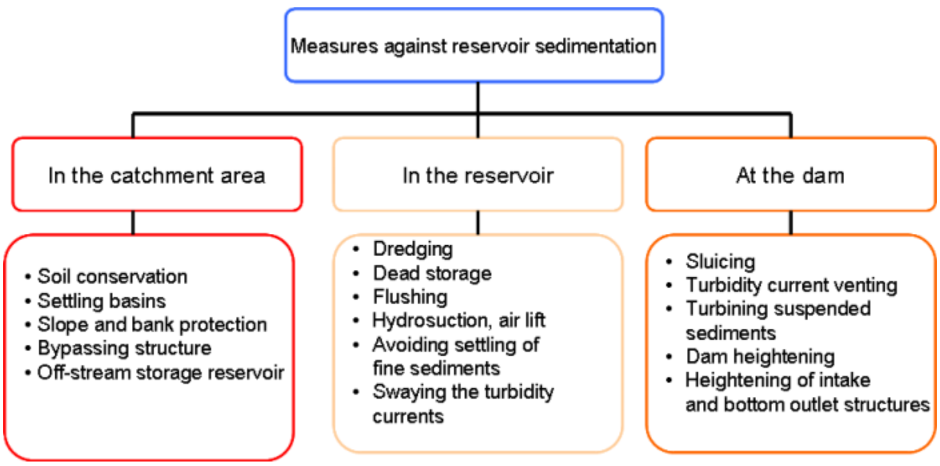


Fig. 38: Inventory of possible measures for sediment management (Schleiss and Oehy, 2002)

A sustainable sediment strategy should also include the downstream reaches; therefore monitoring data should also include downstream impacts as well as sedimentation processes in the reservoir (Morris and Fan 1997).

4.3.5.1 Measures in the catchment area

Soil conservation: A reduction of sediment yield by soil conservation in the catchment area can be very effective, and can solve the reservoir sedimentation problem in a sustainable way. Where the climatic conditions allow vegetation practices, the soil can be protected from erosion by afforestation or vegetation screens. However, these measures are very complex and often related to other agricultural techniques. In catchment areas, erosion protection can only be achieved with engineering measures such as gully control, as well as slope and bank protection works on rivers (Oehy 2003).

Settling basins: Settling basins are often constructed in the catchment area to limit gully erosion. The small size dams trap only the coarser sediment particles and the sediment load quickly builds up again downstream. Therefore, this measure has rarely a major impact on the sediment yield. The construction of such debris trap dams in the upper catchment areas may be a solution; but without proper regular maintenance, these will fill up by bed load transport very quickly and in the long term they serve no purpose. A further problem with upstream sediment trap dams is finding a place for continuous, long-term disposal of the incoming sediments, which accumulate indefinitely. Often the settling basins are also too small to significantly affect the sediment yield into the reservoir.

By pass tunnels: Worldwide, limited numbers of sediment bypass tunnels have been constructed because of topographical, hydrological or economical conditions. Bypass tunnels, however, have many advantages such as they can be constructed even at existing dams and prevent a loss of stored reservoir water caused by the lowering of the reservoir water level. They are also considered to have a relatively small impact on the environment downstream because inflow discharge can be passed through tunnels very naturally during flood time (Sumi 2004).

4.3.5.2 Control of sedimentation within the reservoir

Dead storage: The most common method to conserve the storage capacity is to oversize reservoirs, i.e. to keep some of the impoundment available for sedimentation. In case this volume is not available for reservoir operation, it is called dead storage (Schleiss and Oehy 2002).

Obstacles, screens, water jets and bubble curtains for controlling turbidity currents: In a case study in Lake Grimsel, the possibility of influencing the turbidity current with submerged dams was evaluated with numerical models (Oehy 2003). The result showed that due to the blocking effect of the dam, the sediments can be retained efficiently and sediment deposits in the area of the intake and bottom outlet structures can be prevented.

Flushing: Sediment Flushing is a technique whereby previously accumulated and deposited sediments in a reservoir are hydraulically eroded and removed by accelerated flows created when the bottom outlets of the dam are opened. Flushing can be classified into flushing under pressure and free-flow flushing. During flushing under pressure water is released through the bottom outlets while the water level in the reservoir is kept high. For free-flow flushing the reservoir is emptied and the inflowing water is routed through the reservoir, resembling natural riverine conditions. If flushing is carried out under pressure, only a very limited area in the reservoir is cleared (Schoklitsch 1935, ref. Brown 1943). Free-flow flushing can transport a much greater sediment load (sometimes even consolidated sediments) than flushing under pressurized conditions.

Flushing is often associated with a host of adverse environmental impacts. Generally, flushing methods must be chosen with the aim of limiting the impact of the downstream reaches of the river (OFEFP 1994). Moreover, legal requirements may restrict or prohibit the practice of removing solids from surface waters and reintroducing them into the flow at a later time (Suter 1998; Boillat and Pougatsch 2000).

Hydrosuction: Hydrosuction systems remove deposited sediments by using the available energy head due to the difference between water levels upstream and downstream of a dam. These techniques try to return the system to more natural pre-dam conditions by releasing sediments in accordance with the downstream transport capacity.

The pumping device is equipped with a drill head in order to facilitate the disintegration of the deposits. The volume of the pumped mixture will normally be conducted in decantation basins. It can also be diverted into the downstream river, with a controlled discharge.

Dredging: One obvious alternative to flushing or routing sediments through a reservoir is underwater dredging or dry excavation of the deposited material. The drawback of dredging is the high cost for sediment removal, but as reservoir level drawdown for flushing and sluicing may not solve all sediment-related problems, the impounded reach will need to be dredged due to continued accumulation of gravels (Morris and Fan 1997). Dredging requires less drawdown of the reservoir water level. Another concern is the deposition of the sediments after dredging. Depending on the legal framework, deposition of the sediments stored over years in the reservoir is not permitted or shouldn't be done because of ecological matters. Returning them into the downstream part of the river is delicate since eventually polluted sediments are not appropriate for an ecological system and the concentration is still difficult to control.

Furthermore, muddy lake deposits mainly composed of silt and clay are not easy to remove or use because of their high water contents and organic matter contents.

4.3.5.3 Measures at the dam

Sluicing: During sluicing of sediment, the water level in the reservoir is drawn down to allow for sediment-laden inflow to pass the reservoir with a minimum of deposition. Typical of sluicing in a flood-detention reservoir is that during a rising water level of a flood the out flowing sediment discharge is always smaller than that of the inflow. During the lowering of the water level, the out flowing sediment discharge is greater than the inflow, due to erosion in the reservoir (Fan 1985). Since inflowing sediment concentration during a flood tends to be highest during the rising limb of the hydrograph, the reservoir can be filled with less turbid water following the flood peak (Fan and Morris 1992). Sluicing operations should be timed to accommodate the higher sediment concentrations brought in by flood flows. By opening bottom gates fast enough, the rate of the increase of the outflow can be made equal to the rate of increase of an incoming flood. The detention effect and the least alteration of the hydrograph of the sediment are then minimized. Thus, the sediment outflow approaches the natural flow condition. Sluicing is successful if the capacity of the outflow structures is adequate, the operation is done judiciously, the river is transporting mainly suspended sediments and the flow hydrograph is predictable with confidence at the dam site (Basson and Rooseboom 1997).

Turbidity current venting: Venting of density currents means that the incoming sediment-laden flow is routed under the stored water and through the bottom outlets in the dam. Since the reservoir may stay impounded during the release of density currents, this method is widely used in arid regions where water is in shortage. Fan and Morris (1992) suggested that density-current venting may be well suited at large reservoirs with multiyear storage capacity where drawdown is unwanted. Venting operations have much better chance of accomplishing their purpose when they are timed to intercept gravity underflows as they reach the dam. The correct timing of opening and closing gate is very important. Either a too late sluice operation or too small opening of the sluice gates will result in a smaller amount of sediment discharged out of the reservoir. In the contrary, if the gate is opened too early or the opening is too large, loss of valuable water occurs (Chen and Zhao 1992). The capacity of the bottom outlets has to be high enough to allow turbidity current venting, i.e. at least in the range of the incoming flow.

Heightening of dam, intake and bottom outlet structures: The heightening of a dam and its outlet structures is one of the alternatives for compensating for the loss of reservoir capacity due to sedimentation. Although it might be cost effective in the mid term, dam heightening does not provide a sustainable solution of the sedimentation problem. Construction of new dams to solve the sedimentation problem in the future leads to the same problems. Finally, with the heightening of the intake and bottom outlet structures the dead storage volume is increased and sediment entrainment into the intakes can be prevented for a certain period.

4.3.6 Todays's needs for an approach for Reservoir planning

Sediment removed by flushing affect furthermore the downstream river by the concentrated release of sediment that had been accumulated over a long period compared to the flushing duration. Reservoir sedimentation management is therefore not only desirable for the conservation of storage capacity and reservoir exploitability, but also from the angle of downstream river stability and ecology.

The planning and design of a reservoir require the accurate prediction of sediment yield, transport, erosion, deposition, remobilisation and release. For existing reservoirs knowledge is needed to better understand and solve sedimentation problems, and hence improve reservoir operation.
Most of the existing artificial lakes are still not operated in a sustainable way. With the current knowledge and technology, it is possible for future hydropower project with storage reservoirs to be operated more efficiently and productively, ensuring their sustainability.
As a recommendation, the authors propose to consider all the aspects related to reservoir sedimentation for any new hydropower project. The necessity of sustainable sediment management was neglected for a long time, the knowledge of the decisive erosion, transportation and deposition processes, which lead to reservoir silting-up, were only barely known or ignored before 1950. Neglecting the nowadays known and understood fundamentals of reservoir sedimentation management methods and techniques is hardly understandable and uneconomic for any new hydropower project.

4.3.7 Examples

4.3.7.1 Obstacles: Submerged Dams in Lake Grimsel

Introduction
In Lake Grimsel, in Switzerland, an ongoing design project consists of heightening the two existing dams by 23 m (Spitallamm Arch Dam 114 m; Seeuferegg Gravity Dam 42 m). The excavation and demolition works necessary for the planned heightening generate approximately 150'000 m^3 of rock material. This large amount of materials has to be stored somewhere near the construction site. This led to the idea of building some kind of obstacle in the form of a submerged embankment dam to prevent sediment deposition due to the turbidity currents in the area near the intake structures. A case study is presented to investigate the occurrence and impact of turbidity currents on the reservoir sedimentation and to check the efficiency of such submerged obstacles to retain the sediments (Fig. 39; see also Oehy und Schleiss 2001).

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

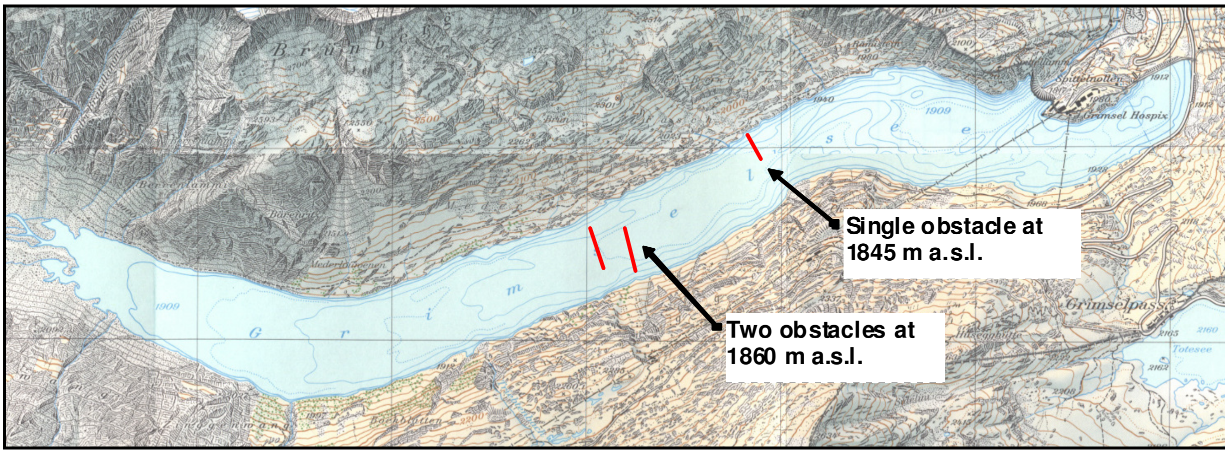


Fig. 39: Overview of the investigated obstacles in a 1:25'000 map (De Cesare 2008b)

Experimental studies were conducted to get basic knowledge in respect to turbidity currents facing obstacles. Based on this fundamental research, on former studies with field measurements (De Cesare 1998) and on bathymetric measurements of the reservoir and on the initial, topographical map of the valley, numerical simulations have been conducted. For the inflowing boundary condition (turbidity current) a hydrograph in the form of an asymmetric bell corresponding to the statistical distribution of Maxwell was introduced.

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

The canyon with the negative slope causes a slowing down of the current and deposition takes place upstream of this place. After passing the ridge the current accelerates again and finally dies out in the deepest area of the lake with maximum deposit heights of approximately 0.10 m. The turbidity current develops with increasing sediment and water discharge. After the peak the driving force of the current decreases and the turbidity current starts to die out until it finally disappears after 84 hours. The concentration decreases continuously from the inflow to the deepest area.

Turbidity current passing over submerged dams
To prevent reservoir sedimentation in the deepest area close to the intake and bottom outlet structures, the efficiency of submerged obstacles was numerically investigated. Two possible configurations for these obstacles were evaluated. The first configuration consisted of a dam, 15 m high and 150 m long, situated upstream of the canyon in a counter-slope of the lake. The second configuration consists of two submerged dams placed in the middle of the lake one after each other in a displaced manner, so that the current needs to turn around or overflow them. In this case, the height of the two dams was 10 m with a length of 210 m each. Both configurations do not extend over the whole width of the valley to keep a free passage for the water flow during emptying of the reservoir. To simulate the obstacle, a thin surface has been introduced in the grid. This surface is assumed to be located between control volumes and allows setting wall boundary conditions on this patch.

The obstacle clearly blocks the flow and reflects the major part of the turbidity current. A considerable amount of sediment deposits occurs, therefore, upstream of the obstacle.
Some of the fluid of the turbidity current flows over the obstacle while a bore will be reflected. The same observations were made in the numerical simulation of the flow over the submerged dams (Fig. 40). Bores travel upstream as was observed in the physical experiments and their numerical simulation. The retention volume upstream of the obstacle is slowly filled with the turbid fluid until it starts overtopping. Because the dam does not block the valley completely a small part of the current continues also flowing around the obstacle.

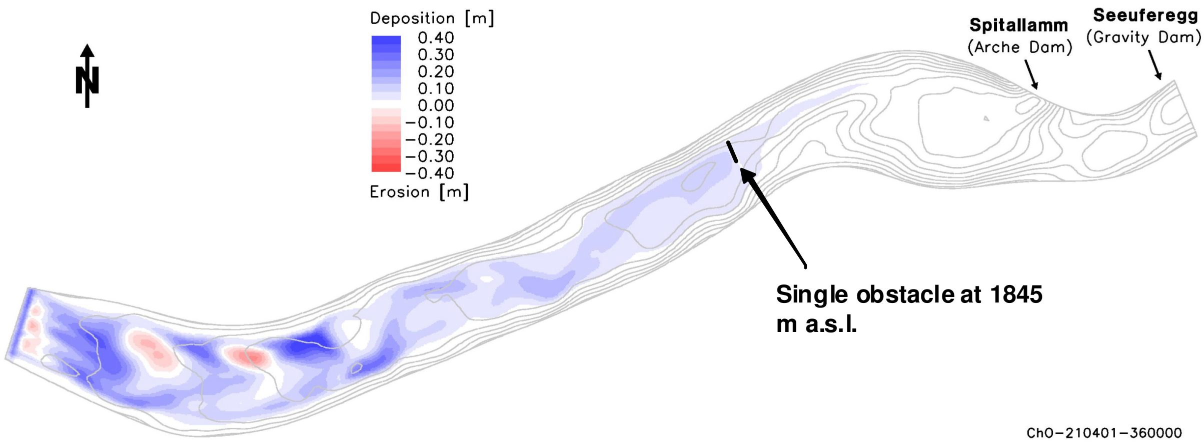


Fig. 40: Sedimentation after the flood in October 2000 (40 m^3/s and 15 g/l) with a single obstacle at 1845 m a.s l. (De Cesare 2008b)

Conclusions

The turbidity current flow over the complex topography of Lake Grimsel shows that significant amounts of suspended sediments are transported to the deepest area of the reservoir, where they settle down. For a single flood event these deposits attained approximately 10 cm in height. The effect of an embankment dam, built of demolition and excavation materials from the heightening of the Grimsel dams, was investigated. In agreement with the physical experiments, it is found that the height should at least extend to twice the height of the approaching turbidity current to block the flow efficiently. A height of the dam of 15 m is sufficient and ensures that the elevation of the dam crest is below the minimum operation level of the reservoir. It is estimated that the retention of sediments behind the dam lasts for at least 20 to 50 years.

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

4.3.7.2 Venting: Hydro Power Sarganserland

Müller (2007) studied the sedimentation problem of the Kraftwerke Sarganserland (see Fig. 41). He aimed to find economically and ecologically feasible measures that could be taken to prevent sedimentation. As part of his study the following areas were treated: Analysis of the bathymetric measures and the annual sedimentation, analysis of the turbidity measurement data, identification of possible measures to prevent sedimentation and development of a concept for venting turbidity currents in Mapragg.

The sedimentation volume in the two reservoirs at the hydroelectric operation "Kraftwerke Sarganserland" increases annually by 75'000 m^3, which is equal to a loss of 0.2% of the volume of the reservoir Gigerwald and 0.4% of the reservoir Mapragg. The main problem is the increasing level of the sediments close to the bottom opening at the dam. In Mapragg the sediments are already above the base level of the bottom outlet. Turbidity measurements have shown that the main solid inflows occur during a few heavy rain events in the summer. In

Mapragg several turbidity currents were measured, which transported solid material to the foot of the dam. Applying this knowledge, possible measures to prevent sedimentation were checked and compared. As an immediate measure for Mapragg, venting of turbidity currents was recommended and a concept to do so was implemented. For Gigerwald the automation of the water intakes in the Weisstannental will have to be installed quickly, so that during flood events water with high suspension concentration levels will no longer be taken and diverted to Gigerwald.

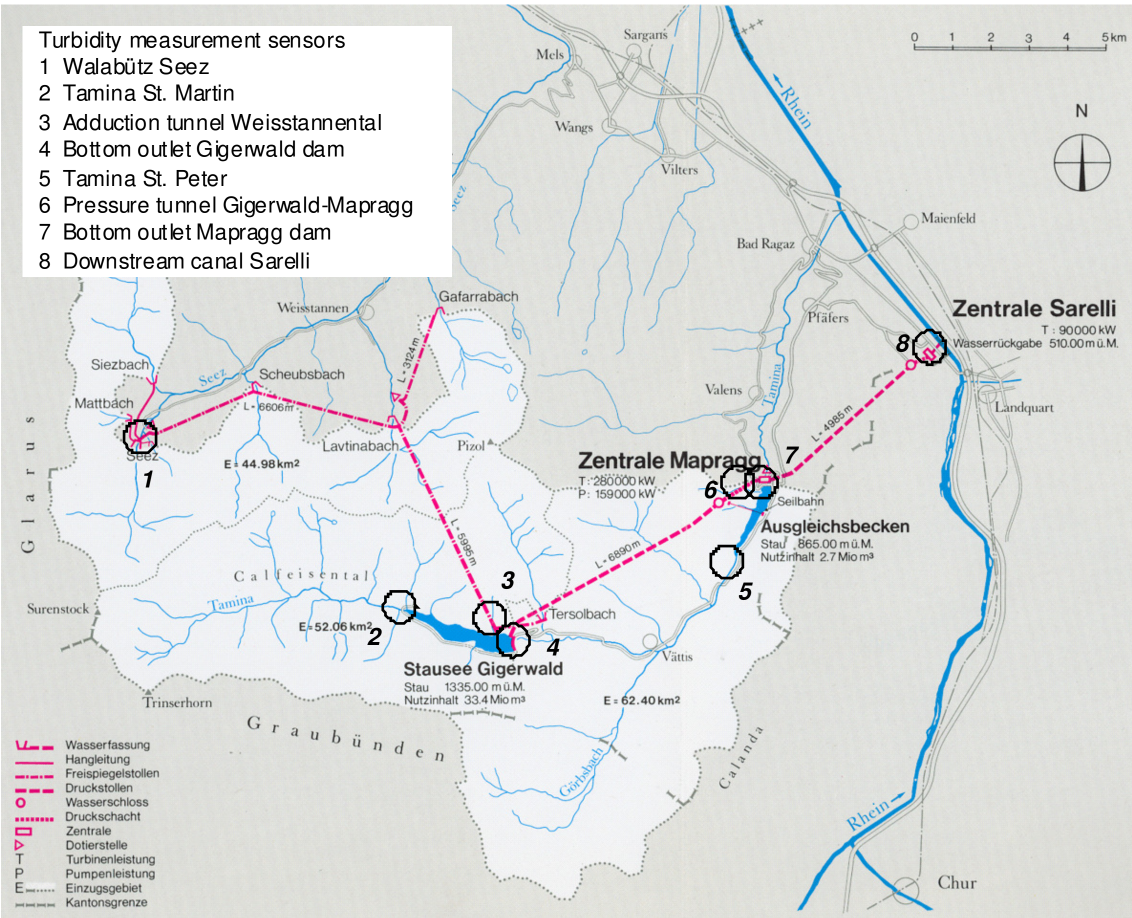


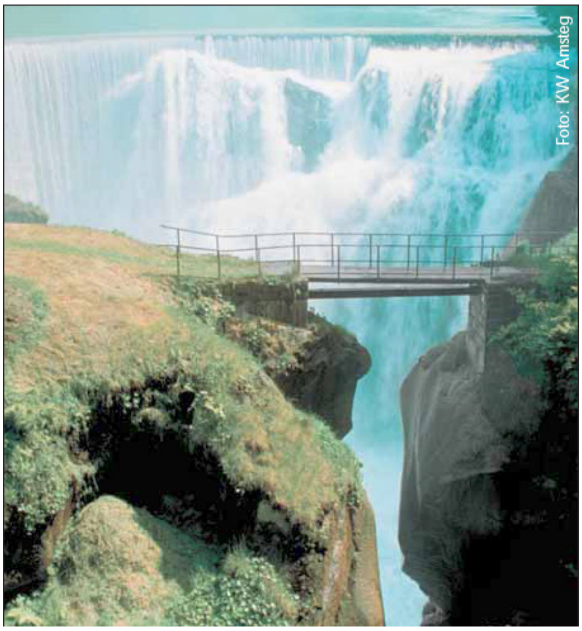
Fig. 41: Layout of the hydroelectric operation at "Kraftwerke Sarganserland" and locations of the turbidity measurement sensors (De Cesare 2008b)

4.3.7.3 Bypass-tunnel: Pfaffensprung

The hydroelectric power plant of Amsteg was put into service in 1922, by the Swiss Federal Railways. It is located in the Reuss valley, on the northern Swiss Alps. Water enters the Amsteg scheme at the compensation basin Pfaffensprung, at an elevation of 807 m a.s.l. Its volume is only 170'000 m^3 retained by a masonry arch-dam built in a narrow gorge.

Because of the large summer discharges and the limited capacity of the Amsteg power plant, a significant portion of discharge is then diverted. To avoid sediment transport to the power plant an auxiliary dam upstream from the basin was erected, with a 280 m long diversion tunnel on its left bank. Further, because the waters may rise rapidly in this region, the tunnel was designed so as to transport the mixture of water and sediment. Sometimes, the discharge can come up to hundreds of cubic meters per second, with thousands of tons of sediment during one event. The tunnel has thus to perform satisfactorily in terms of intake capacity, sediment diversion and deposition. Note that the tunnel did not serve for diversion during construction, because a second tunnel located at the right side of the valley was available.

a)



b)

Fig. 42: View on the Pfaffensprung dam a) from upstream and b) from downstream (Picture: KW Amsteg) (De Cesare 2008b)

Except for the 35 m long inlet portion, the tunnel has a cross-section of horse-shoe shape, with an area of 21 m^2, and a bottom slope of 3%. The capacity of the tunnel is 220 m^3/s, the velocities are between 10 and 15 m/s. The tunnel entrance provides two guard gates each 5 m wide. The inlet portion previously referred to contain an acceleration reach with a difference of 6 m height over 35 m, and a width reduction from 10 to 5 m. The entrance cross-section is 66 m^2 and this configuration allows a suitable hydraulic performance of the tunnel. Due to the extremely restricted covering of parts of the right tunnel side, an asymmetrical cross-section was retained with a definite tilt toward the mountainous side, to resist the unbalanced external forces – obviously a world première for diversion tunnels. Despite the geometrical complexity of the design, the construction performed well over the years. The tunnel ends at a small granite cliff integrated into the left-hand side buttress of the dam, where the water falls into the gorge. The tunnel was lined with granite blocks to resist abrasion by quartz sands that are transported in large quantities. Such precaution has turned out significant because abrasion was a major concern for the diversion tunnel.

Except for abrasion problems, the Pfaffensprung diversion tunnel has performed satisfactorily during the past 75 years. It will remain a key structure of the Amsteg scheme in the future and the designers are confident of its effective performance (Vischer et al. 1997).

4.3.7.4 Bypass-tunnel: Runcahez

The storage basin Runcahez serves as connecting link between the two power plants Sedrun and Tavanasa of the Vorderrhein power scheme in Eastern Switzerland. It is fed by the free surface tunnel from the power station Sedrun, and the 50 km^2 catchment area. The basin has a volume of 436'000 m^3 and is controlled by a 35 m high and 180 m long gravity dam. The dam has two overflow structures each 14 m long, and two bottom outlets, such that the 1000 year flood of Q = 350 m^3/s can be controlled. The bottom outlets with a total capacity of 60 m^3/s serve for both emptying the basin and flushing the reservoir, in addition to flood diversion.

To counter reservoir sedimentation, in the year 1962 a diversion tunnel along the right valley side was provided, which passes the bed load from the Somvixerrhein around the compensation reservoir of Runcahez (Fig. 43). Its length is 572 m and the horse-shoe section has a width of 3.8 m and a height of 4.5 m. The tunnel is lined with concrete, and its capacity is 110 m^3/s. If the bottom outlets would not be available during flood periods, the 1000 year flood could also be diverted by adding the tunnel. The transported bed load has an average diameter of 0.23 m and a maximal grain diameter of 1.2 m. It is chiselled resp. scarcely rounded and has high quartz content. The tunnel is subject to abrasion (Jacobs et al. 2001). A concrete groyne spanning over the entire delta region directs the flow to the intake of the diversion tunnel. Normally the tunnel entry is closed by a sector gate, and all the water flows into the compensation reservoir. Once the discharge rises above Q = 30 m^3/s, the armoured river bed is ripped and an enormous bed load transport is induced. During flood events the gate is completely open, and the whole Somvixerrhein is conducted as a free surface flow through the by-pass. After 30 years of operation, the diversion tunnel has successfully served during floods and for sediment transport. Normally the tunnel was in operation for several days per year during the flood periods (Vischer et al. 1997).

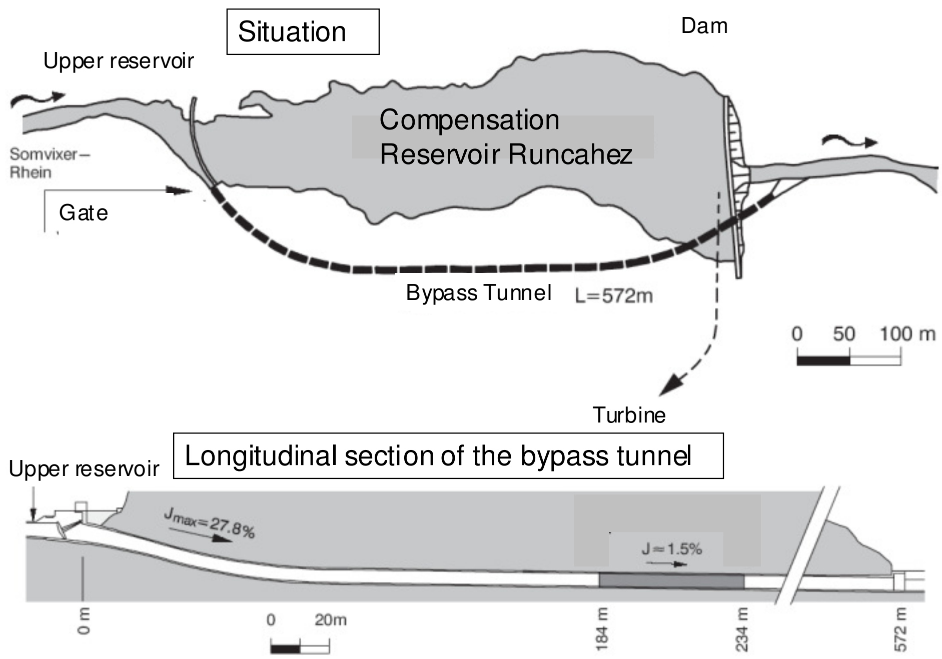


Fig. 43: Situation of the reservoir with bypass tunnel and longitudinal section of the bypass tunnel (De Cesare et al 2008a)

4.3.7.5 Sediment evacuation through power intake: Gübsensee

The diurnal reservoir Gübsensee was built from 1898 to 1900. The natural cavity in "Gübsenmoos" was extended by the construction of two earth-dams and one gravity-dam. The reservoir is fed by two collectors, bringing water from the rivers Sitter and Urnäsch (Fig. 44). At each inlet a sand trap eliminating the coarse sediments is installed. Fine sediments, however, attain in suspension the lake, where they settle down. Bathymetric records of the years 1976, 1997 and 2007 show locally a volume loss of up to 50 % compared with the original lake topography. The deposits are mainly registered in the areas of the two collector inlets, the water intake and the bottom outlet. These deposits were locally dragged and redeposited in the western part of the lake. The whole sediment quantity takes 25% of the original reservoir volume.

The last bathymetric record, executed in the year 2007, revealed that during the last 10 years more than 100'000 m^3 were deposited. In October 2007, during two weeks an experiment has been carried out, evacuating the sediments through the turbines. Fine sediments were led to the power station Kubel, characterized by an installed capacity of 13.5 MW, a maximum discharge of 18 m^3/s and an average head of 90 m.

The experiment highlighted that in case of small reservoirs at any rate there is a potential of such evacuation methods leading to a sustainable sediment management (De Cesare et al. 2008). In order to transit the suspended sediment load to the power intake, the flow between the galleries outlets and the power intake should always exceed the critical velocity as a function of particle grain size. Numerical simulations showed, that by means of guiding islands in Gübsensee Lake, nearly 50% improvement of flow efficiency distribution and thus expected less sediment deposits on the way may been reached.

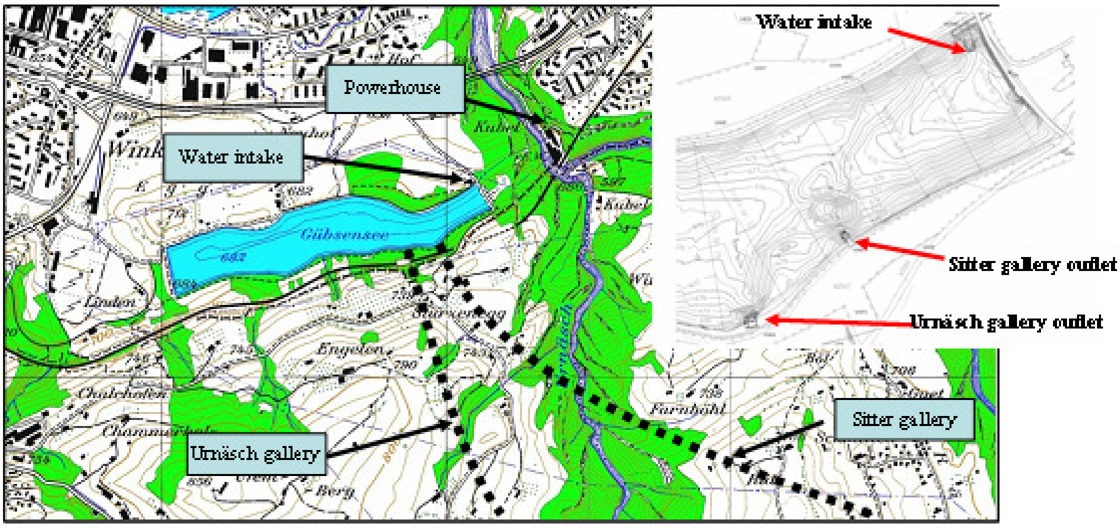


Fig. 44: Schematic map showing the main components of the hydropower scheme (lake, galleries, water intake and powerhouse) (De Cesare et al 2008a)

Fig. 45: Sediment laden water release in front of power intake (De Cesare et al 2008a)

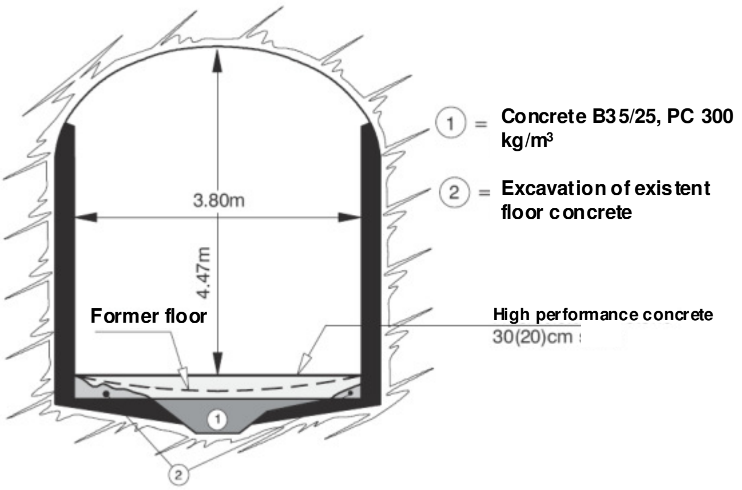


Fig. 46: Cross section of the bypass tunnel. For abrasion reasons, instead of the concave a plane bottom has been installed (De Cesare et al 2008a)

5 Available sediment data

5.1 Switzerland

5.1.1 Historic background

For about hundred and fifty years, sediment observations have been carried out in Switzerland. Different thematic weighting can be found in time:
Bathymetry and delta surveys were carried out in the 19th century. The purpose was to achieve basics for water economical question formulations (e. g. waterpower). On the other hand there was a geological interest (denudation, watershed modifications). Homogeneous survey methods and descriptions of the applied procedures were not yet so important.

The first studies on suspended sediments in Switzerland were carried out at the end of the 19th century in the river Arve during one year. Later on, more such investigations were carried out, however with different methods and quality. 1904 the Rhone River was examined for a year, with special regard to suspended sediments.

At the beginning of the 20th century, measurements directly in the catchment area were done. Besides sediment transport, discharge processes were in the foreground, too. The Federal Institute for experimental forestry introduced the investigation fields Sperbeland Rappengraben. During and immediately after the First World War, the first studies and the publications about sediment observations resulted, for example suspended sediment observations (Rhone, Port du Scex, Massa, Drance, Trient) and about sediment accumulations (river Aare at Bern).

Between the two world wars, more investigations on suspended sediments and delta formation were carried out. In addition, cross-sectional profiles have been taken at different rivers. The experimental watershed of Melera was established, mainly for sediment deposit observations in the retention basin. After the 2nd world war, the works carried out up to the time were extended and complemented. Many delta surveys were in particular carried out with more modern survey techniques.

In the 70s of the last century, a subgroup "Sediment observation" of the Group for Operational Hydrology (GHO) was founded under the chairmanship of the Hydrological Survey. The aim was to achieve more results from detailed sediment observation to provide basics and information for practical use. In
1979, the GHO transmitted to this subgroup the task to elaborate a concept for future activities on the field of sediment observation in Switzerland. On account of this task, different studies and other activities resulted.

5.1.2 Sediment observations today

Since 1987, the Federal Hydrological Survey, the Federal Institute for Forest, Snow and Landscape and interested cantons have registered sediment deposits in retention basins. Goal of this program is the long-term and low-cost recording of the sediment output from small Swiss catchment areas. Moreover, university institutes and private institutions carried out observations within the framework of studies and investigations in order to find solutions for particular problems concerning hydraulic engineering and also to receive the basics for model calibration or verification (see Tab. 8). Today's sediment observations in Switzerland are concentrated on three levels:

1. Surveys within the frame of a network

- Suspended sediment concentration (Fig. 47)
- Sediment deposits in retention basins (Fig. 48)

These surveys are executed by the federal authorities (Hydrological survey, in the case of sediment deposits with the aid of many cantons). The suspended sediment observation network consists at the moment of:

- 13 stations with each two samples per week
- 15 stations with periodic sampling (special campaigns)
- 2 stations with continuous sampling

In addition, the turbidity is continuously measured at 5 monitoring stations.

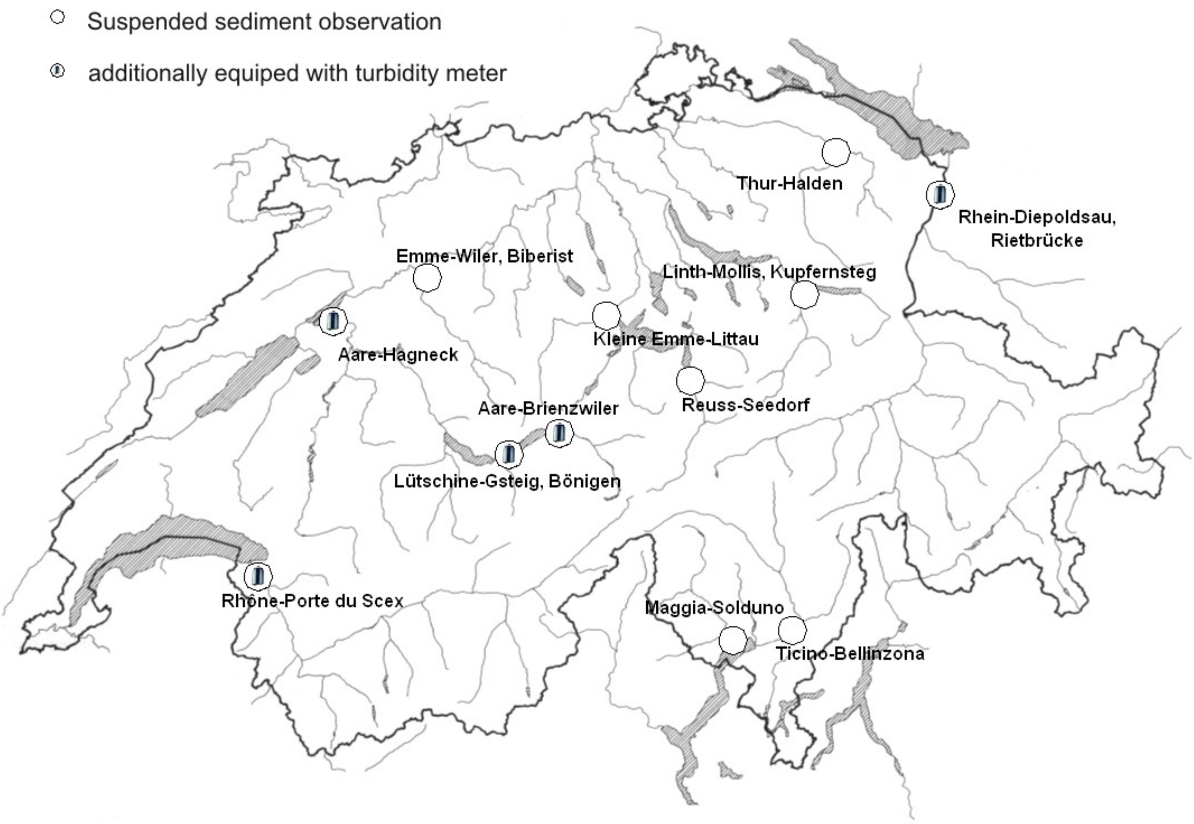


Fig. 47: Map of suspended sediment observation network (LHG 2005)

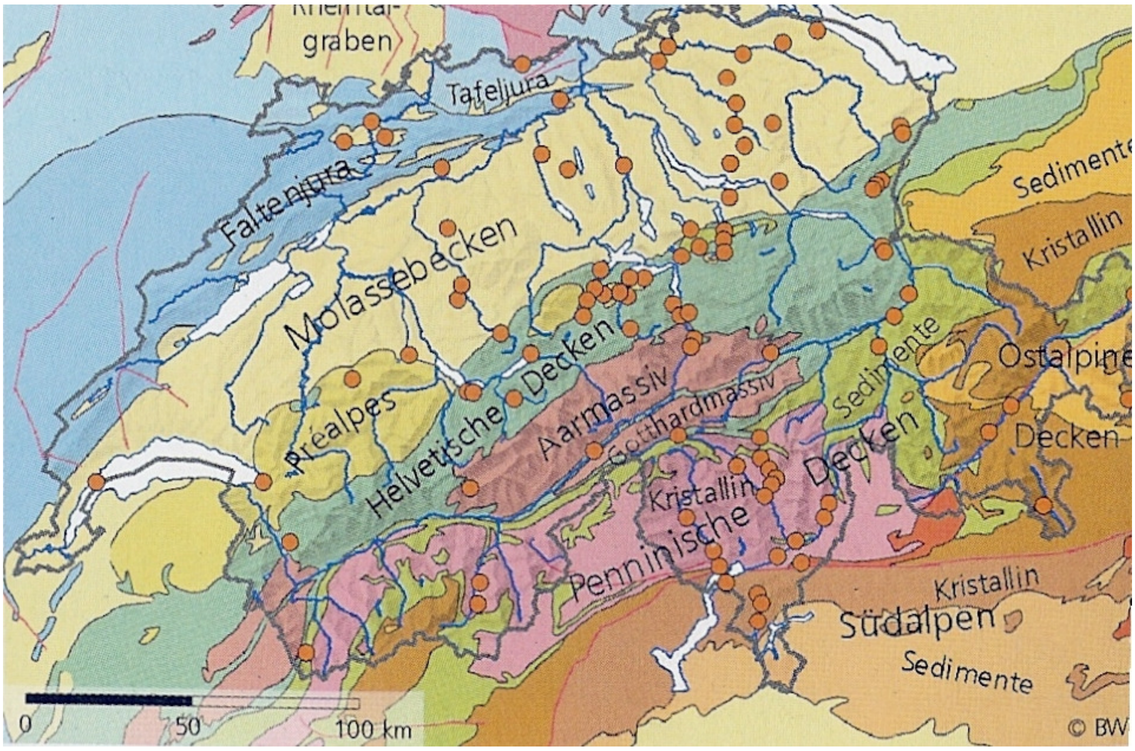


Fig. 48: Observation of sediment deposits in retention basins. Red points indicate sediment retention basins which are part of the observation network (LHG 2005)

<u>2. Special surveys</u>
They are carried through on request or periodically, mainly executed by federal institutions (Swiss National Hydrological Survey), also by universities and, to a small extent, by cantons. This category contains mainly the already mentioned delta surveys, which recently have become rather rare due to financial problems as well as river bed surveys (longitudinal profiles and cross sections). Further on, debris flow observation by the Federal Institute for Forest, Snow and Landscape and University of Bern is done at several sites.

<u>3. Investigations carried out by private enterprises in the frame of special projects</u>
Since recent times, federal and cantonal authorities ask comprehensive basic investigations for hydraulic and environmental projects. These special investigations include in many cases sediment transport assessment and calculations. The same has to be done by danger zone mapping.

Tab. 9: Overview of sediment observations carried through actually in Switzerland

Sediment	Torrents	Rivers	Lakes
Bed load	Annual load estimations, sistematically in test sites only and within the GHO network Catastrophic events: Estimation of accumulation volumes or deposits in retention basins. Estimation of sediment transport of future events with aid of GHO (1996) "Hydrograph" of sediment (in test sites only)	Bed load discharge: Sporadic measurements	
Suspended load	Suspended sediment load and discharge Systematically in test sites only	Suspended sediment concentration At many measuring stations Suspended sediment load Systematically in a few river stretches Suspended sediment discharge (at measuring stations)	Mean discharge of sediments for several years Sporadically in lake delta and retention basins Sedimentation rates By special inverstigations Properties of sediment By special inverstigations Suspended sediment budgets By special inverstigations
Special features	Grain size distributions, bulk density with special investigations	Grain size distributions sporadic investigations	Grain size distributions sporadic investigations
Wash load	Discharge of wash load Estimation at special events	Discharge of wash load Sporadically after flood events Ice discharge Sporadic estimations	Discharge of wash load estimations after flood events
Supplement observations	Erosion potential Sediment budget based on special methods for its estimation	Cross sections and longitudinal profiles Every 10 years in many river stretches River morphology in single cases Turbidity measurements	Bathymetric surveys poradically Turbidity measurements At spezial cases

5.2 Germany

5.2.1 Historical Background

Water level observations especially those of extreme floods have been recorded since medieval times. From 1770 onwards gauging stations have been systematically established in the Rhine basin. Around 1820 a basic network of gauging stations existed. Another 50 years later, around 1870, water level records could be supplemented by information on the related discharges (establishment of rating curves). Along the free flowing reach today at fifteen stations discharge measurements are carried out mainly by using ADCP (Acoustic Doppler Current Profiling).

First attempts to measure sediment transport in large European rivers were carried out at the Danube in the early thirties of the 20th century (Ehrenberg, 1931). At the Rhine river systematic measurements of sediment transport were introduced by the Federal Institute of Hydrology in 1968 (Hinrich, 1972). First bed-load transport measurements were concentrated on the Upper Rhine. Here they were expected to give an answer to the question whether it is possible to stabilize the degrading riverbed by feeding it with gravel instead by constructing a new barrage. Due to the finding that the free flowing Rhine suffers heavily from a severe bed load deficit, measurements of bed load and suspended sediment transport were systematically extended over the whole free flowing reach (BfG, 1985). Meanwhile bed load and suspended load are measured regularly at about 40 cross sections between Iffezheim and the German-Dutch border. In addition suspended sediment concentration is measured at 11 permanent stations between Lake Constance and Emmerich/Lobith.

5.2.2 River bed

The riverbed is characterized by its geometry and geology. Over long reaches the Rhine is an alluvial river flowing on its own mainly Pleistocene deposits. This holds for the Upper Rhine, the Northern Middle Rhine and the Lower Rhine, whereas, due to the morpho-tectonic uplift of the Rhenish massif, a bedrock channel with rocky islands and irregular cross sections has developed over a length of some tenth of kilometres between Bingen and St. Goar.

5.2.2.1 Geometry

Echo sounding surveys are an important tool for detecting and analyzing morphological changes of the river bed. Depending on the specifications of the survey and the available resources this can be single beam, multi-channel or multi-beam echo soundings.

<u>River bed</u>
The prevailing hydrographical measurement programme of the Water and Shipping offices responsible for the Rhine is based on biennial echo-sounding surveys of the river bed. The echo soundings are carried out as cross-section surveys with single beam sounders, whereby not only the navigation channel is surveyed but also the whole width of the river including side channels. The surveys are made at water levels between low and mean flow. Given all available sounding systems are optimally used, the survey of the entire free-flowing reach of the German Rhine can be completed within four to six weeks.

<u>Land connections</u>
The land connections are checked in intervals of several years and adapted to the latest developments. The period for a new survey depends on the morphological characteristics of the bank areas. Areas that include groynes, side channels and other distinctive features, where information on temporary accretion or degradation is available, are surveyed more frequently.

<u>Floodplain profiles</u>
The floodplain profiles are updated approximately every 20 years by means of an aerial survey.

Data quality and availability

The quality check and evaluation of the echo-sounding data is carried out by the Water and Shipping offices. The land connections are attributed to the channel cross section profiles and recorded in the TIMPAN program system.
From the multi-channel and multi-beam data of the river bed digital terrain models are derived. Together with the data from the bank areas and the floodplain data collected for example from laser scanner aerial surveys it is possible to develop large-scale terrain models covering the entire river.

At present terrain models are available only for certain sections of the river Rhine. Channel profiles, however, are available for the total length and cover the period from 1930 up to the present time. There are only a few echo-sounding surveys for the time before the Second World War but thereafter the entire length of the Rhine was surveyed systematically every five years at a distance of 100 m. As mentioned before, in the free flowing section echo-sounding surveys are nowadays carried out every two years from Iffezheim to the German-Dutch border.

5.2.2.2 Geology

Due to numerous investigations and geological surveys the structure, petro graphic composition and evolution of the Rhine valley are well known. The geologic situation is shown in Fig. 49 emphasizing the role of Quarternary uplift of the Rhenish massif and the adjacent Mainz basin forming an important morpho-tectonic barrier between the subsystems of the Upper Rhine and Middle+Lower Rhine.

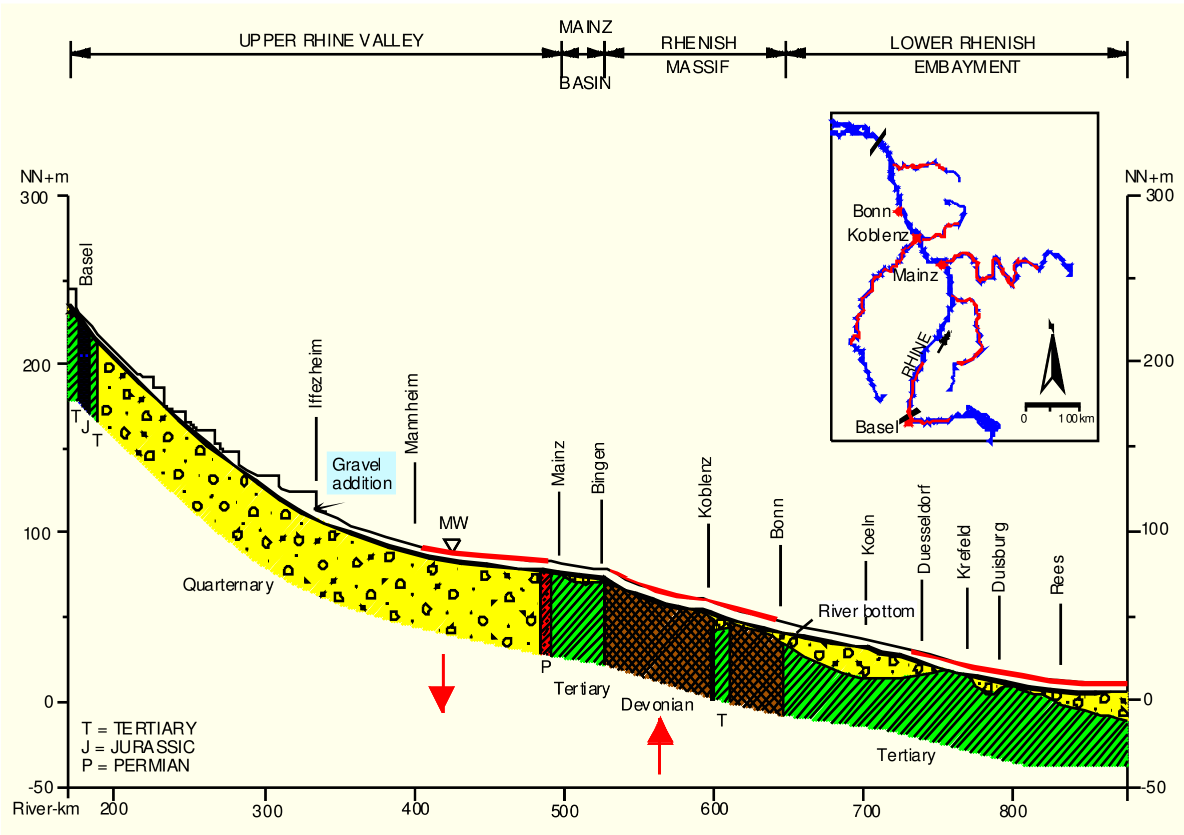


Fig. 49: Geological – hydrological longitudinal section (Basel – Emmerich)

In order to obtain a better understanding of the recent channel forming processes, on behalf of the Ministry of Traffic and its subordinated Water and Shipping Administration the riverbed has been investigated during the last decades by sounding, drilling and direct sampling by means of diving bell crafts (see chapter 6.2.1). In the course of these investigations a lot of geological and sedimentological informations about the structure and the grain-size composition of bed surface and subsurface were collected and evaluated (BfG 1985; BMV 1987).

Between Iffezheim and Mannheim bed sediments of the Upper Rhine consist mainly of gravel whereas further downstream the portion of sand increases steadily (Fig. 50). In the Mainz basin the fine grained sediment forms large dunes (BfG 1993, Carling et al. 2000a, 2000b) but is partly suspended when passing the "Binger Loch" at the entrance of the Rhine gorge. The rest is transported on a rocky and cobbly river bottom through the narrow gorge. Entering the Lower Rhenish embayment the river flows on sands and gravels of the Pleistocene valley fill. Between Düsseldorf and Rees the Lower Rhine has locally cut through the Pleistocene gravel layer and is actually eroding the underlying fine sands of Tertiary age (Gölz, 1987). These sands are easily eroded and transported away in suspension, thus favouring the development of deep scours.

Depending on the grain-size composition of the valley fill, the hydraulic conditions and the recent bed load supply various bed types have developed which are described in detail by Gölz and Dröge (1989) und Gölz (1992). Both bed surface and subsurface information have been collected in a special data base (SedDB) meanwhile containing some thousands of bedding profiles and bed-surface descriptions together with the associated grain-size information (see chapter 5.2.4).

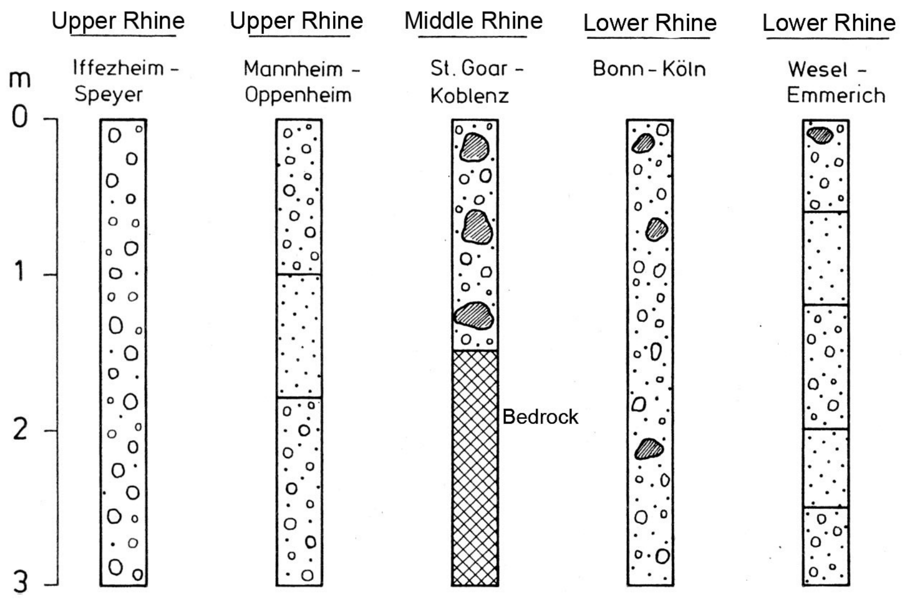


Fig. 50: Sediments of Pleistocene valley fill (BfG, 2008)

5.2.3 Sediment transport

Field measurements of bed load and suspended load provide an important basis both for the analysis of the recent morphological situation and for predicting morphological changes, especially concerning bed-level development.

5.2.3.1 Bed load

Beginning with first sediment transport measurements at the Upper Rhine in the late sixties the measurements were extended during the seventies and eighties over the whole free flowing Rhine. Meanwhile cross section measurements of bed load and suspended load are carried out at about 40 stations between Iffezheim and the German Dutch border (see 6.2.2). At each station sediment transport is measured four to five times a year, which allows to establish sediment balances over the whole reach. This time and manpower consuming procedure is necessary to control the success of the multiplicity of bed-load management measures, which have been implemented during the last years to stop bed degradation by achieving a dynamic stabilization of the riverbed (BMV 1997, Gölz 2004; PGEKG 2005). Fig. 51 shows a simplified longitudinal profile of the mean annual bed forming load in conjunction with the sites and quantities of artificial sediment supply and sediment extraction.

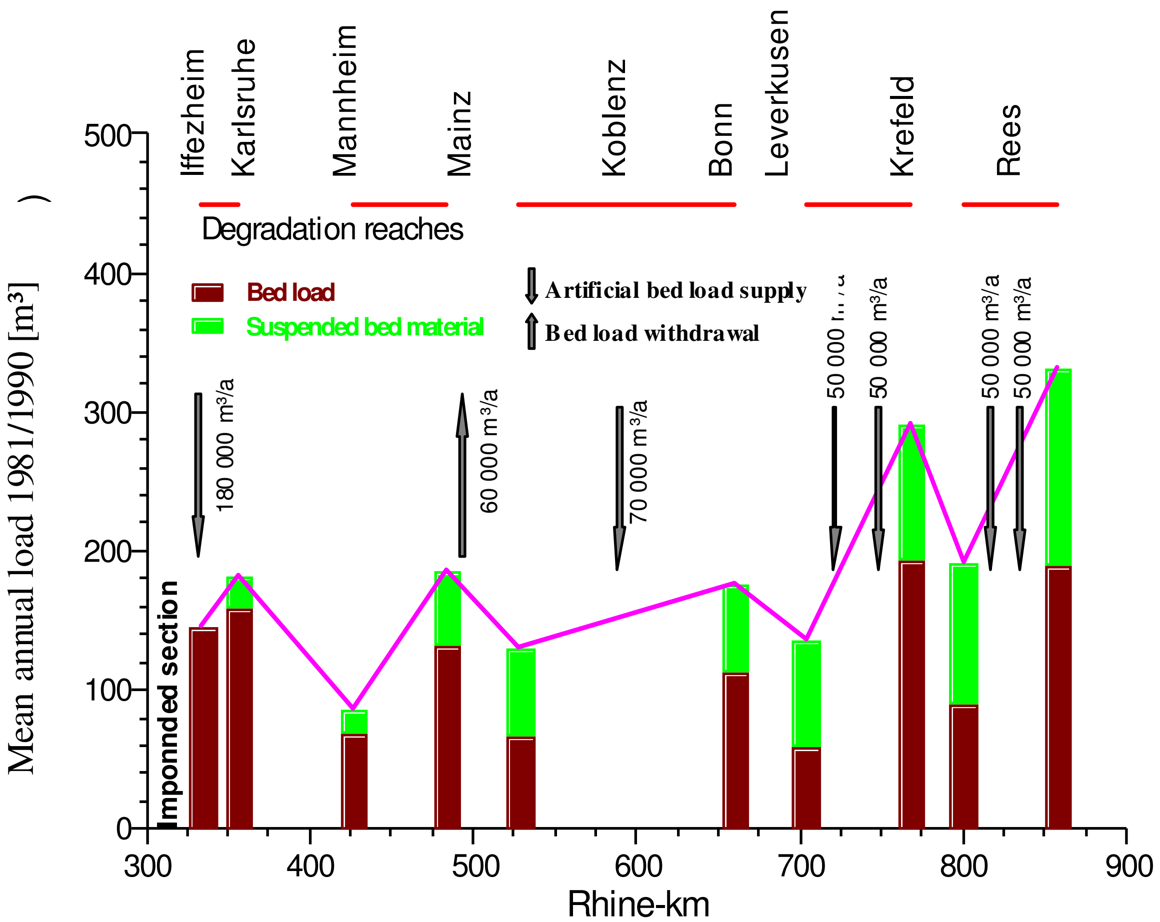


Fig. 51: Bedload distribution and bed load management measures at the Rhine between Iffezheim and the German/Dutch border (BfG, 2008)

Bed load and suspended sediment load data gained by cross section measurements are stored together with sedimentological and geological data in the data base SedDB, which is operated by the Federal Institute of Hydrology.

5.2.3.2 Suspended load

Besides the above mentioned cross-section measurements suspended load is measured at 11 permanent monitoring stations between Lake Constance and the Dutch border (see Tab. 10).

Tab. 10: Permanent stations for suspended load monitoring

Station	km	Begin of recording
Reckingen	90.2	04/11/1972
Albbruck-Dogern	108.9	31/10/1972
Weil	173.0	22/07/1970
Kehl	294.0	13/05/1970
Plittersdorf	339.8	06/10/1977
Maxau	362.3	25/05/1965
Nierstein	480.6	11/11/1963
St. Goar	557.0	01/06/1994
Weißenthurm	608.2	02/02/1971
Düsseldorf	744.2	22/08/1990
Emmerich	851.9	03/05/1983

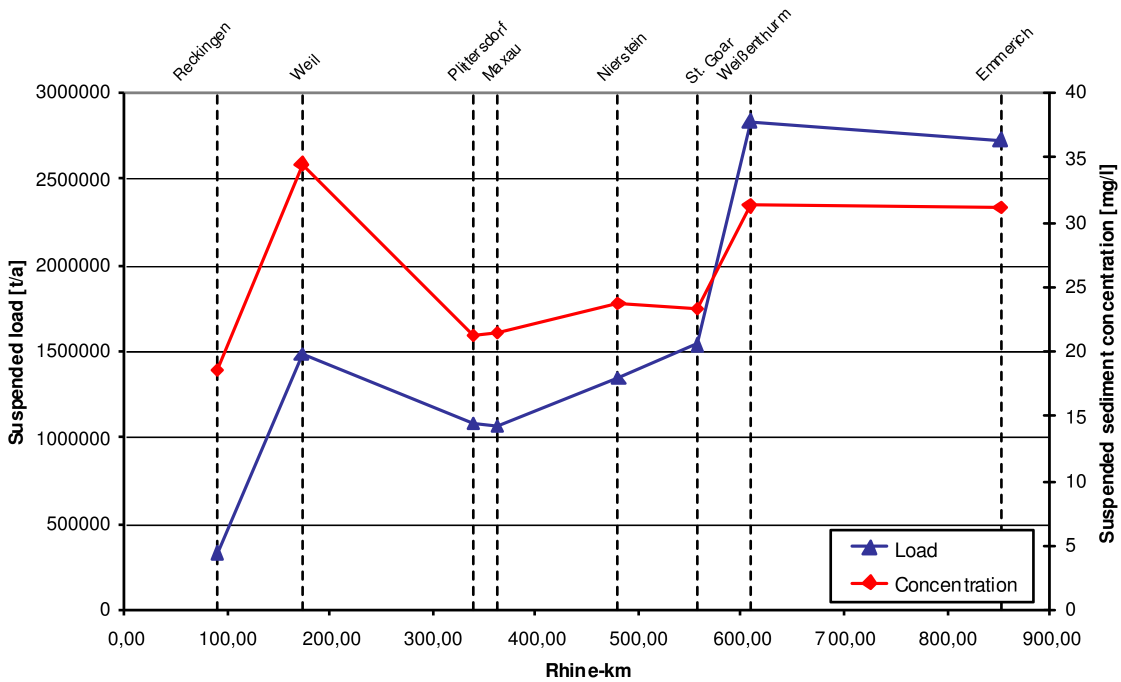


Fig. 52: Longitudinal section of mean annual suspended sediment concentration and mean annual suspended load (1995-2004) (BfG, 2008)

These point measurements allow to establish longitudinal sections of suspended sediment concentration and suspended load (see Fig. 52). The data are stored in a separate data base

SchwebDB at the Federal Institute of Hydrology and are partly published in the "Deutsches Gewässerkundliches Jahrbuch" (German Hydrological Yearbook).

5.2.4 Grain size

Both sediment samples of the riverbed and sediment samples collected by the cross-sectional bed load measurements are subject to a grain-size analysis by sieving or by combined sieving and elutriating. Within the last 40 years several thousands of grain-size analyses have been carried out, allowing to characterize in detail bed sediment mixture and bed load composition along the German Rhine. The longitudinal section of Fig. 53 shows, that the mean grain-sizes of the bed sediment and of bed-load material may be nearly identical (Upper Rhine) or may differ considerably as it is the case along the Middle Rhine and parts of the Lower Rhine. This means that the bed sediment of Upper Rhine is very mobile, whereas for the Middle Rhine an armoured bed surface is characteristic. Grain size data of bed sediment and of bed load material are stored together with the sediment transport data in the above mentioned SedDB.

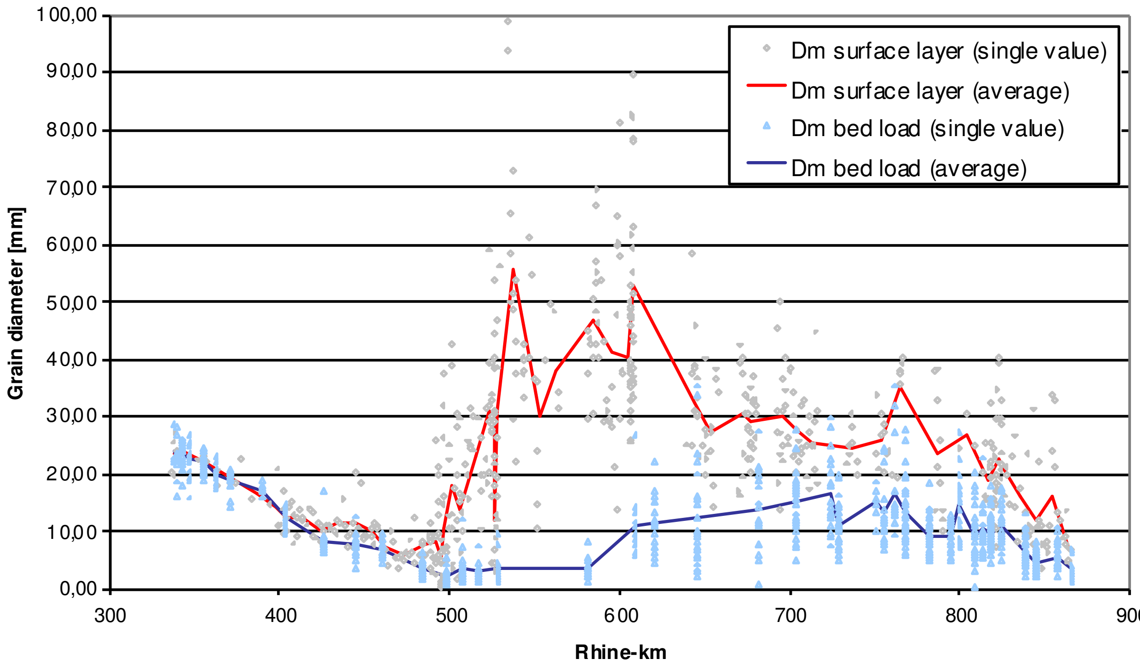


Fig. 53: Mean diameter of bed sediment and of bed load material along the free-flowing Rhine (BfG, 2008)

5.2.5 Petrographic composition

Within the research project "Discharge and bed load conditions of the Rhine" initiated and financed by the Ministry of Transport in the seventies and eighties of the last century (BMV 1987) the petro graphic composition of the Rhine sediments was analysed in detail. An important outcome of these investigations was, that only 20 to 30 percent of bed sediments of the Lower Rhine originate from the Upper Rhine and that recently only sand and fine to medium-sized gravel are transported from one subsystem to the other.

Fig. 54 shows the petro graphic variation of three different fractions along the 700 km long reach between Basel und the German-Dutch border. The petro graphic data have not been stored in a special data base but the results of the investigations are documented in two internal reports of the Federal Institute of Hydrology (BfG 1980, 1982) and are published in scientific journals (Gölz 1986, 1990).

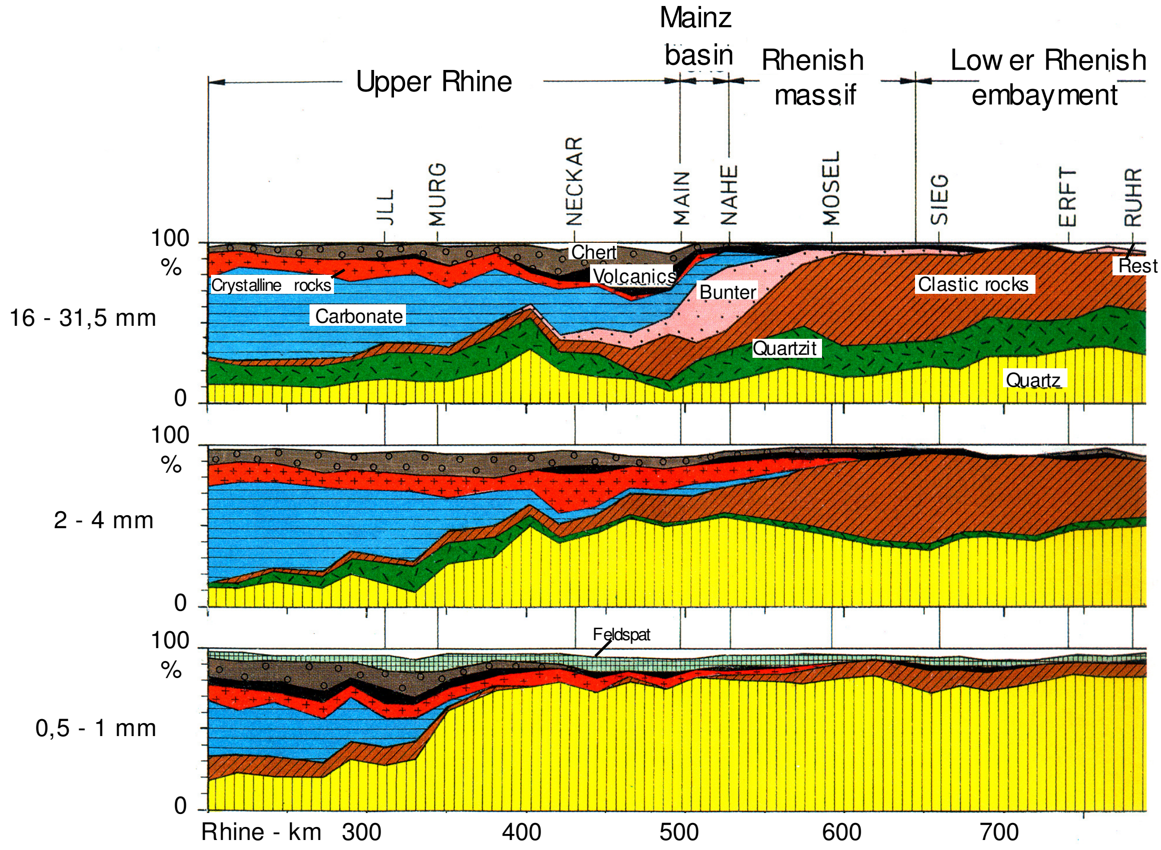


Fig. 54: Petrographic variation of bed sediment (BfG, 2008)

5.2.6 Data storing

Echo sounding data of the river bed are archived in the TIMPAN program-system and administrated by the Water and Shipping offices Freiburg, Bingen and Duisburg, which are responsible for the maintenance and development of the inland waterway Rhine. The sedimentological and geological data as well as the sediment-transport data are quality checked, evaluated and administrated by the Federal Institute of Hydrology. Here the suspended load data of the permanent stations of all German inland waterways are stored in the data base *SchwebDB* and are partly published in the "Deutsches Gewässerkundliches Jahrbuch".

A second data base named *SedDB* contains not only the sediment-transport data (suspended load and bed load data) obtained from cross section measurements but also all geological and sedimentological information about the river bed like bedding profiles, bed-surface descriptions, photos, and grain-size distributions of bed sediment. The SedDB is a GIS-supported data base which offers different evaluation and display possibilities (see Fig. 55).

Fig. 55: Web-based BfG sediment data base SedDB (BfG, 2008)

Furthermore the data stored in SedDB and SchwebDB are available for the individual users inside of the Water and Shipping administration via the web-based information and analyzing system GGInA functioning as Geoportal of the Federal Institute of Hydrology and offering search and download options (Fig. 56).

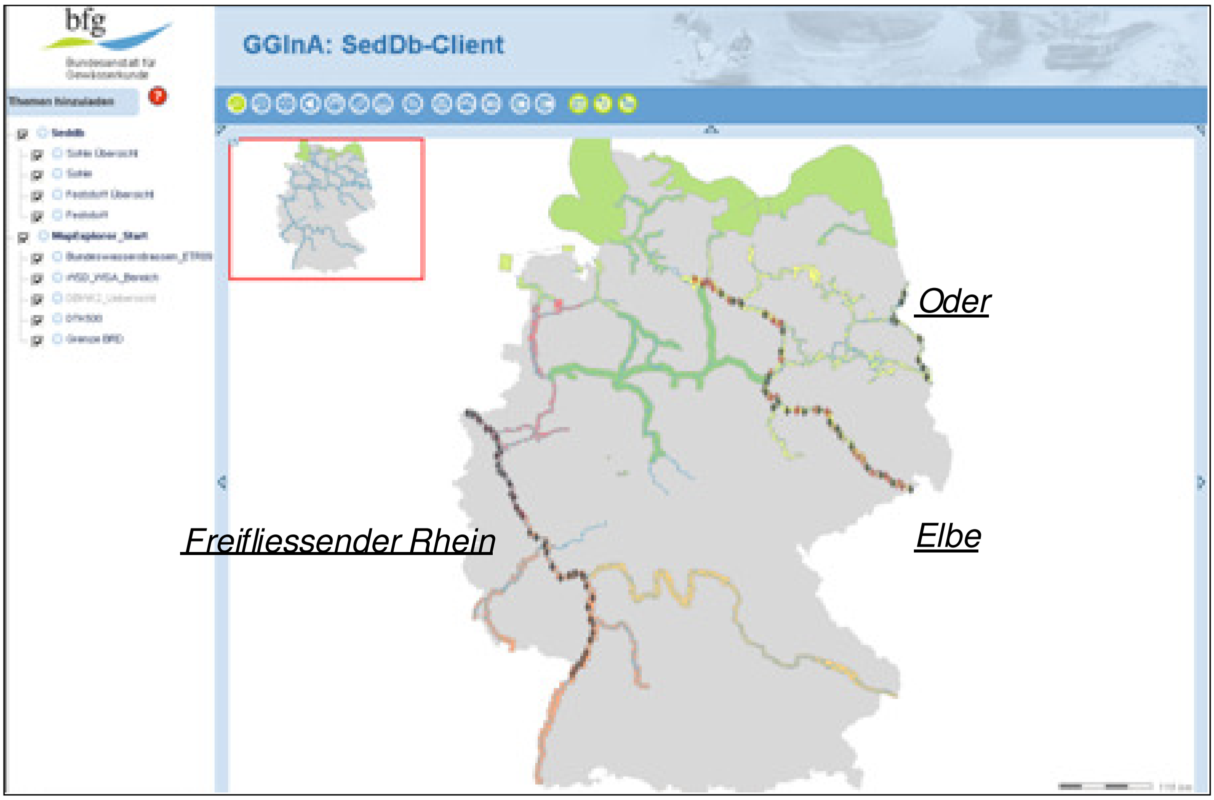


Fig.56: Web-based BfG sediment data base SedDB; SedDB map-explorer (BfG, 2008)

5.3 The Netherlands

5.3.1 Historical background

Measurements have been carried out in the Rhine for a long time now. The oldest measurement records are from more than two centuries ago. For instance, there are measurements available from 1790 taken to determine the distribution of the Rhine discharge among the various Rhine branches at their bifurcation points. This theme is still highly topical nowadays. Even older are the details about water levels at certain locations along the river. More recent are the records of riverbed levels, sediment transport and grain size. But for these river characteristics, too, we can bring more than half a century's worth of monitoring data to the task. The Rhine may well be the best-monitored river in the world.

Rijkswaterstaat carried out the measurements on sediment transport, grain size and riverbed level in the past. At present Rijkswaterstaat still carries out the measurements on riverbed level. The measurements on sediment transport and grain size, however, are carried out by research institutes (universities mainly) and private firms, conducted by Rijkswaterstaat. These measurements are done within the framework of special research projects and not on a regular basis. Rijkswaterstaat stores the historic and present data. The data are (partly) published in scientific journals.

5.3.2 Bed levels

Measurements of the summer bed level are frequently taken in the Dutch Rhine. The bed levels of the most important channels are monitored either annually or once every two years. On other locations, the frequency is sometimes lower. But the available information about the bed level is always topical to a high degree. The Directorate-General for Public Works and Water Management (Rijkswaterstaat) has been applying this routine of mapping bed levels for many years. The oldest records of the bed levels of the Rhine branches date from 1926.

5.3.3 Available data on sediment transport

In The Netherlands sediment transport measurements are not carried out as a routine, ongoing monitoring program. Instead the measurements are done within research projects that focus on specific river problems at specific locations. Over the last years focus has been on the morphological behaviour of bifurcations in the Dutch Rhine. Sediment transport measurements during floods and at low discharge have been combined with measurements on flow conditions and the sediment composition (grain size) of the riverbed. All in all, during half a century, sediment transport data have become available for all the Dutch Rhine branches, with which a sediment budget of the Dutch Rhine river system has been made (see chapter 11).

5.3.4 Available data on grain size

The grain size of bed material has been studied in 1966, 1976, 1984 and 1995. In these years the left and right parts of the riverbed of the Rhine branches in The Netherlands have been sampled at intervals of 1 km. From these samples grain-size distributions have been determined (see Fig. 57 for the data of 1995) and the percentiles D10, D50 and D90 have been calculated.

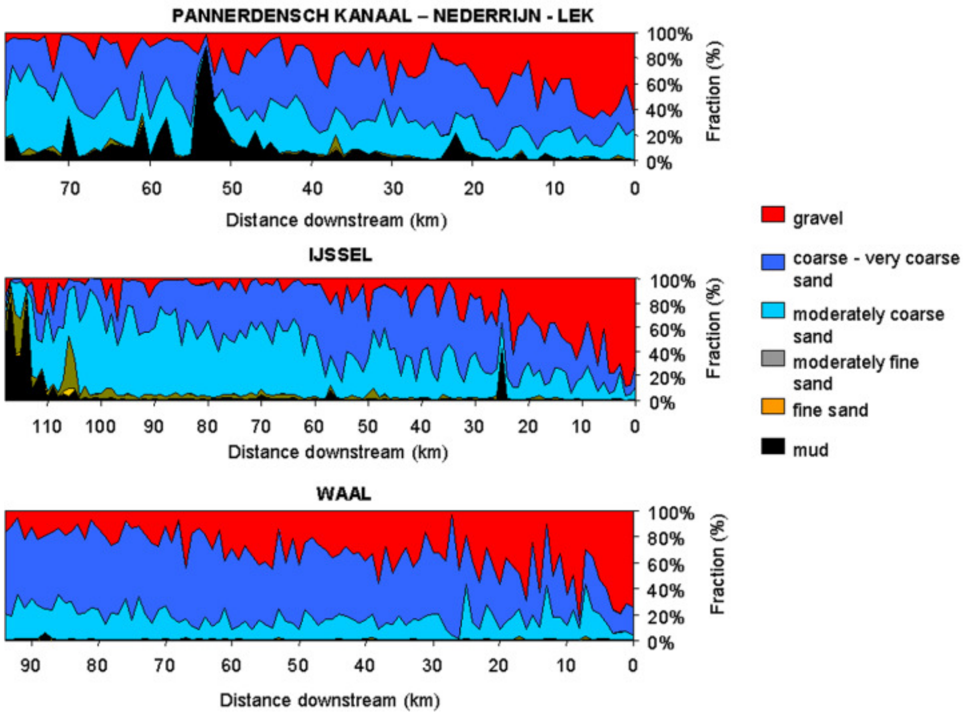


Fig. 57: The grain size distribution of the top 10 cm of the river bed of the Dutch Rhine branches, according to Van Veen grab samples taken in 1995 (Ten Brinke 2005)

In addition to these Van Veen grab samples, drilling cores of the riverbed have been extracted at specific locations (bifurcations, transition of Niederrhein to Bovenrijn) for specific projects in the last years. Grain size analysis on sediment samples from these drillings have been integrated with shallow water seismic measurements to give an area picture of the grain size distribution and sedimentary structures in the substrata (see Fig. 58).

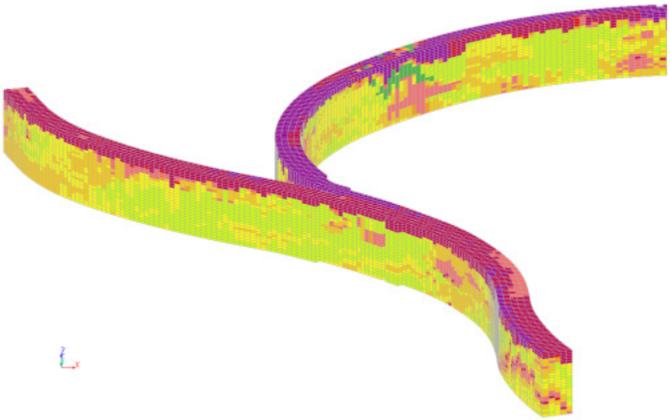


Fig. 58: A 3D picture of the grain size of the subsoil at one of the bifurcations in the Dutch Rhine river system: purple = gravel, yellow-green = sand, dark green = clay (Ten Brinke, 2005)

6 Monitoring equipments and methods

6.1 Switzerland

6.1.1 Bed load

Hydrophones
The direct measurement of the bed load in torrents is limited today to few test sites. There are three measuring stations with hydrophones in operation in the Swiss Rhine basin. Installations with underwater microphones allow a continuous recording of the bed load discharge. The sensor is positioned at the bottom of a steel slab that is installed in a concrete check dam. The most important element of the sensor is a piezoelectric crystal. If stones roll over the steel slab, the strokes of the stones cause oscillations which are transmitted onto the piezoelectric crystal. The oscillations make a tension in the crystal which is amplified and measured. From the size of the tension conclusions can be drawn with respect to the strength of the stroke. An impulse is registered each time the tension exceeds a minimum value (boundary value). The number of impulses measured per unit time is a measure for the intensity of the bed load transport (Fig. 59).

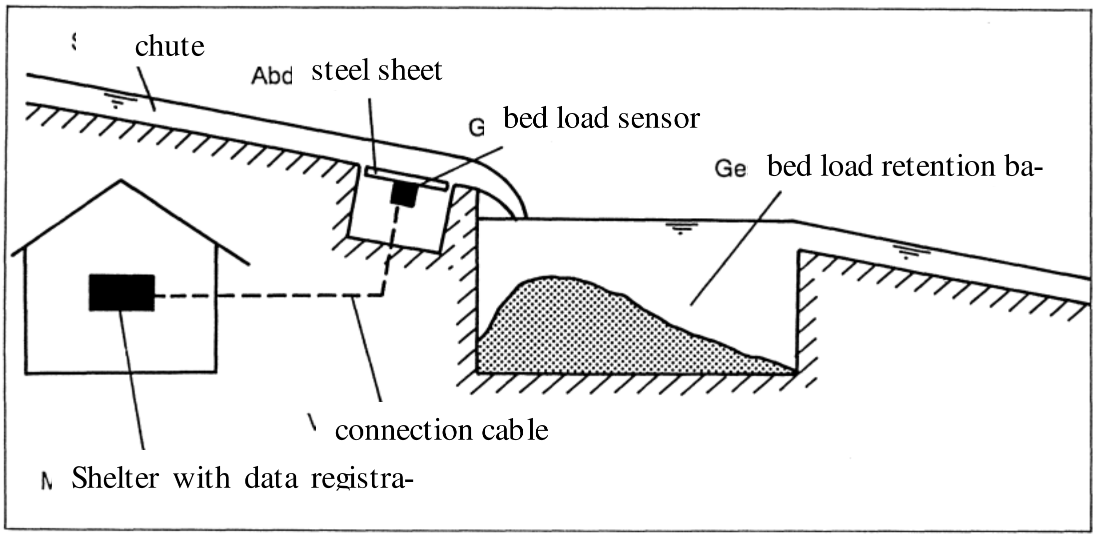


Fig. 59: Schematic sketch of a hydrophone installation (BfG, 2008)

Sediment retention basins
The relevant possibilities of volume determination in sediment retention basins are measurements of cross sections and determination of volumes of the transported material by trucks during clearance.

6.1.2 Suspended sediment

Suspended sediment concentration can be determined by direct measurements taking some samples. The determination of the sediment concentration in the sample is made by filtration. The concentration is calculated as the ratio between the weight of the filtered matter with respect to the total sample weight. The concentrations are used to calculate the suspended sediment load.

The operational measurements with manual sampling devices (Fig 60) are taken at a representative point of the measuring section providing a moment's concentration value.


Fig. 60: Suspended sediment sampling device (left); Turbidity sensor (right) (Grasso, et al. 2007)

This representative point is determined by means of specific concentration measurements over the whole river width. Based on these specific measurements the most representative point for the determination of the average suspended sediment transport in the river is selected. Since the samples are not taken continuously, larger flood events can be missed, which leads to larger uncertainties by the computation of the suspended sediment load. In order to better interpret the discontinuous concentration measurements, we can integrate these discontinuous concentration monitoring with the continuous turbidity measurements by a nephelometric (turbidity probe) device (Fig. 60).

6.1.3 Turbidity

The turbidity of the water is the result of the transparency decrease due to suspended matters. These consist generally of inorganic particles (clay, mud, fine sand), and of organic substances (plankton, algae, bacteria, pollen etc.) and colloidal particles smaller than 1µ. The turbidity has an aesthetic (for humans) and an ecological effect on living beings. The turbidity is often a measure and/or an indicator for impurities in the water. The turbidity is a non-specific measurement of the suspended solid concentration and its measurement unit is FTU (formazin turbidity units).

6.1.4 Suspended solid load

For the estimation of the suspended load the information about concentration and discharge in continuous form have to be available. The daily suspended load is determined as product of the daily average of the suspended matter concentration and mean daily discharge.

While the daily discharge can be determined relatively simply, the estimation of the daily concentration of the suspended solid is more complex, since the discontinuous sampling leads to data gaps in the concentration hydrograph curve.

Under certain conditions and assumptions (Grasso, et al. 2007) it is however possible to estimate the suspended sediment concentration by means of continuous turbidity measurement (Fig. 61) and develop a continuous suspended solid concentration hydrograph curve.

The availability of the daily concentration and the discharge allows estimating the daily sediment load (Fig. 62).

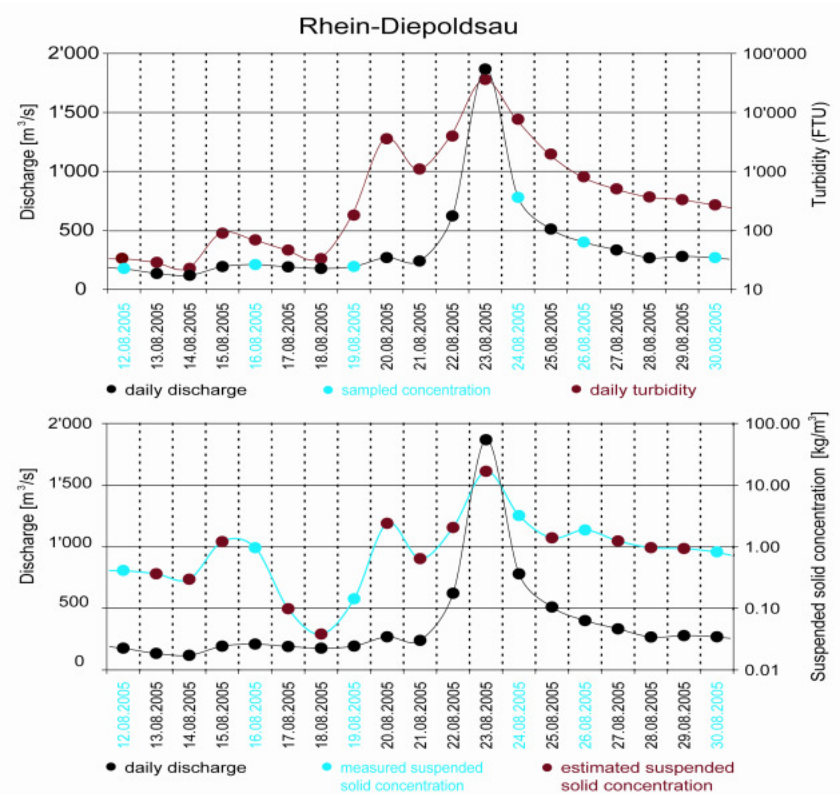


Fig. 61: Estimation of the daily suspended sediment concentration during the flood of August 2005 by means of turbydity values (Grasso, et al. 2007)

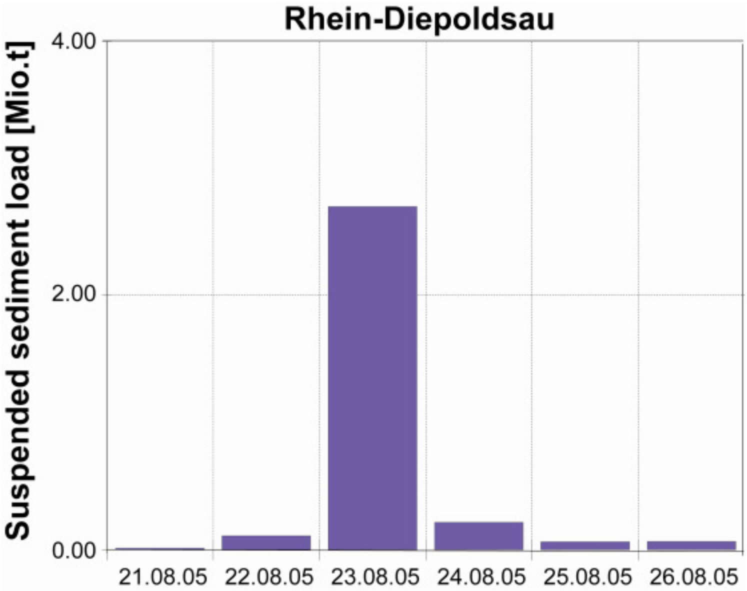


Fig. 62: Estimation of the daily sediment load during the flood of August 2005 by means of the product between daily suspended sediment concentration and discharge (Grasso, et al. 2007).

6.2 Germany

6.2.1 Geometry of the river bed

As mentioned above, the riverbed is surveyed by echo-sounding. During the last decades the technique has developed from single beam echo-sounding over multi channel application to multi-beam systems. Although all three systems are still in operation at the Rhine River the technique of the near future will be exclusively the multi-beam echo-sounding. After a period of testing the survey-vessels of the Water and Shipping Administration will be successively equipped with multi-beam technique supported by high-precision satellite-based positioning systems (DGPS).

6.2.2 Geology and sedimentology of the river bed

Beginning in 1968 a lot of sampling campaigns and special investigations have been carried out, in order to gain detailed information about the structure and composition of the riverbed. Deeper strata were investigated by drilling and sounding whereas the bed surface was probed by grab-sampling. In order to get a better understanding of the prevailing channel forming processes the river bed has been investigated by two diving-bell watercrafts (see Fig. 63). These special vessels had originally been conceived for snagging; however since 1979 they have been used more and more for geological and sedimentological investigations of the river bed. The caisson with its open bottom does not only allow direct investigation of the bed surface but also of deeper strata by drilling and sounding.

Fig. 63: Diving-bell craft „Carl Straat“(BfG, 2008)

Fig. 64: Freeze-coring in the diving-bell (BfG, 2008)

In this context various coring equipments have been developed. One of them is a special freeze-corer providing the possibility of taking undisturbed samples down to a depth of 1.5 m below bed surface (Fig. 64).

6.2.3 Bed load

The systematic measurement of bed load transport in large rivers is difficult and time-consuming. Relying on the positive experiences made with bed load samplers in the late sixties this method has been further developed by the Federal Institute of Hydrology and intensively applied at the Rhine, Elbe and Odra rivers.
The measurements are carried out with the bed load sampler "Arnheim-Koblenz" consisting of a heavy frame, a sampling basket with a mobile rectangular mouth (16 to 8 cm) and a so called diffusor between mouth and basket (see Fig. 65). When lowered to the riverbed the mobile mouth nestles closely to the bed surface. To control the correct hub of the sampler and the undisturbed inflow of sediment a video camera is mounted directly above the mouth.

Fig. 65: Bed load sampler „Arnheim-Koblenz" (BfG, 2008)

The measurements are made by boat. First the cross section profile is surveyed by echo sounding. Depending on the width, 5 to 8 verticals are defined, where the vessel is anchored successively for sampling (see Fig. 66). The sampler is lowered by a winch to the bed surface for five to 15 minutes, at least three times at each vertical. After each measuring act the bed load sampler is heaved on deck to collect the trapped sediment for weighing and sieving in the laboratory.

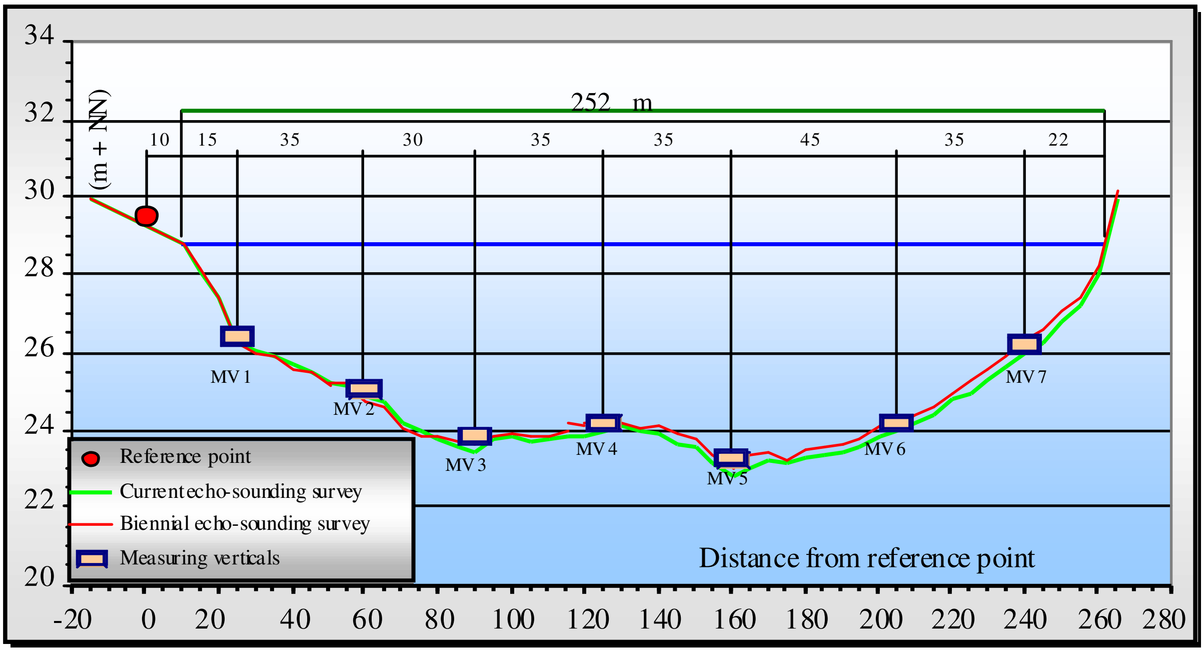


Fig. 66: Cross-section with measuring verticals (BfG, 2008)

6.2.4 Suspended load

As already mentioned suspended load of the Rhine River is measured both at eleven permanent stations and in defined cross sections.

6.2.4.1 Permanent monitoring stations

At the permanent stations monitoring is done by means of 5-litre-samples of water, taken every working day at one point approx. 50 cm below the water surface in the middle of the river. The samples are filtrated and sediment concentration is gravimetrically determined by drying and weighing the solid residuum in a climate constant lab according to the instructions given in DVWK (1986). The procedure is shown in Fig. 67.

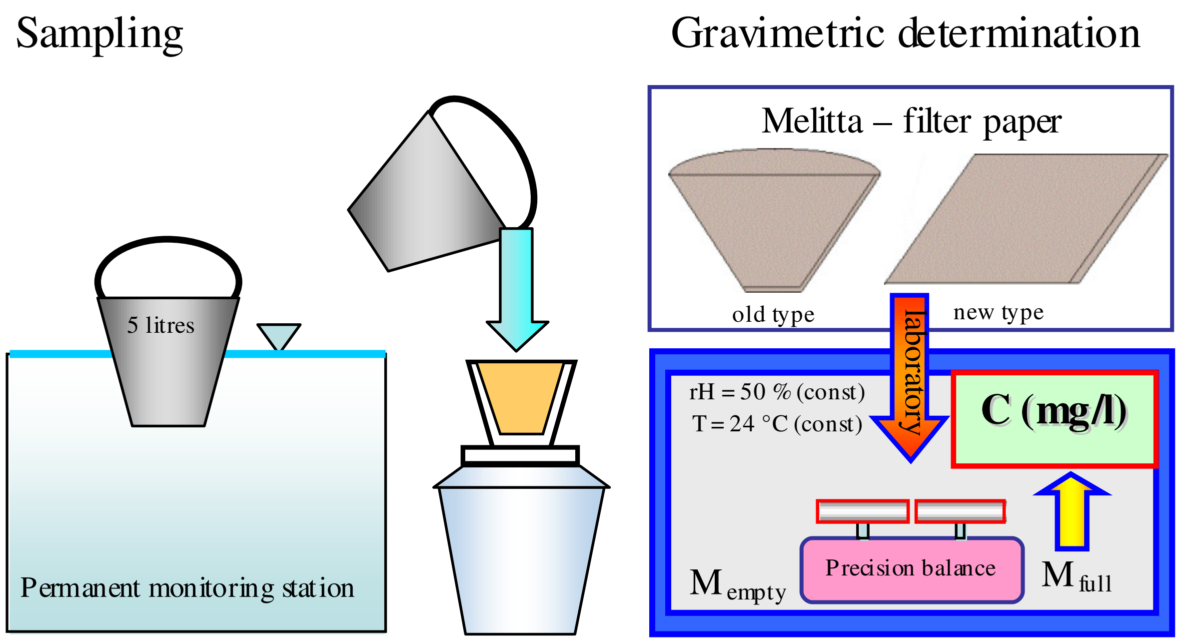


Fig. 67: Gravimetric determination of suspended sediment concentration (BfG, 2008)

6.2.4.2 Cross-section measurements

In combination with the bed load measurements suspended sediment concentration is measured at the same verticals in four to five depth levels below the water surface giving detailed information about the distribution of stream velocity and concentration over the whole cross section. This allows to calculate transport rates of suspended matter for various hydrological and seasonal conditions. At each measuring point, a water sample of 50 litres is pumped, and particles with $d > 63$ µm are separated by the application of an appropriate sieve. The mass of particles $d \leq 63$ µm is quantified by filtrating 5 litres of water and weighing the residuum as it is done with the samples from the permanent stations. The whole procedure is schematically described in Fig. 68.

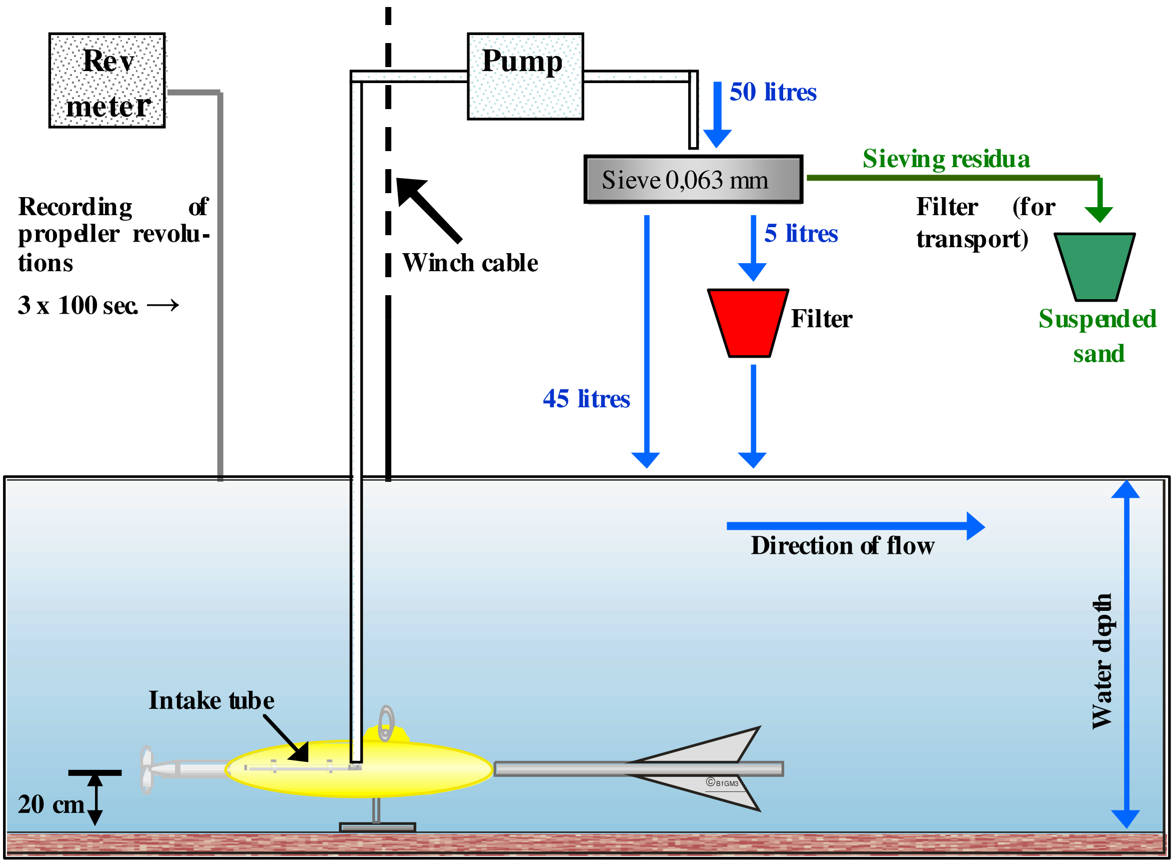


Fig. 68: Suspended sediment measurement at cross sections (BfG, 2008)

6.3 The Netherlands

6.3.1 Riverbed

In the first half of the previous century, the bed level was measured by dropping a piece of lead on a wire to the bottom and reading off the calibrated scale on the wire. In due time, the system was changed to measuring the bed level by means of sound waves. The time between the transmission and reception of a sound signal is a measure for the depth of the water column and therefore the bed level. Nowadays, instruments are used with which various sound waves can be transmitted simultaneously in various directions to the bottom, resulting in a three-dimensional depth map.

6.3.2 Bed load

Where the measuring techniques for riverbed levels and water movement have undergone a huge development in recent years, the measuring techniques to determine sediment transport have not gone through such a big change. New instruments for these measurements are being developed continuously, but one still tends to rely on relatively old instruments when carrying out these measurements. This may be because the sediment transport is much less easily measured than the riverbed levels and water movement. As a result of this, even the latest techniques still have their limitations. Suspended solids and bed load transport are monitored separately and with different techniques. The amount of bed load sediment transport is determined by collecting it during a few minutes in a bag placed on the bottom: in The Netherlands this is done with a Helley Smith bed load sand transport meter (see Fig. 69).

Fig. 69: The Helley Smith bed load sediment transport meter (BfG, 2008)

To make the calculation of the amount of sediment transport as reliable as possible, enough measurements must be taken at various positions in the cross section and at various depths in the water (see Fig. 70). Moreover, the measurements must be repeated at various times, because the size of the transport will vary from time to time, especially when there are bed forms (dunes) moving over the riverbed. This makes the quantification of the amount of sediment transport a cumbersome, labour intensive and expensive affair.

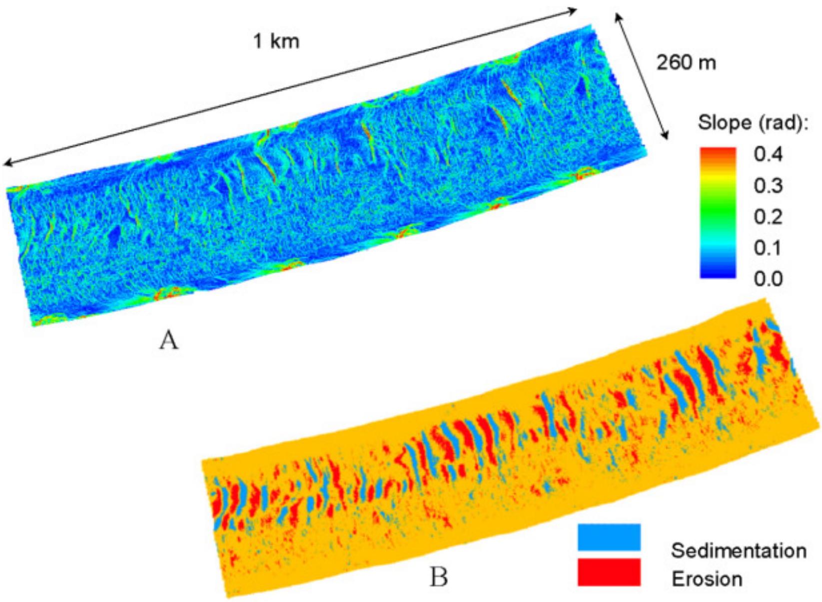


Fig 70: River bed survey showing the pattern of dunes and ridges on the bed (A). If two of these measurements of the same section of the river are deducted from each other on two consecutive days, the pattern of erosion and sedimentation will reveal the shifting of the dunes (B) (Ten Brinke 2005)

A large part of the sand and gravel transport in the river moves in the shape of shifting bed forms across the summer bed. A method has been developed to calculate the sediment transport on the basis of the properties of the bed forms. This technique is called 'dune tracking'. With dune tracking the sediment transport is calculated as the product of the height of the dune, the displacement velocity and a correction factor. Dune height and displacement velocity can be deduced from bed depth measurements, for the displacement velocity by comparing the measurements of two consecutive days and looking for the same dunes again (Fig. 70). Statistical techniques are used for this.

6.3.3 Suspended load

Various instruments are used to monitor the transport of suspended sand and silt. This has everything to do with the various properties of grains of sand and silt flocs. The concentration of suspended sand grains can best be monitored by means of sound waves (acoustic). For silt, or, rather, turbidity, a measuring principle based on the diffusion or obscuration of light is used (optical). In recent years, the suspended transport of sand has been monitored in the Rhine branches by means of the so-called Acoustic Sand-Transport-Meter (ASTM, Fig. 71). The ASTM used in the river consists of a 1-metre long frame with a weight of 220 kg, suspended in the direction of the flow rate by means of fins. The head of the frame contains a sensor with which sound waves are transmitted and two sensors with which the signal is received back again. One of these two sensors is located in line with the sound source. This sensor monitors the extinction of the signal between source and receiver. The second receiver sensor is located below an angle to the line from the sound source to the extinction sensor. This sensor monitors the amount of sound diffused after colliding with the sand grains. The concentration and velocity of the suspended sand grains can be calculated on the basis of the signals received. If it is assumed that the sand grains move at the same speed as the water, then the velocity of the flow rate is also evident.

The turbidity of the water is a criterion for the concentration of silt: the higher the concentration, the more turbid the water. Turbidity can be monitored in two ways by means of a light sensor: either by measuring the weakening of the light signal after it has passed through a volume of water or by measuring it after it has been reflected by the silt particles in this volume of water. With the first method, the degree of extinction will indicate how much silt there is in the water volume, with the second method, the silt concentration follows from the extent of the reflection. To convert the degree of turbidity into silt concentration, calibration samples are needed. In the Rhine branches, the silt concentration does not vary much during the course of time. That is why measurements with turbidity sensors are often not required to nevertheless obtain an accurate picture of the silt transport: it is mostly enough to filter a few water samples.

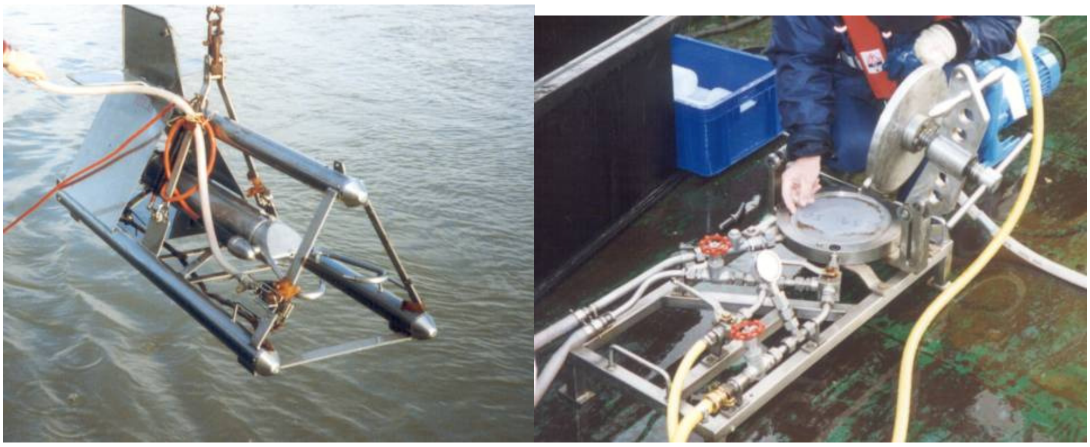


Fig. 71: The Acoustic-Sand-Transport-Meter (ASTM) (left) and the filtering system that is used in The Netherlands to obtain fine-grained sediment samples (right) (BfG, 2008)

7 Estimation Techniques

7.1 Switzerland

7.1.1 Recommendation for the assessment of sediment yield in mountain streams

The following recommendation for the assessment of sediment yield in mountain streams can be considered as a contribution to the understanding of mountain stream processes and describes a method for the assessment of a future mountain stream event. The method was developed by the Geographical Institute of the University of Berne in association with the Swiss National Hydrological and Geological Survey and the Swiss Federal Office for Water Economy. For the recommendation, it has been attempted to collect the current information into a practical guide for specialists who are familiar with hydrological, geological, geomorphological and hydraulic engineering issues and have specific problems to solve in the area of mountain stream processes.

The recommendation consists of two volumes. Volume 1 contains a description of the method and volume 2 discusses the basic technical background knowledge. The calculations can be done with the aid of a computer program. With this method the sediment yield of an event can be assessed in the following manner (Fig. 72):

<u>Preparations</u>
The main part of the preparation work can be done in the office and involves the following:

- A preliminary examination of the transport process which involves an ascertainment of the mountain stream's capability for debris flow, using available documentation, descriptions of past events, maps and aerial photographs.
- A preselection of the most important sediment sources that can be determined using maps and aerial photographs.
- For „no debris flow mountain streams“ and in the case that no measurements are available: construction of a simplified hydrograph to calculate the sediment transport capacity of the channel.

<u>Field Work</u>
In the field the following has to be undertaken:

- Assessment of the channel's capability for debris flow, in case that this is not known
- Division of the mountain stream into channel sections. In each channel section the following has to be undertaken:
    - Estimation of the sediment potential of the main sediment sources
    - Estimation of possible deposits
    - Mapping-out of cross sections with slope, bed width and d90 d50 d30 of bed material for „no debris flow mountain streams“. These parameters are used in the calculation of the transport capacity.

The significance of a sediment source can be judged using the following two criteria:

- Material composition
  Sediment sources consisting of loose material are important. Those originating from bedrock are less important, unless the rock is easily erodible and slaty, as the

sediment discharge in the channel (e.g. from a rock slide) is not directly related to a flood event in the mountain stream.

- Location of the sediment source and transport path of the material in the channel
  Sediment sources of loose material lying near the channel will be eroded during an event and are to be considered of great importance. Mountain streams with large sediment sources in the channel area tend to be especially active. As a rule large sediment volumes are to be expected.
  The transport path for sediment sources outside of the channel area is important. Large sediment sources such as talus cones, open erosion scars, etc. are meaningful when their material is able to directly reach the mountain stream via side channels or gullies.
  For sediment sources that do not have a direct path of connection to the channel, the slope gradient plays an important role. If the gradient of the slope is less than 30°, then the material tends to come to rest on the slope from where it can be eroded at a later time.

Analysis

Back in the office an analysis of the data can be carried out that involves a detailed calculation of the sediment yield and a check of the field investigation (plausibility check). For each channel section the following is calculated:

- The sediment potential
- The sediment transport capacity using the hydrograph (not applicable for „no debris flow mountain streams")
- The volume of possible deposits
- And for each cross section moving downstream the difference between the sediment potential and the transport capacity taking into consideration the deposits. These differences are then summed together to create a sediment budget (Fig. 73). At the last cross section the volume of the sediment yield at the cone is found
- In the case of debris flow mountain streams these calculations cannot be done in as much detail as there is no way of calculating the transport capacity of debris flows. The sediment and deposit potential in each channel section is recorded so that the sediment budget can be constructed on a channel section basis.

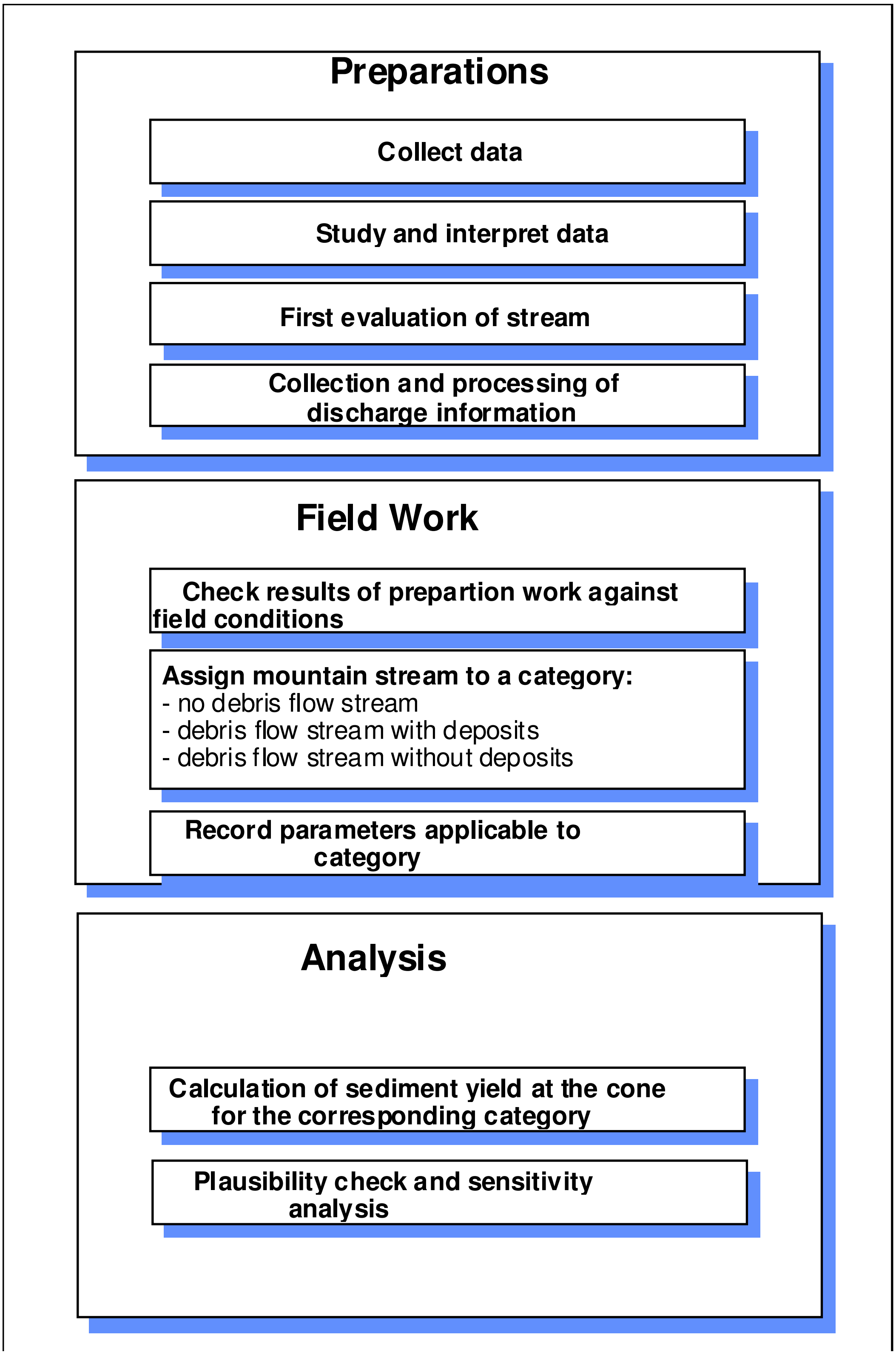


Fig. 72: Overview of the steps required for the assessment of sediment yield (GHO 1996)

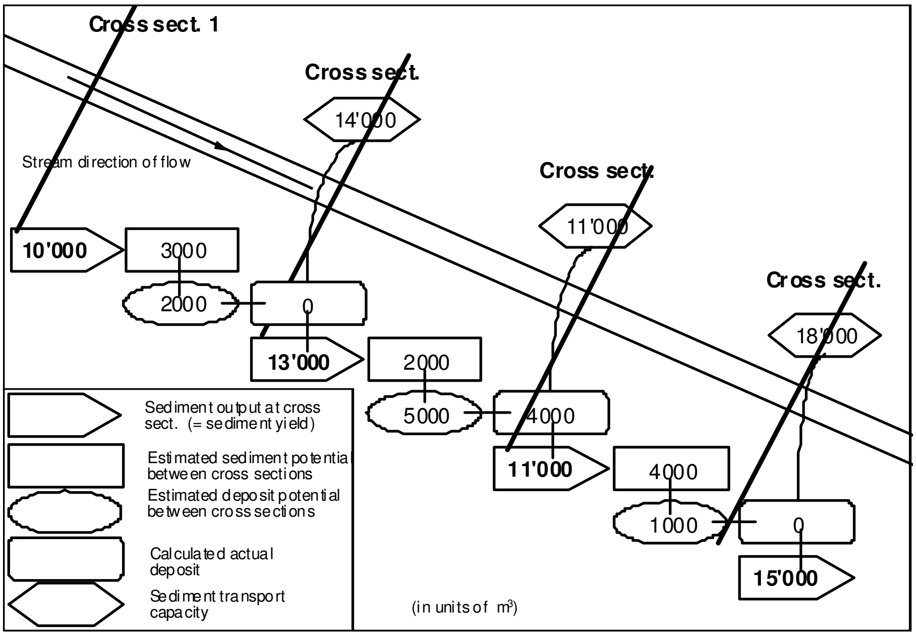


Fig. 73: Determination of the sediment yield in mountain streams (GHO 1996)

<u>Results from the calculations</u>
Fig. 74 is an example of a representation of the result of calculations which were done for the Guppenruns in the canton of Glarus. The flow of the stream from cross section no. 21 (gorge) down to mouth at the Linth (no. 1) is plotted in the diagram. The larger natural deposit points (to be observed at cross sections 19, 18, 13, as well as 8 and 7) are not sufficient to reduce the sediment input in the Linth so that the danger of damming can be ignored.

Fig. 74: Sediment transport during a large event in the Guppenruns, canton of Glarus

So it is possible that much material could be deposited at the fan (cross sections 2 and 1) and cause damage there. It was shown that planning a bed load deposit area near cross sections 8 and 7 together with further retaining measures (near cross sections 14-12) can drastically reduce the sediment yield of a large event which would practically prevent a possible damming of the Linth.

7.2 Germany

7.2.1 Estimation of sediment loads in the German Rhine

7.2.1.1 General remarks

Cross section measurements of bed load transport and suspended load transport are the basis for estimating annual sediment loads. The total sediment load can be divided in the wash load, in the bed load and in the morphological active sand load. The latter is that part of the sand load which is only temporarily suspended and exchanges with the bed sediment (Fig. 75). Therefore it can also be described as suspended bed material.

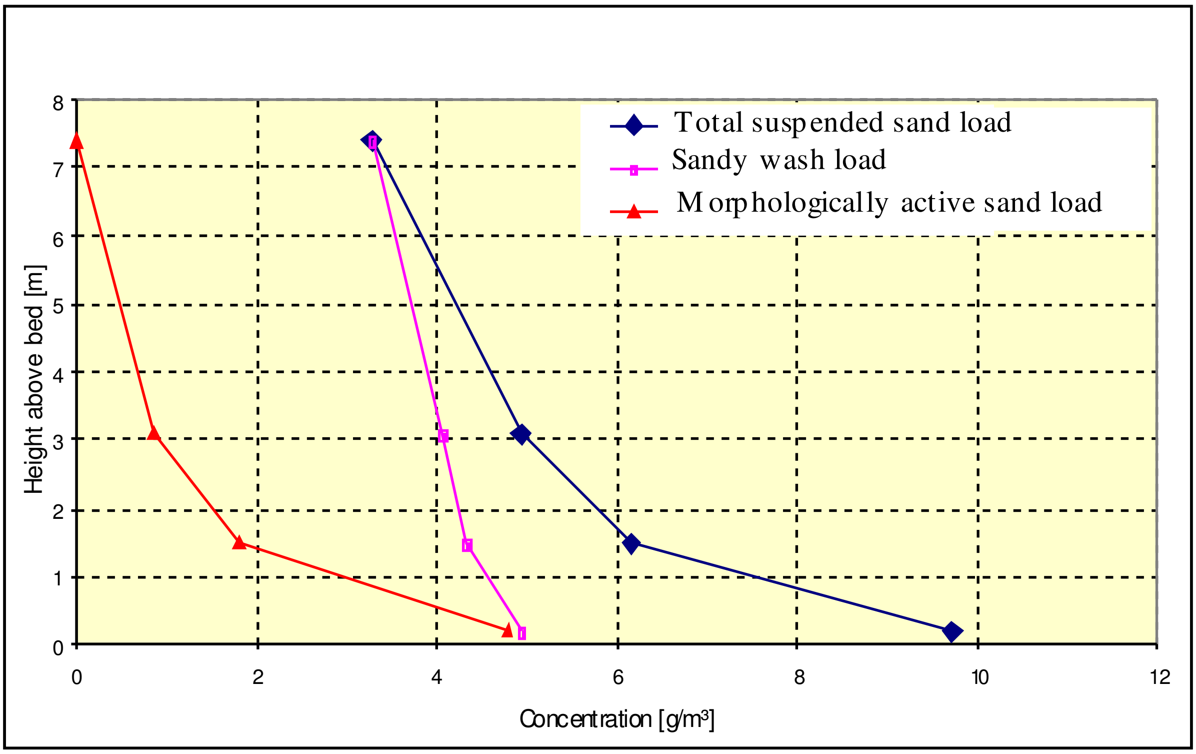


Fig. 75: Discrimination of wash load and morphologically active sand load (BfG, 2008)

Due to the fact that the sediment load is measured at about 40 cross sections, it can be balanced from section to section. Hereby the increase of bed load from one cross section to the next downstream means bed degradation, whereas decrease of bed load indicates aggradation of the river bed.

In the next step degradation and aggregation rates can be computed and compared with the results received from echo-sounding surveys and water-level observations (Dröge et al. 1992). In order to evaluate the effects of the various bed load management measures implemented in recent years, a manual for the combined evaluation of sediment transport data, bed level data and water level data has been elaborated by a working group of the Ministry of Transport, Building and Urban affairs (PGEKG 2005).

7.2.2 Bed load

As stated in chapter 6.2.3 bed load measurements are carried out at five to eight verticals per cross section. From these measurements the unit bed load transport for each vertical is derived. By integrating unit bed load transport over the whole cross section the bed load transport (rate) related to the specific discharge prevailing at the time of measuring is obtained (see Fig. 76).

As bed load measurements are carried out four to five times a year at different discharge situations, after a period of two and more years a bed-load rating curve (bed load as function of discharge) can be established, describing the relation between discharge and bed load transport. In combination with the daily discharges this relation enables the calculation of bed loads for any duration.

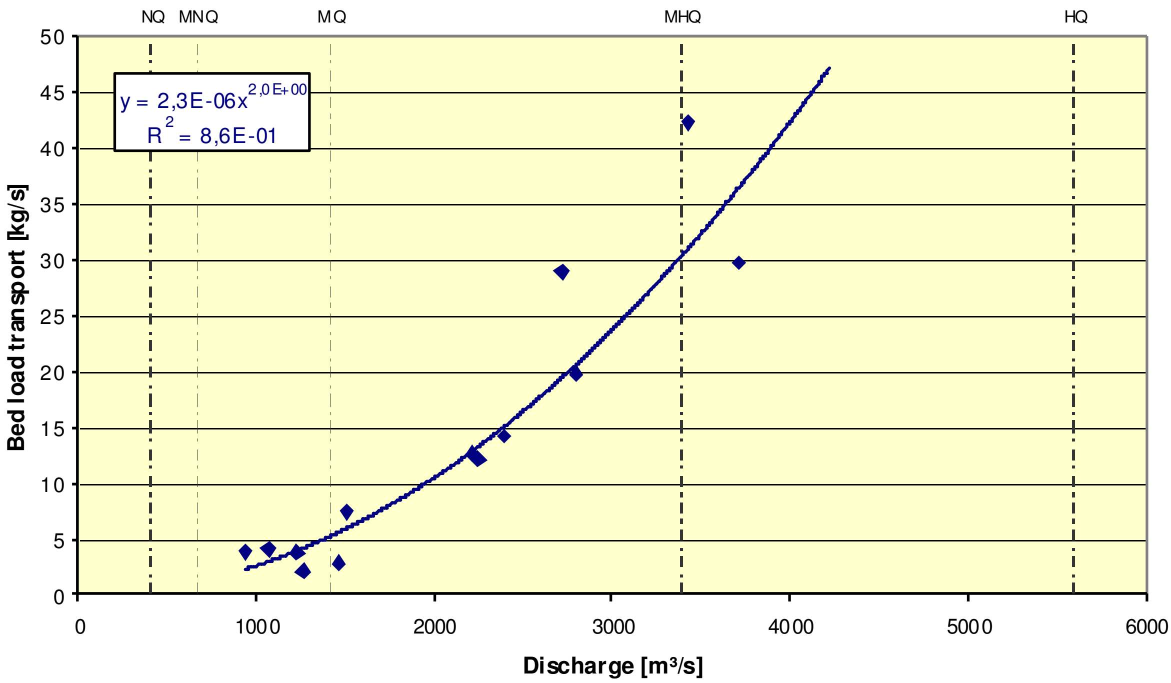


Fig. 76: Bed load transport rating curve, Nierstein, Rhine-km 483.5 (BfG, 2008)

7.2.3 Suspended sand load

Suspended sand load is measured at the same verticals as bed load. From these multi-point measurements the suspended sand load transport is derived and assuming that there are enough measurements, a rating curve for suspended sediment load transport analogous to the bed load rating curve can be established.

As explained before, only part of the suspended sand load is morphologically active. Until quite recently, based on analytical considerations, it was assumed that along the German Rhine two thirds of the suspended sand load belong to the wash load and only one third is morphologically active (Dröge, 1992).

Meanwhile a special investigation carried out at the University of Utrecht has revealed that in the course of the river the portion of the morphologically active suspended sand strongly varies depending on the porosity of the bed sediment (Frings 2006). The approach and results of this study are outlined in detail in the chapter Examples.

7.2.4 Total suspended load and wash load

There are two possibilities to estimate total suspended load. If the total suspended load is determined by multi-point measurements in the cross sections, a rating curve can be established and connected with the discharge hydrograph. The wash load is obtained by subtracting the morphologically active sand load.

The other possibility is to calculate the suspended load by using the daily sediment concentration data of the permanent monitoring stations and combining them with the respective discharge values. As the samples are collected only half a meter below the water surface, it is very likely that the suspended sediment measurements at the permanent stations collect mainly the wash load.

7.2.5 Sediment balance and sediment budget

Sediment balances for the German Rhine are established separately for suspended load and for the so called bed forming load (bed load plus morphologically active suspended sand load). The balances are established by using the annual loads of the individual measuring stations and the cross sections respectively and plotting them in form of longitudinal sections, in order to determine the gradients. Herein increasing loads mean sediment supply by tributaries or erosion of bed sediment, whereas decreasing sediment loads indicate deposition.

Suspended sediment load
Fig. 77 shows the annual suspended loads between Lake Constance and the German Dutch border for the time period 1987-2002. It is obvious, that the first strong input into the system is made by the Aare River, that furthermore part of the suspended load is lost in the impoundment chain of the Upper Rhine, and that the most important input comes from the Moselle River.

The loads were calculated from the data of the permanent stations by using the data base SchwebDB and represent mainly the wash load portion of the suspended sediment.

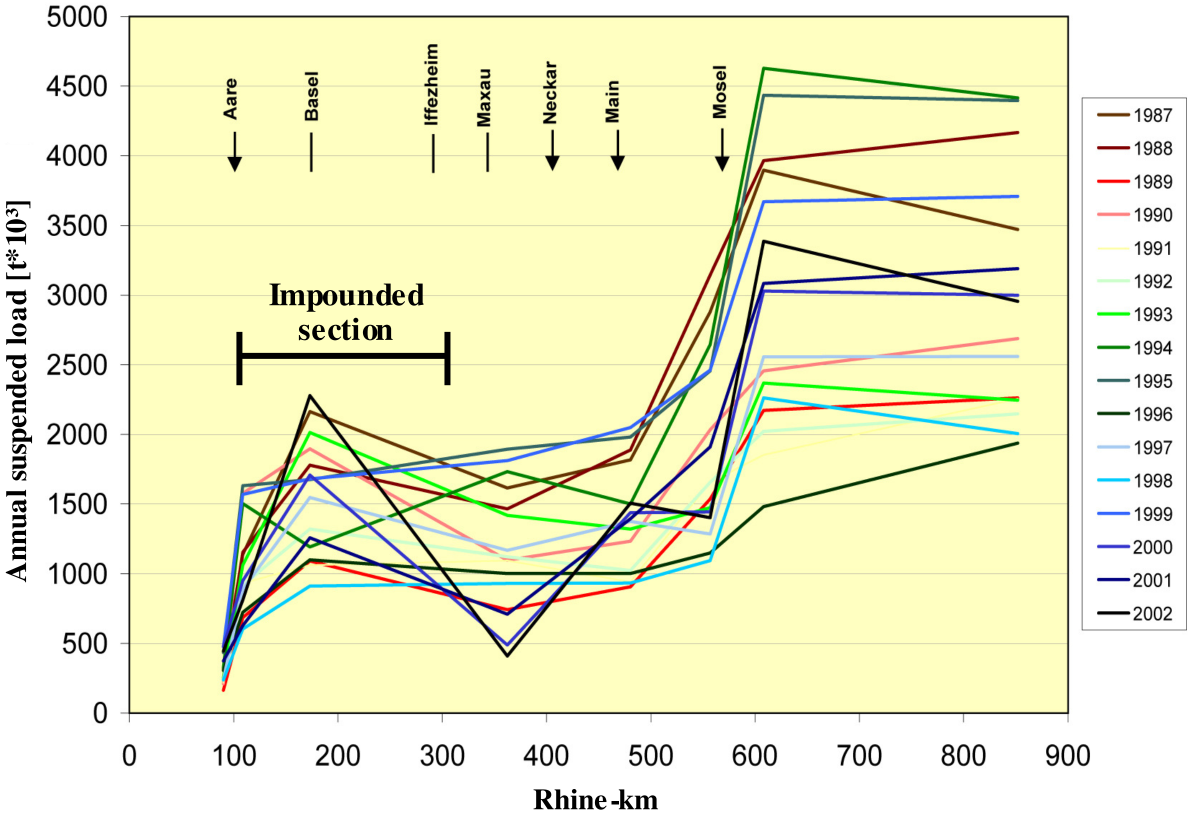


Fig. 77: Longitudinal section of the annual suspended load (1987–2002) (BfG, 2008)

<u>Bed forming load</u>

The bed forming load is calculated by summing up the bed load and the morphologically active suspended sand load. Both loads are derived from cross section measurements. The transport data are calculated by and stored in the data base SedDB. The balances are established by means of a special balance module connected with the SedDB (see Fig. 78) and plotted in terms of a longitudinal section. Herein the loads at the individual cross sections are shown as columns, divided into two segments, one for bed load, the other one representing the morphologically active suspended sand load (Fig. 79). Because the main tributaries of the Rhine are impounded and do not deliver a significant bed load yield, in this graph increasing loads mean bed degradation only. On the other hand decreasing loads indicate aggradation tendencies.

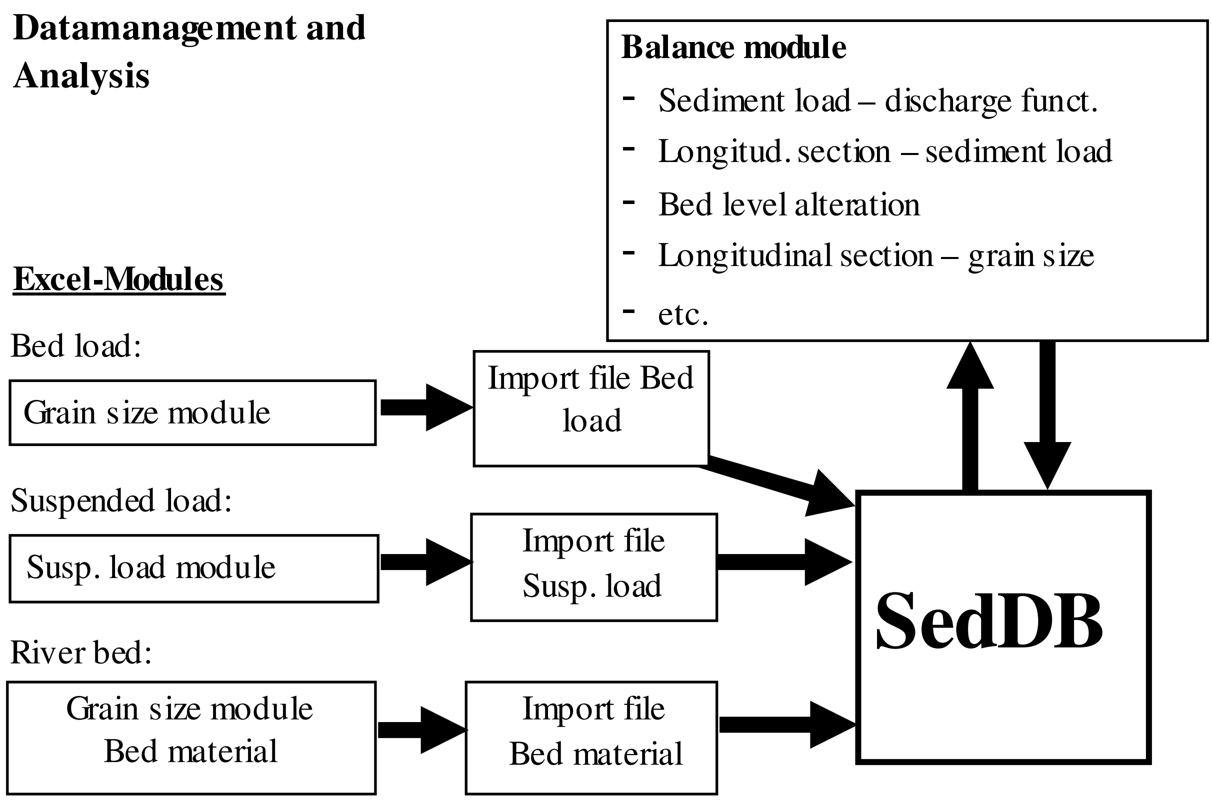


Fig. 78: Sediment data base SedDB and affiliated modules (BfG, 2008)

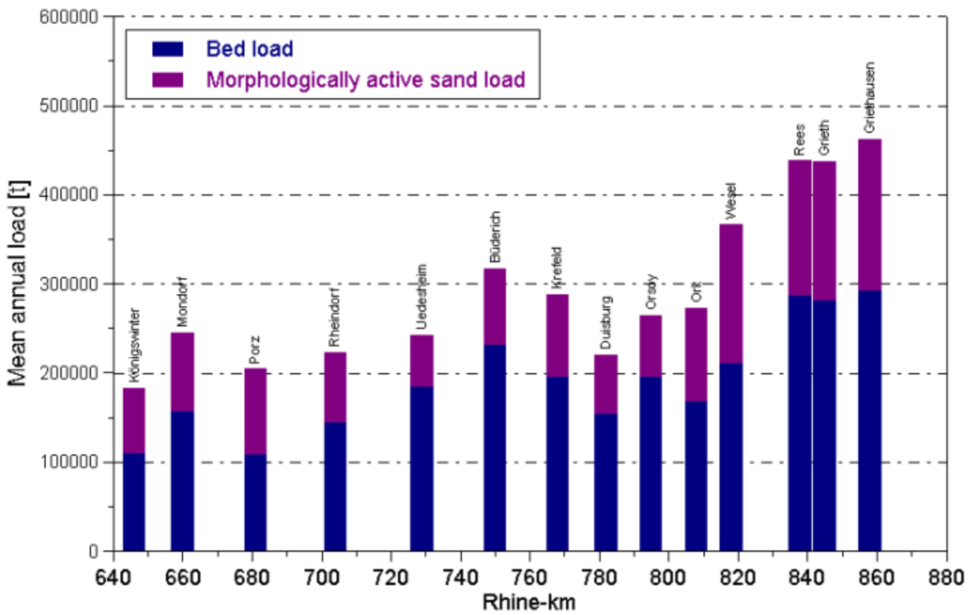


Fig. 79: Longitudinal section of bed-forming load of the Lower Rhine (BfG, 2008)

As already shown, this type of sediment balance serves as a basis for bed-load management measures especially for positioning and dimensioning artificial bed load supply (see also chapter Examples)

7.2.6 Comparison of hydrologic, geometric, and sediment transport data

River stage investigations make it possible to obtain a continuous overview of bed level development from the beginning of systematic stream gauging in 1870 to the present time. An important precondition for the correct interpretation is the consideration of changing discharge conditions by means of a suitable standardization method. Here, it is mainly the development of low water stages that provides information on river bed degradation, as in the case of depth/width ratios of approx. 1:100, the lowering of the water level can be equalled to the bed lowering in good approximation, provided external interferences do not distort the development.

Contrary to this indirect determination of bed level changes, the comparison of the results of repeated cross section surveys has the advantage that the geometry of the river bed is directly measured. Due to the inaccuracy of echo-sounding, however, reliable results can be obtained only on reaches with high bed-level alteration rates and by considering appropriate temporal intervals.

Another indirect method is to calculate the annual sediment loads. The difference of the bed forming sediment loads between two neighbouring stations allows to calculate the eroded or deposited volume of bed material and consequently to derive the erosion and sedimentation rates. This presupposes frequent measurements of sediment transport for the updating of the sediment rating curves.

Tab. 11 e.g. shows the bed-level changes determined by means of river stage investigations, cross-section surveys, and sediment transport measurements in the 20 kilometres long reach between Wesel and Emmerich. The degradation rates determined by the different methods deviate by only about 20%. For hydrological investigations this is a high degree of agreement, demonstrating that all three methods applied are appropriate for the task of erosion monitoring (Dröge et al. 1992).

Tab. 11: Bed level changes determined by different methods in the period 1980–1985 (Wesel – Rees)

Method	Degradation rates [mm per year]	Deviation from the average [%]
River stages	15	6
Cross sections	18	18
Sediment loads	14	12

In a joint BfG/RIZA study bed level and water level developments were compared over a river reach of about 40 kilometres near the German-Dutch border (Ten Brinke and Gölz 2001). Here bed degradation and water level lowering rates showed major differences especially for periods lying farther back. Only for the period 1985-1995 the ratio of bed lowering to water level lowering is near 1. This underlines the necessity to incorporate additionally the results of the bed load measurements into the analysis of bed level development.

This in mind the working group for the success-control of bed load management in the Rhine established a detailed analyzing program containing cross-section surveys by echo-sounding, water-level analysis and sediment-transport measurements taking into account the dredging/dumping volumes as essential elements (PGEKG 2005). The results of these individual evaluations are superimposed in a longitudinal section (Fig. 80) serving as the basis for assessing the effects of the bed load management measures.

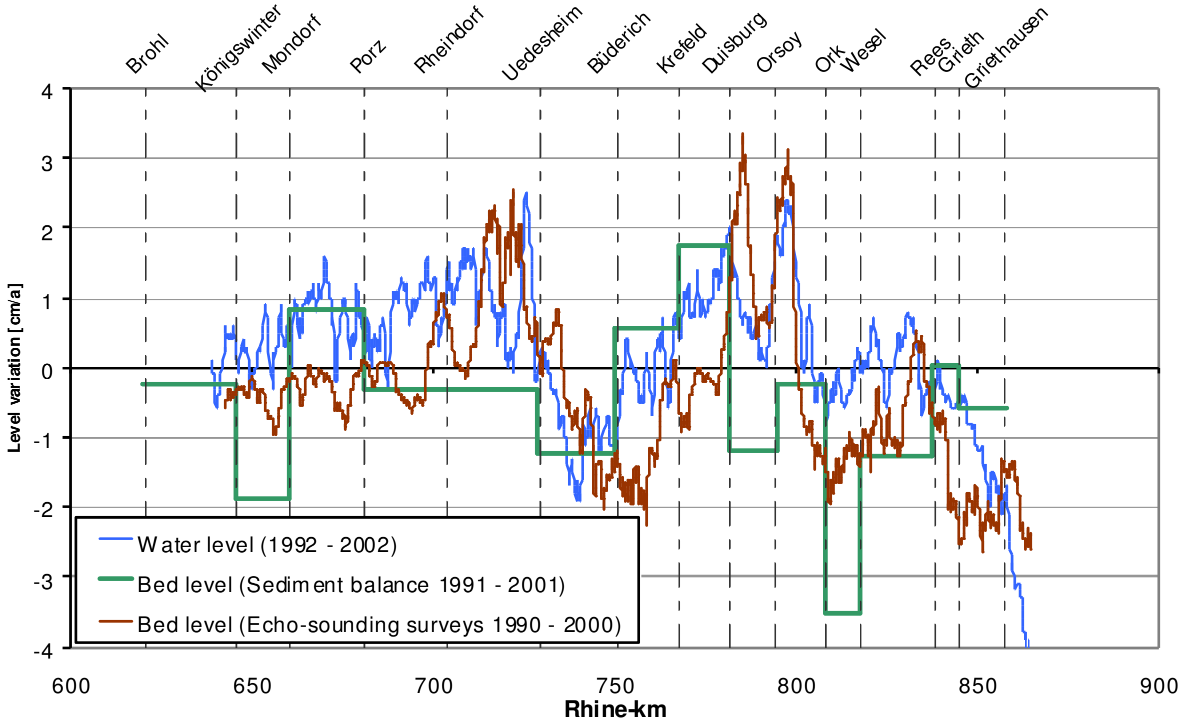


Fig. 80: Variation rates of water level and of bed levels, derived from evaluating the sediment balance and from echo-sounding surveys (BfG, 2008)

7.2.7 Morphological models

Morphological models are numerical tools to estimate the future changes in sediment transport as well as changes of the bed level and the water level on the basis of predetermined boundary conditions (hydrograph, sediment supply and grain composition). By application of a suitable transport equation, sediment loads are determined according to the transport capacity of the system. By using these models the effects of maintenance and construction measures on the various parameters (scenario calculations) can be assessed and the measures can be optimised according to these results. Furthermore, sediment transport models are suitable for the estimation of the development of the abovementioned parameters in the past.

One-dimensional sediment transport models are primarily used to describe large-scale and long-term effects. With these models it is possible to estimate the changes, for example, of the mean bed level over several decades for a distance of some hundred kilometres. The results thus attained are to be understood as the forecast of temporally and spatially averaged developments; it is not possible to make evaluations specific to a particular time and place. Nevertheless, one-dimensional sediment transport models can make a significant contribution to the optimisation of bed load management. One-dimensional models work with cross-sectional averaged values. The geometry of the river bed is exactly covered only at profile stations. Multi-dimensional models however have the advantage, amongst others, of a completely three-dimensional coverage of the flow margin. With their capacity to describe locally flow velocities and flow depths coupled to eddy inceptions, multi-dimensional models are particularly suitable for solving problems that require a high temporal and spatial resolution.

On the German Rhine only one-dimensional sediment transport models have been used up until now and only for limited sections. Multi-dimensional sediment transport models are still at the testing stage. At present a continuous one-dimensional sediment transport model is being developed by the German Federal Institute of Hydrology (BfG) in cooperation with the Dutch Centre for Water Management (formely RIZA) for the whole free-flowing river from Iffezheim down to the Dutch Rhine branches.

7.3 The Netherlands

<u>Preparation</u>
In The Netherlands, the quantification of the cross-section integrated sediment transport is the basis for sediment yield assessments. The cross-section integrated transport is combined with information on hydrodynamics and grain size of the top layer of the riverbed to calibrate sediment transport formulae in numerical models. Also, these results are combined with time series of echo soundings to quantify sediment budgets of the Dutch river system. The method for the quantification of the cross-section integrated sediment transport is more or less standardized and published in a scientific journal (Kleinhans and Ten Brinke 2001).

<u>Field work and analyses</u>
In the field a series of different measurements are carried out, focussing on the sediment transport, the hydrodynamics and the composition of the bed. These measurements are mostly conducted during floods: generally the same measurements are repeated at several stages of the flood wave.

Bed load: The bed load is determined by placing the Helley Smith bed load sampler on the river bed for one or two minutes and measuring the amount of sediment (sand and gravel) that is trapped in the bag. These samplings are conducted 10 or 20 times in a row and from these data 1 average number for the bed load is quantified. This procedure is carried out at several positions across the channel (see Fig. 81). Additionally, the bed load is calculated from the displacement of bed forms following the dune track approach. The benefit of the dune track approach is the fact that these measurements (multi-beam echo soundings) can easily be carried out over a large area in a short period of time. Hence, bed load from dune track can be determined over larger areas than the approach with only the Helley Smith bed load sampler. The Helley Smith samples are needed, however, to calibrate the dune track results. The dune track approach in The Netherlands has been published in a scientific journal (Wilbers and Ten Brinke 2003).

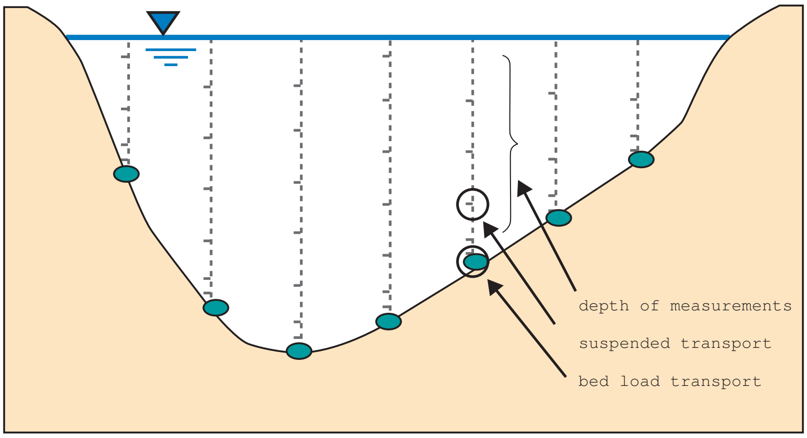


Fig. 81: Diagram of the manner in which the sediment transport is determined by means of measurements throughout a cross section of the river (Ten Brinke 2005)

Suspended load: With respect to suspended load a distinction is made between sand and silt. The suspended sand load is determined by moving the Acoustic Doppler Current Profiler up and down the water column at the same locations and moments of the bed load sampling. At regular times water samples are taken that are filtered using a pump filter set. These samples are used to validate the ADCP: the ADCP is calibrated before the measurements in a flume at different current velocities.

The suspended silt load is determined from water samples that are taken at several positions across the river. In the Rhine the silt load is by far highest in the rising stage of flood waves. During a flood wave the silt concentration strongly varies whereas during low discharges it stays more or less the same. Hence, silt measurements on the Dutch Rhine focus on the strong variation during a flood wave.

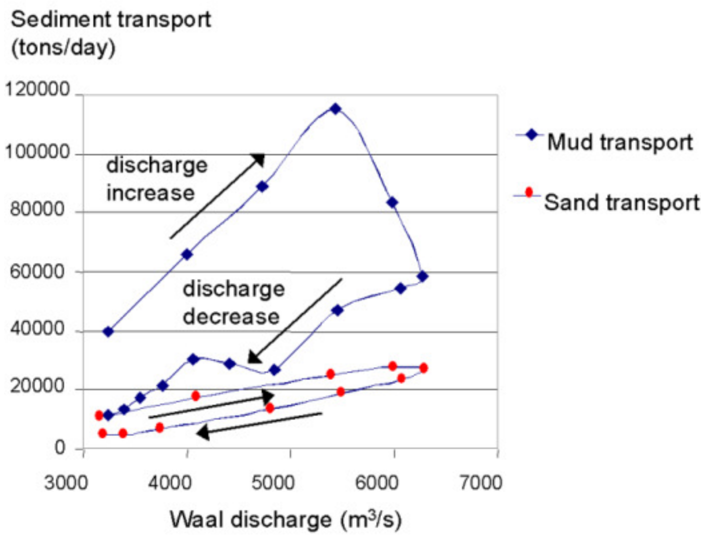


Fig. 82: Sand and silt entrainment at various discharge rates while the river discharge increases and decreases during a discharge wave on the Waal. The hysteresis for the transport of silt (mud) is much more extreme than that for the transport of sand (Ten Brinke 2005).

Hydrodynamics: In The Netherlands, water level is measured at several positions along the rivers continuously. When sediment transport is measured, additional water level measurements are conducted near the transport measurements to obtain the hydraulic (energy) gradient in sufficient detail. Also, current velocity and discharge measurements are carried out in the cross-section where the sediment load is sampled. All these measurements are carried out during the period of time of the sediment sampling, which is on average two weeks.

Grain size riverbed: When sediment transport measurements are conducted in The Netherlands, they are part of extensive research projects. Over the last years, drilling cores into the bed has also been part of these projects. From these drillings samples were taken to obtain sieving curves. When no drillings are carried out, Van Veen grab samples are taken.

Application results in sediment budgets

The sediment budget of the Dutch Rhine river system represents the incoming flows of sediment from upstream, the exchange of sediment with the riverbed and the floodplain (through erosion and sedimentation) and the outgoing flows where the Rhine branches flow into the coastal zone or Lake IJssel. The sediment budget refers tot a specific period of time: for the Dutch Rhine generally annual sediment flows are determined from datasets that cover a period of 10-20 years. These data are cross-section integrated sediment loads and echo soundings.

Application data in models

For the Dutch Rhine one and two-dimensional morphological models are used. The one-dimensional model is also available as a graded model (calculations can be made with a variety of grain sizes). In the next years, the two-dimensional model will also become available as a graded model.

8 Legal, administrative and organizational aspects

8.1 Laws

8.1.1 Switzerland

The Federal Constitution of 1874 (FC) proves that it has been recognized how important the protection of the living space before floods was already at that time. In article 24, the federation was assigned the superintendence over hydraulic and forest police. At the same time, the possibility to financially support water correction works was created. In 1877 with the Water Surveyor's law, the first federal law in the field water resources management was created. Some Swiss laws in historical order are lined out in Tab. 12.

Tab. 12: Laws and resolutions in Switzerland for the benefit of the protection of men and nature

Year	Law / resolution
1804	Resolution of the "Tagsatzung" about the Linth correction
1848	Art. 21 of FC about public works
1874	Art. 24 hydraulic and forest police
1877	First federal water surveyor's law, use of waters
1908	Art. 24bis of FC use of waterpower
1916	Second federal law (water law)
1919	Art. 24ter of FC navigation; protection of waters
1953	Art. 24quater of FC water conservation
1955	Third federal law (water conservation law)
1975	New article for water economy in FC: as base for: (also retrospectively)
1971	Federal law about water conservation (qualitative protection of waters)
1992	Law of 1971 revised, (for example for a minimum residual water discharge)
1994	New law on hydraulic works

Apart from the federal laws, there are the cantonal laws, which might vary in details from federal law, but are not conflicting with the former.

8.1.2 Germany

There are several Federal acts for the protection of water resources, soil, natural resources, and other environmental issues, but due to the Federal system in Germany the executive competence for water resources management belongs mainly to the Federal states. In this context responsibility for sediment management in Germany is split regionally in waterways (large rivers and canals) and remaining waters. Responsible for the latter are the water boards of the individual states, whereas the Federal Ministry of Transport, Building and Housing and its subordinate authorities like the Waterways and Shipping Administration operate and supervise the waterways.

The relevant national laws concerning water and sediment are the Water Management Act (WHG) and the Federal Waterways Act (WaStrG). For specific riverine management activities the Environmental Impact Assessment Act (UVPG), the Federal Soil Protection Act (BodSchG), the Closed Substance Cycle and Waste Management Act (KrW-/AbfG) and the Federal Nature Conservation Act (BNatSchG) have to be considered.

Since 2002 the European Water Framework Directive has come into force. As a consequence the national Water Management Act has already been adapted to the new European directions. The same holds for the Federal Nature Conversation Act, which was adapted with the 2nd amendment to the EC Fauna–Flora-Habitat-Directive. Adaption or modification of other national regulations to future European legislation e.g. concerning the Federal Soil Protection Act (thematic strategy for soil protection) or the European Waste Directive will follow.

8.1.3 The Netherlands

There are several laws in The Netherlands to protect the Dutch water systems from different points of view. In the context of sediment management the most important laws are those dealing with water (and soil) quality, with water quantity and with the protection of the hinterland against flooding.

In the 1969 Surface Water Pollution Act the draining of pollutants on surface waters is regulated. This law also regulates the activities with respect to dredged (and polluted) sediments. In the 1989 Water Management Act the management of water quantities in the water systems in The Netherlands has been regulated.

In the 1996 Flood Protection Act safety standards for the Dutch flood defences have been set. These standards require a minimum height and strength of dikes and constructions surrounding a given flood prone area.. Large-scale measures such as those within the Room for the River Project, aim at adapting the river system in such a way that the legal standards are met. At present, an integrated Water Act is being prepared that is supposed to integrate and replace the acts mentioned above.

8.2 Regulations

8.2.1 Switzerland

The regulation of hydraulic engineering of 1994 (Wasserbauverordnung WBV) regulates financial support and priorities for the construction of protective works. The evaluation of basic data is also regulated, both by federal authorities as well as by cantons.

The regulation about water conservation (Gewässerschutzverordnung, GSchV) protects all waters from negative impact and enables their sustainable use.

The forest regulation (Waldverordnung, WaV) of 1992 regulates the use of forests in the country. As forests have also a protective function against natural hazards (erosion, landslides etc.) the forest regulation includes the elaboration of basic requirements in the field of risk assessment (mapping etc.)

8.2.2 Germany

With respect to dredging, relocation and disposal of sediments in the Federal waterways there are two internal regulations of the Ministry of Transport, Building and Housing: these are the „Handlungsanweisung für den Umgang mit Baggergut im Binnenland (HABAB-WSV) and the "Handlungsanweisung für den Umgang mit Baggergut im Küstenbereich (HABAK-WSV). In addition the "Handlungsanweisung für die Berücksichtigung von Naturschutz und Landschaftspflege bei der Unterhaltung von Bundeswasserstrassen (HANATSCH-WSV) might have to be considered. Depending on its contamination the deposition of dredged sediment on land is subject to the Federal Soil Protection and Contaminated Site Ordinance (BBodSchV) and the ordinance of Waste Dumping (DepV) respectively. Some Federal states in Germany have established individual regulations for handling dredged sediments.

8.3 Bilateral and multilateral agreements and treaties

On the 17th of March 1992, the riparian states of the Rhine basin ratified the basic agreement about the protection and the use of international rivers and lakes. This basic agreement imposes the following obligations on the riparian states:

- to avoid, control and reduce water pollution
- to use transnational waters in an environmentally compatible way and protect water resources
- to use transnational waters in a reasonable and fair way
- to secure the protection and at all events the restoration of ecosystems

8.4 Cooperation in international River basin committees

Because of the significance of the Rhine River basin various international commissions have been active for some time already. A survey on these Commissions and the scope of their work is given in Tab. 13.

Tab. 13: nternational organizations in the Rhine River basin

Name	Task	Activity
KHR International Commission for the Hydrology of Rhine basin	• Support of co-operation of the scientific hydrological institutes and hydrological services in the Rhine basin • Promotion of data and information exchange in the Rhine basin • Standardization of data in the Rhine Basin countries	• Comparison of hydrological models and instruments • Forecasting of floodwaves • Flood analysis • Investigations on sediment transport • Geographical Information System Rhine • Influence of climate change on runoff in the Rhine
IKSR International Commission for the Protection of the Rhine	• Investigations on sources, transport and sinks of pollutants • Recommendations for the govemments of the Rhine basin countries	• Investigations on pollutants in the water, flora and fauna of the Rhine • Biological and chemical monitoring • Research on ecomorphology

Name	Task	Activity
	• Drafting contracts for the protection of the Rhine • Realization of govemmental Agreements • Plan of action related to floods	• Investigation on point and non point sources of pollutants • Alarm modeling • Surveillance of emissions
IKSMS International Commission for the Protection of the Mosel and Saar	• Investigations on pollution of the rivers Mosel and Saar • Recommendations for the Governments of the riparian countries • States • Realization of governmental agreements	• Research on ecosystems • Planning of measures against pollutant inputs • Standardization of measuring systems • Inventory of main pollutants and their reduction • Alarm modeling
IAWR International Association of Water Treatment Plants in the Rhine Basis	• Monitoring of water quality • Standardization of water analysis concerning drinking water supply • Improvement of water quality	• Comparison of techniques used in water treatment plants • Comparing and standardizing of analytical procedures • Investigation on techniques for the improvement of the quality of drinking water
IGKB International Commission for the Protection of Lake Constance	• Monitoring of the water quality of Lake Constance • Recommendations for the riparian countries • Advice concerning future antipollution measures in the basin	• Promoting research on water quality and limnology • Continuous evaluation of water quality • Planning of further use of water (drinking water supply, recreation)
ZKR Central Commission for Navigation on the Rhine River	• Cooperation of the riparian countries with regard to Navigation, maintenance of on the waterways standardization of technical/policy guidelines	• Individual working groups draft proposals and supervise navigation on international waterways within the Rhine basin

8.5 Organizations responsible for monitoring

8.5.1 Switzerland

Sediment monitoring is executed by the Swiss National Hydrological Survey of the Federal Office for the Environment. In addition, several cantons operate sediment observation stations.

8.5.2 Germany

Sediment monitoring at waterways is controlled by the Federal Institute of Hydrology (BfG), at the remaining rivers by the State Agencies for Environment. These Institutions also operate the data bases for water and sediment. Sampling and measuring are done by the Water and Shipping offices and the offices for Water Management of the states respectively.

8.5.3 The Netherlands

Sediment monitoring in the main rivers and in the large fresh water lakes is executed by the Centre for water Management (formely RIZA). At the streams sediment monitoring is the responsibility of the water boards.

9 Selected recommendations concerning sediment management

9.1 Flushing and emptying dammed waters

The Swiss Federal Law on the protection of waters demands the following:

1. The holder of a water damming installation shall as far as possible ensure that in flushing or emptying a storage basin or in controlling equipment for draining water and relieving flood water, fauna and flora living in the waters below the dam in question shall not be impaired.
2. Flushing and emptying shall take place only with the permission of the cantonal authority. The responsible authority shall consult interested competent agencies. If periodical flushing and emptying are required in order to maintain operational safety, the authority shall fix only the times and types of such operations.
3. If a holder is obliged to lower the water level of a reservoir on safety grounds as a result of exceptional occurrences, he shall immediately inform the responsible authority.
4. Any person who dams-up water shall refrain from returning to the water any flotsam which he may have removed for operational reasons. The authority may permit exceptions.
5. The holder of a water damming installation shall periodically collect flotsam in the area of his installation according to the instructions of the authority.

The Swiss Federal Water Protection Ordinance translates the law in concrete terms:

1. Before an authority authorises the flushing out or emptying of dammed-up waters, it shall ensure that sediments are removed other than by washing away if this is environmentally compatible and economically acceptable.
2. When washing away sediments the authorities shall ensure that biocoenoses of plants, animals and micro-organisms are interfered with as little as possible, in particular by prescribing:
   a. time and type of flushing out or emptying;
   b. the maximum concentration of suspended matter in the water which must be respected during the flushing out or emptying;
   c. to what extent washing away must be carried out so that during the flushing out or emptying, fine matter deposited in watercourses is removed.
3. Paragraphs 1 and 2 do not apply to immediate subsidence resulting from an exceptional event.

The following example shows how a cantonal authority implements this law into practice:
1. Flushing has to be executed during normal flood events
2. Boundary limits of sediment concentration may be:
   a. 10 ‰ as short time highest value
   b. 5 ‰ for duration of less than 24 hrs
   c. 2.5 ‰ 48 hrs
   d. 1.25 ‰ of more than 48 hrs.

   or instead of using boundary limits of sediment concentration, detailed specifications have to be complied with, concerning:
   - hydrobiologic conditions in the channel
   - flushing itself
   - observation program

3. The water table of the sediment load reservoir has to be sunk as low as possible
4. The opening of the outlets shall be done slowly to simulate as much as possible a natural flood
5. After flushing, rinse the channel bed with clear water to wash out the sediment surplus downstream
6. Before and after the flushing, a comprehensive biological and sedimentological observation has to be executed
7. The sediment concentration has to be checked before, during and after flushing
8. If technically possible, an addition of clear water near the dam has to be provided to reduce sediment concentration.

9.2 Extraction of gravel, sand and other materials from water courses

The Swiss Federal Law on the protection of waters demands the following:
"Anyone wishing to extract gravel, sand or other materials to carry out preliminary excavations for such extraction shall require a permit."

1. Permits for such work shall not be granted:
   a. in groundwater protection zones
   b. below the groundwater table of groundwater resources whose amount and quality are suitable for water catchment;
   c. for watercourses where the flow of detritus may be negatively affected.
2. For groundwater resources whose amount and quality are suitable for water catchment, extraction may be permitted above groundwater level, provided there is a possibility of a protective layer of material above the maximum groundwater level. The dimension of this protective layer shall be chosen in accordance with to the local conditions.

The Swiss Federal Water Protection Ordinance translates the law in concrete terms:

In order that the bed load economy in a watercourse is not unfavourably influenced by extraction of gravel, sand and other materials, the authorities must ensure that:

1 the quantity of bed load extracted from the watercourse does not exceed the quantity naturally fed into it
2 the extraction does not in the long term lead to a subsidence of the bottom outside the extraction perimeter
3 the extraction does not render impossible the maintenance and reestablishment of meadows that have been included in an inventory
4 the extraction does not lead to a substantial change in the particle size distribution of the bottom material outside the extraction perimeter.

Extraction according to paragraph 1 should not lead to turbidity that may impair fishing waters.

10 Rhine sediment quality and its management

10.1 Sediment quality and assessment

Sediment is an essential and integral and dynamic part of any river basin, also of the Rhine. A healthy Rhine river needs sediment as a source of life. Sediment forms a variety of habitats. Many aquatic species live in the sediment. Microbial processes cause regeneration of nutrients and the important functioning of nutrient cycles for the whole water body. Sediment dynamics and gradients (wet-dry and fresh-salt) form favorable conditions for a large biodiversity, from the origin of the Rhine river to the coastal zone. Sediment is also a resource for human needs. For millennia, people living at the Rhine have utilized sediments as fertile farmland and as a source of construction material (Salomons & Brils, 2004).

Unfortunately, sediment also acts as a potential sink for many hazardous chemicals. Since the industrial revolution, human-made chemicals have been emitted to the Rhine surface waters. Due to their nature many of these chemicals stick to sediment. Hence in areas with a long record of sedimentation, Rhine sediment cores reflect the history of the pollution. Whereas water quality at most places in the Rhine is improving, the legacy of the past is still present in sediments hidden at the bottom of the Rhine river, behind dams, estuaries and on the Rhine floodplains. These sediments may become a secondary source of pollution when they are eroded (e.g. due to flooding) and transported further downstream.

Along the course of the river Rhine to the Nord Sea, transportation, dilution and redistribution of sediment-associated-contaminants occurs. Many, relatively small inputs, all complying with emission regulations, may accumulate to reach higher levels by the time sediment reaches the Rhine river delta. In the estuary, uncontaminated marine sediments are mixed with contaminated fluvial sediments. This natural 'dilution' decreases contamination level in a gradient towards the sea over short distances, but does not alter the actual transported quantity of contaminants.

Contaminants can be degraded or fixed to sediment components, thus decreasing their bioavailability. The relation between sediment quality and risks is complex and site specific. However, at a certain level contaminants in sediment will start to impact the ecological or chemical water quality status and complicate sediment management. In the end, effects may occur such as the decreased abundance of sediment dwelling (benthic) species or a decreased reproduction or health of animals consuming contaminated benthic species. Such impacts have also been demonstrated for contaminated Rhine sediments and floodplains (see e.g. Den Besten *et al.*, 1995 and De Jonge *et al.*, 1999).

For the assessment of contaminated sediment, there is not one 'best' method available. Each specific management question requires a tailor-made solution. Chemical analysis can be used to determine concentrations of selected, hazardous chemicals and then it can be checked if the concentrations exceed pre-defined standards or guideline values. The toxic effects of sediment on organisms can be tested by using bioassays. Through a field inventory the long-term impact on sediment biota can be investigated. These assessment methods (chemical, bioassay, field) are complementary by giving a unique answer that cannot be given by any of the individual methods by themselves. But each method also has its own unique drawbacks and uncertainties (Salomons & Brils, 2004).

10.2 Trends in Rhine sediment quality

Catalysed by the Sandoz Rhine accident in 1986 (Giger, 2007) and due to the Rhine Research Project (1984–1994) of the Port of Rotterdam (Port of Rotterdam, 2001) and due to the committed implementation of the Rhine Action Programme (1987–2000) of the International Commission for the Protection of the Rhine (ICPR), the Rhine bordering countries implied great efforts to reduce inputs of noxious substances and nutrients from industry and municipalities. Since then the water quality of the Rhine has fundamentally improved, which resulted in a continuous improvement of the biological state of the Rhine and its tributaries and the species number continues to rise (ICPR, 2007a). All these efforts also led to a significant improvement of the chemical quality of newly settled sediments.

Tab. 14: Five step classification taken ICPR target values (class 1) as basis

Pollutant	Unit	Class 1	Class 2	Class 3	Class 4	Class 5
Cd	mg/kg	≤ 1	> 1 – 2	> 2 – 4	> 4 – 8	> 8
Cu	mg/kg	≤ 50	> 50 – 100	> 100 – 200	> 200 – 400	> 400
Hg	mg/kg	≤ 0.5	> 0.5 – 1	> 1 – 2	> 2 – 4	> 4
Ni	mg/kg	≤ 50	> 50 – 100	> 100 – 200	> 200 – 400	> 400
Pb	mg/kg	≤ 100	> 100 – 200	> 200 – 400	> 400 – 800	> 800
Zn	mg/kg	≤ 200	> 200 – 400	> 400 – 800	> 800 – 1600	> 1600
Benzo(a) pyren	mg/kg	≤ 0.4	> 0.4 – 0.8	> 0.8 – 1.6	> 1.6 – 3.2	> 3.2
HCB	mg/kg	≤ 40	> 40 – 80	> 80 – 160	> 160 – 320	> 320
PCB 153	mg/kg	≤ 4	> 4 – 8	> 8 – 16	> 16 – 32	> 32
PCB (sum of 7)	mg/kg	≤ 28	> 28 – 56	> 56 – 112	> 112 – 224	> 224

In the last ten years a lot of sediment and suspended particulate matter (SPM) investigations have been made to evaluate the level of contamination. A first, basin-wide inventory of contaminated sediment in the Rhine was published by S. Heise (Heise, S. *et al.* 2004). In the water quality monitoring program of the ICPR every year the contaminant situation of heavy metals in SPM is evaluated in comparison with the ICPR target values (ICPR, 2007b). On basis of these target values, and based on a five step classification (concentration steps as a multiple of the ICPR target values - see Tab.14), a first assessment of relevant sediment contaminants was possible:

- heavy metals: **Cd** (Cadmium), **Cu** (Copper), **Hg** (Mercury), **Ni** (Nickel), **Pb** (Lead), **Zn** (Zinc)
- organic compounds like: **Benzo(a)pyrene** (for Polycyclic Aromatic Hydrocarbons), **HCB** (hexachlorobenzene)**, PCB** (Poly Chloro Biphenyl) **153** and **PCB (Sum of 7)**.

The main relevant contaminant of sediment cores in the Upper Rhine barrages is HCB. It is known that during the period 1960-1985 large amounts of HCB, mainly as by-product from chemical production near Rheinfelden (km 148) were discharged into the Upper Rhine. Sediments of the Lower Rhine and the Dutch Rhine are – in contrary – mainly contaminated with PCB and heavy metals like cadmium and mercury. In the tributary Main at the Eddersheim barrage high concentrations of cadmium, mercury, copper, lead, zinc and also PCB could be found in the headwater sediments.

10.3 Contaminated sediment re-suspension risks

Although in general water quality and thus also Rhine sediment quality is improving, deeper layered, historically contaminated sediments remain potential sources of adverse affects on water resources through remobilization and the release of contaminants to surface waters and groundwater (Salomons & Brils, 2004). Hence, the remobilization of noxious substances of contaminated sediments of the Rhine and its tributaries due to floods and/or due to the excavation may be problematic (ICPR, 2007a).

On behalf of the ICPR a research project was carried out in the years 2000 until 2003 aimed to assess the re-suspension risk of contaminated sediments (Witt, O. *et al.* 2003, Witt, O. 2004). The main objective of the investigation was to obtain an insight into the erosion stability of contaminated sediment layers as a function of physical sediment parameters and to quantify the contamination. A risk remobilisation assessment based on both hydrodynamic and chemical parameters was thus developed for high water. At the Institute for Hydraulics, University of Stuttgart, a specific cohesive sediment erosion testing device was developed to quantify the critical erosion shear stress. Further development of the experimental set-up enables to quantify not only the critical erosion shear stress but also the erosion rate as another key parameter in quantifying and modelling erosion processes. A special sediment sampling technique allows undisturbed sampling of sediment cores with a diameter of 13,5 cm. An empirical correlation between the different physical parameters such as erodibility, bulk density, gas content etc. and chemical parameters can be established by parallel sampling of neighbouring sediment cores. These data allow to investigate different flood scenarios to provide a first estimate of the amount of released contaminants due to re-suspension.

The results of this ICPR research project show that contaminated sediments in the tributary Main (see previous section) are partly consolidated and the risk of re-suspension during high flood events is low. However, the HCB contaminated sediments at the Upper Rhine barrages showed low values of critical shear stress and thus could easily be re-suspended. For example the HCB release at the Marckolsheim barrage is estimated at 6 to 17 kg during high water (> 3000 m³/s). These contaminated sediments move downstream when they become remobilized (e.g. by high floods or dredging activities) and settle in areas of low flow velocity like the two final barrages in Gambsheim and Iffezheim.

Tab. 15: HCB concentrations of sediments in barrages of the Upper Rhine

Barrage	Average Value in µg/kg	Maximum Value in µg/kg
Iffezheim	158	910
Gambsheim	128	400
Strasbourg	223	2300
Gerstheim	135	1500
Marckolsheim	609	4100

Tab. 15 shows HCB content of sediments in a depth of 0-1,2 m. The results are taken from the ICPR research project. Further investigations prove, that especially in the headwaters of the

Marckolsheim and Rhinau barrages sediment contamination is a source for ongoing pollution downstream.

10.4 Sediment management

In general, sediment management challenges and problems relate to quality and quantity issues. Quality issues relate to contamination, legislation, perception, risk-assessment, source control and destinations of dredged material. Quantity issues mainly relate to erosion/re-suspension (see previous section), sedimentation, flooding, the effects of damming and the resulting morphological changes downstream. Often quantity and quality aspects are interrelated: the overall umbrella is the river basin. Furthermore, contamination adversely effects sediment management, as handling of contaminated material, e.g. in the case of dredging, is several times more expensive than handling clean material. However, also clean sediment can have environmental and socio-economic impacts. For instance turbidity and excessive sedimentation have a physical effect on benthic life, too much sediment in navigation channels requires costly dredging, and sedimentation behind dams and barrages decreases the economic lifetime of that dam or barrage. Furthermore, dams and barrages decrease the supply of sediment needed to support downstream wetlands, estuaries and other ecosystems (Salomons & Brils, 2004).

The European Sediment Network SedNet (see: www.sednet.org) pointed out that sediment – due to being an essential, integral and dynamic part of rivers basins – should be managed at the river-basin scale. Thus, according to SedNet, sediment quantity and quality management should be an integral element of Water Framework Directive (WFD, 2000) River Basin Management Plans (Salomons & Brils, 2004) and exceptions from including sediment management into these plan should be justified (SedNet, 2006).

10.5 Towards a management plan for contaminated sediments

Mandated by the ICPR, the ICPR expert group "SEDI" since 2005 elaborates a comprehensive strategy for sediment management in the Rhine basin. Main objectives are a sediment management plan for contaminated sediments addressed to competent authorities in the watersheds for implementation in measure programs according to WFD and the "improvement of sediment quality in order to relocate dredged material without harm" (Art. 3 of the ICPR Rhine Convention). The group consists of experts from the countries CH, D, F and NL. Water management authorities, waterways and shipping directorates, environment ministries and scientific institutes are involved.

The two main questions addressed by the expert group SEDI are:

a. How do historically contaminated sediments nowadays effect the water and suspended sediment quality during high flood events and/or during dredging and relocation activities?
b. Are contaminated sediments of the Upper Rhine also a risk for sediment quality in regions far downstream like the Netherlands?

The mandate of the SEDI group covers three points: First, to draft a management plan for contaminated sediment. This includes an inventory of relevant sediment studies so far, the determination of the extent of contamination and the quantity of contaminated sediments, the assessment and classification of sediments according to their risk potential, and proposals for an economically and ecologically acceptable handling of sediments of different classes. Second, peripheral conditions to be taken into account. These are national regulations as well as inter-national recommendations and strategies for action aimed at the management of sediments and dredged material handled in the Rhine basin so far. Third, a survey of hot spots including priority action has to be provided. The results of the ICPR research project mentioned before have been an important part of the current draft of the comprehensive strategy for sediment management in the Rhine basin.

The conceptual approach for the sediment management plan drafted by the SEDI group is based mainly on the recommendations of SedNet (Apitz *et al.*, 2007) and a study of contaminant situation along the river Rhine (Heise *et al.*, 2004) and was developed in three steps as follows:

1. Identification and classification of contaminants that are relevant in the watershed;
2. Identification and classification of areas with an increased contaminant load;
3. Identification and classification of areas of risk.

The whole rule-based evaluation for the identification of areas of risk is shown in Fig. 1. After detailed data analysis of the sediment and suspended sediment contamination along the Rhine and discussion by the expert group the value for relevant sediment contamination was set with excess of the 4-fold value of the Class 1 (see Tab. 14). This value is substantial higher than values which can be found nowadays in suspended sediments along the river Rhine but in this way it is intended that measures lead to a significant improvement of contaminant situation. In the second step the appropriate amount of contaminated sediment was set to >1000 m³. In the third step the risk of remobilization of contaminated sediments is assessed by adequate flood event investigations or by comparison of critical shear stress of the sediments with shear stress at high flood HQ_{10} (= discharge recurring once in 10 years according to the flood statistics).

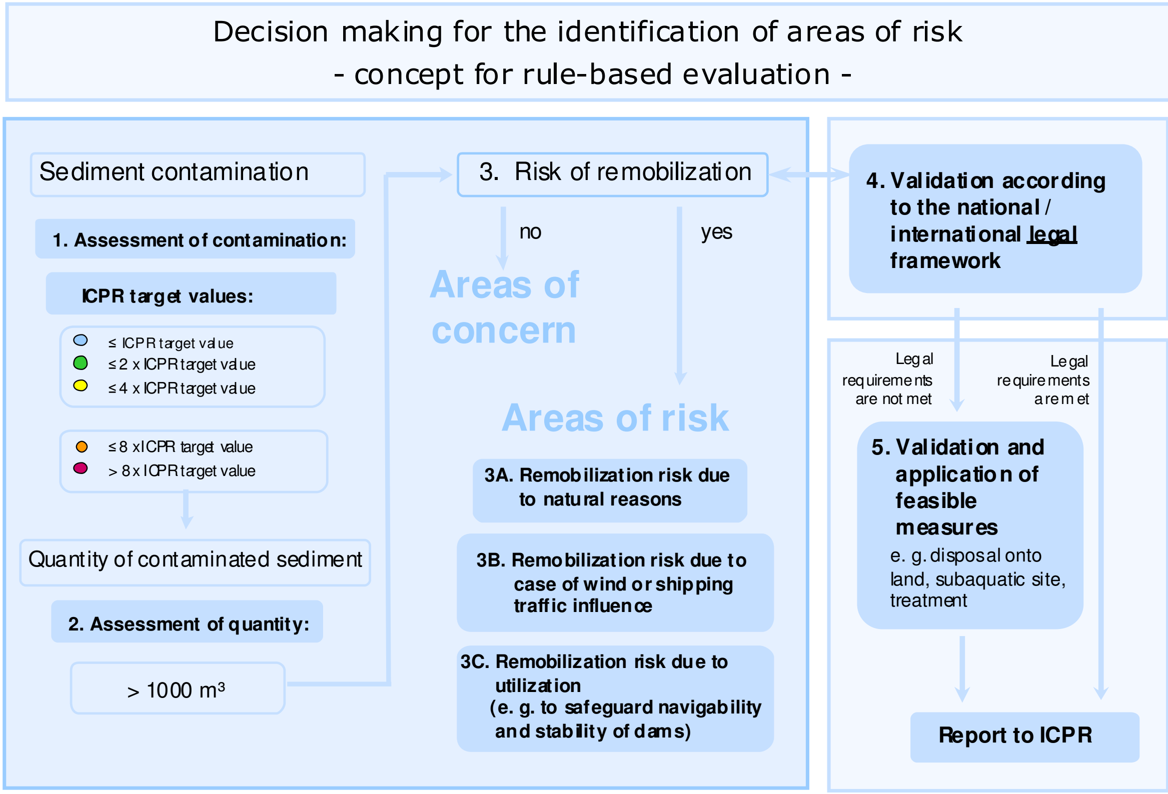


Fig. 83: Scheme of a rule-based evaluation of areas of risk

As seen in Fig. 83 three types of remobilization risk are distinguished and in the range from 3A to 3C there is an increasing control of the risk of remobilization. For assessing the risk of remobilization also national or international legal framework (step 4 in Fig. 83) is taken into account.

Step 4 and 5 are site-specific and are addressed in reference sheets for each area of risk and each area of concern. The reference sheets had been designed with the following information:

- Summary of Data
- Risk assessment
- National legislative framework
- Recommendations of measures in the Rhine basin management plans.

In a further chapter of the reference sheet the potential of remobilization and the uncertainty of data with regard to the level of pollution, the amount of polluted sediment, and the level of remobilization are discussed.

10.6 Preliminary findings SEDI group

From 93 sediment sites under investigation 22 sites have been identified as areas of risk, of this 16 as type A, 2 as type B and 4 as type C. Further 18 sites have been identified as areas of concern (ICPR 2009). The high contaminated sediment sites at the Marckolsheim and Rhinau barrages are recommended for remediation because these sites are a source for HCB contaminations of sediments downstream. The amount of high contaminated sediments is estimated at 300.000 to 500.000 m³ altogether. After this local remediation the level of HCB contamination in sediments of the Gambsheim and Iffezheim barrages will decrease within a few years.

In general most of the identified contaminated sediments concern historical contaminations more than 15 years old. In some cases, in impoundments and in harbors, increasing sediment contamination correlates with increasing sediment depth. The decreasing trend in contamination level of suspended matter reflects the sediment contamination only in areas with high mobility of cohesive sediments. In the Upper Rhine area sediment is mainly contaminated by HCB and to a little part by PCB. In the Lower Rhine area the sediments are mainly contaminated by PCB and heavy metals and partly by PAH.

11 Examples of sediment studies

11.1 Switzerland

In recent years, there was a number of sediment related studies executed in the Rhine basin in Switzerland. The following examples serve as a selection and are not a comprehensive recital. Each of the three examples shown below represents a special category of investigation:

- Numerical simulation of sediment transport (Alpenrhein and Thur)
- Comprehensive study of sediment budget (Emme River, Canton of Bern)
- Assessment study of sediment yield in a small alpine watershed (Lütschine, Bernese Oberland)

11.1.1 River Alpine Rhine

Catchment area

At Reichenau the Upper Rhine and Lower Rhine join and form the Alpine Rhine (Fig. 84 and Fig. 85). It discharges after 90 km into the Lake of Constance and drainages a catchment area of 6'123 km², which is situated in Switzerland (Cantons Grisons, St. Gallen and Ticino), in Austria (State of Vorarlberg), in Principality of Liechtenstein and in Italy. The ratio of glaciers lies below 1.4% and the medium altitude of the catchment is about 1800 m a.s.l. In addition to Upper and Lower Rhine, the rivers Plessur, Landquart and Ill are the most important tributaries concerning river morphology and sediment transport. Apart from these mountain rivers several torrents such as Maschänser Rüfe, Tamina or Frutz discharge into the Alpine Rhine.

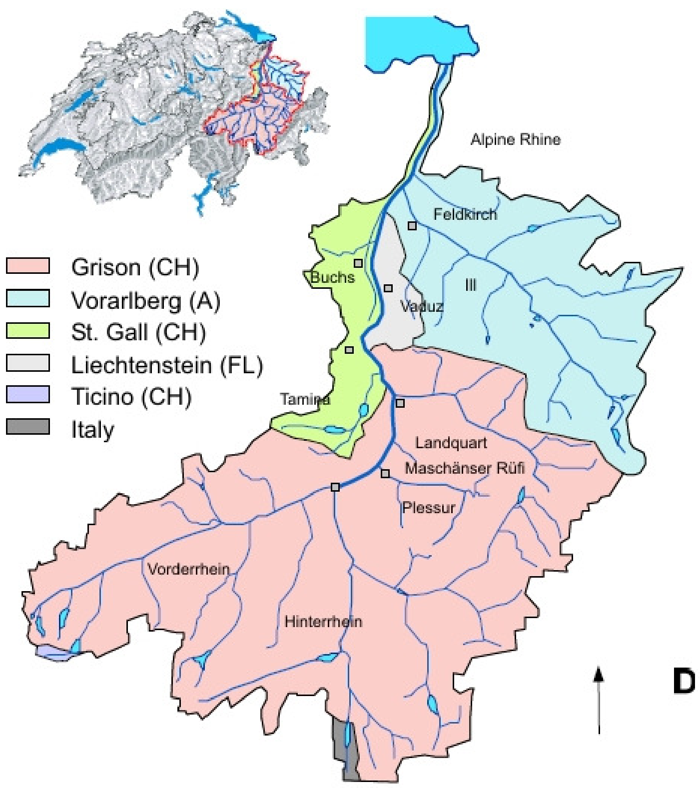


Fig. 84: Catchment area of the Alpine Rhine and its tributaries (Zarn, 2005)

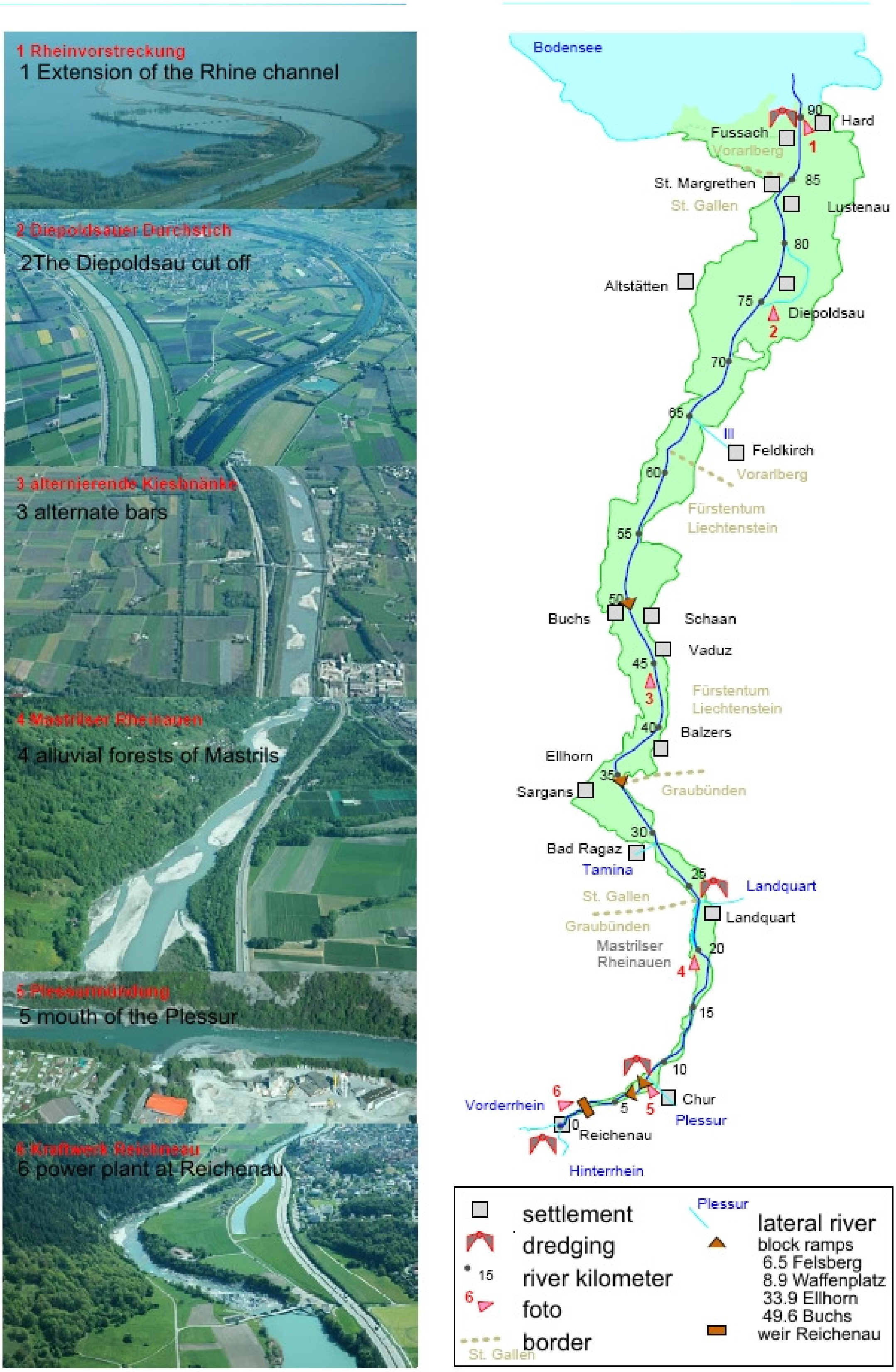


Fig. 2: Overview over the Alpine Rhine.

Fig. 85: Overview over the Alpine Rhine (Zarn, 2005)

Development of the Rhine Valley
Prior to the systematic river training the settlements concentrated with few exceptions on the numerous mountain debris fans, because the Alpine Rhine flooded its valley periodically. In1927 the flood embankment broke at Schaan for the last time. Since then the Alpine Rhine has not inundated its Valley anymore due to the sound flood protection measures. Flood protection was an important condition for the rapid development of the Rhine Valley. Communities and little towns grew out of former hamlets. The settlements developed mainly in the Rhine plain (Fig. 86). The population grow between 1960 and 2000 from 280'000 to 451'000, and the jobs increased between 1970 and 2000 from 150'000 to 238'000 (ARGE Rheinblick 2005).

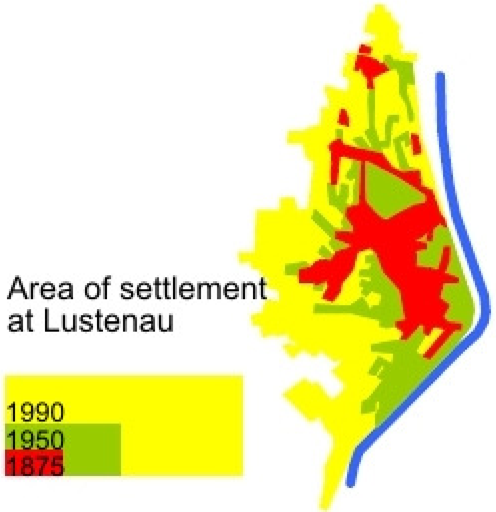


Fig. 86: Development of the settlement area at Lustenau 1875 to 1990 (Zarn, 2005)

Discharge regime
The discharge of the Alpine Rhine is affected by snow melt, floods and the usage of the hydro power. The snow melt causes high summer runoff with a definitive maximum in June (Fig. 87). The large storage lakes, which have been built in the catchment of the Alpine Rhine since 1950, shift part of the summer runoff into the winter (Fig. 88). The natural runoff is superposed by the daily discharge fluctuation, which depends on the energy production on demand.

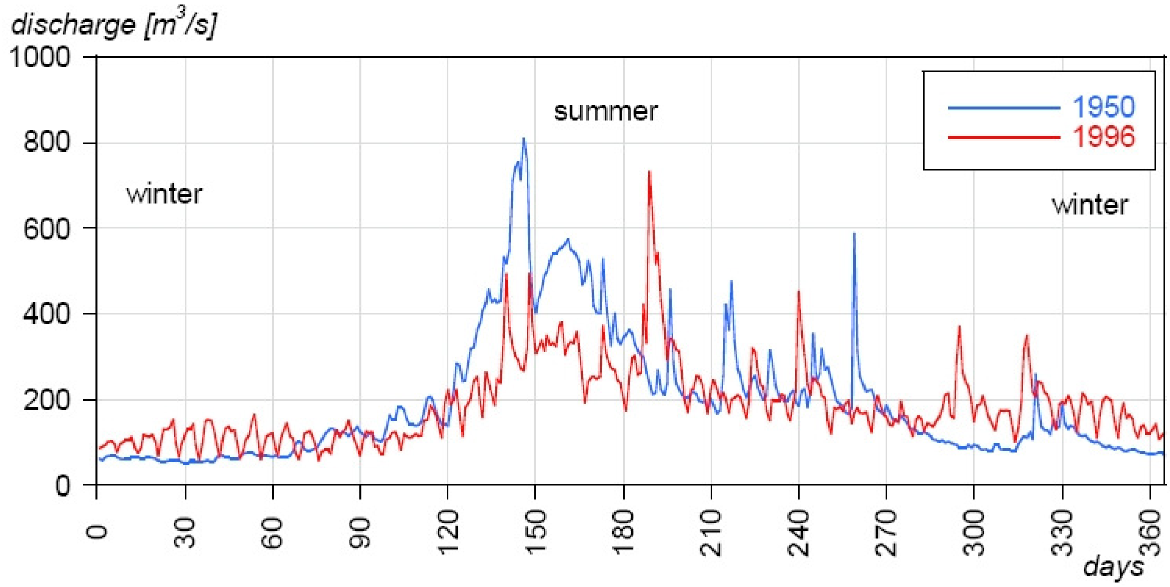


Fig. 87: Discharge hydrograph from 1950 and from 1996 at Diepoldsau (average daily value) (Zarn, 2005)

At the mouth of the Lake of Constance the mean annual discharge lies at 230 m³/s. The 100-year flood amounts in this reach to 3'100 ± 200 m³/s (Fig. 88). The peak discharge of the floods of 1834, 1868 and 1927 are in this range. At the flood of June 1987, the storage lakes, which were hardly filled at that time of the year, reduced the peak discharge of about 450 m³/s. Without these retention the peak discharge of the 1987-flood would have been in the magnitude of the 100-year flood (Fäh et. Al 2002, INGE Hydrologie Alpenrhein 2003). Because in the Alpine Rhine large floods occur frequently in autumn and the storage lakes are filled at that time of the year or the mean precipitation does not take place in the catchment of the storage lakes, the flood retention capacity can be clearly smaller as in 1987.

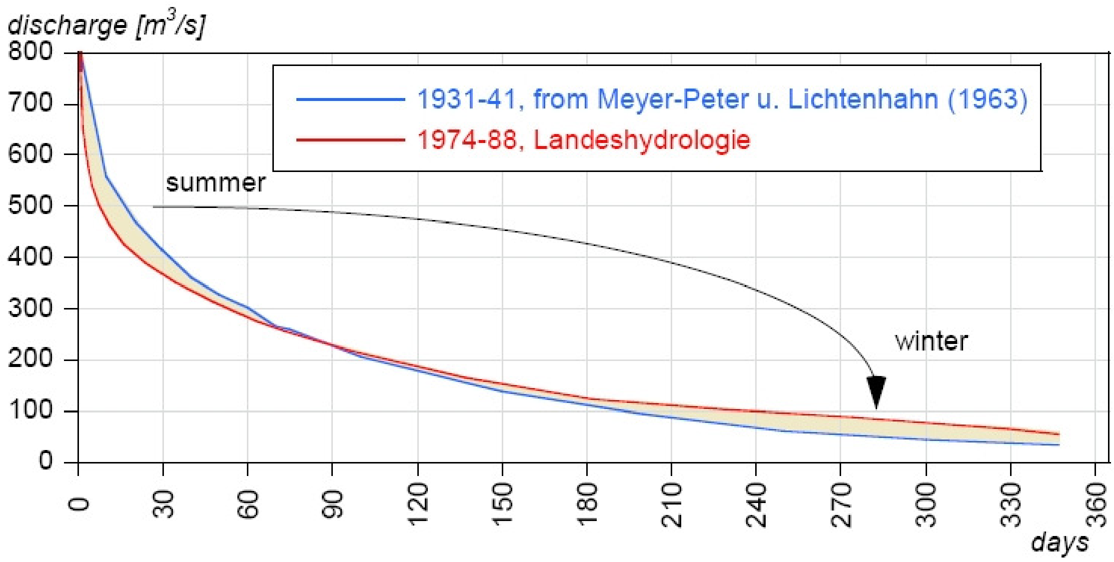


Fig. 88: Displacement of summer run off into winter at the example of two flow duration curves at Bad Ragaz before (average 1931-41) and after the building of the hydro electric power plants (1974-88) (Zarn, 2005)

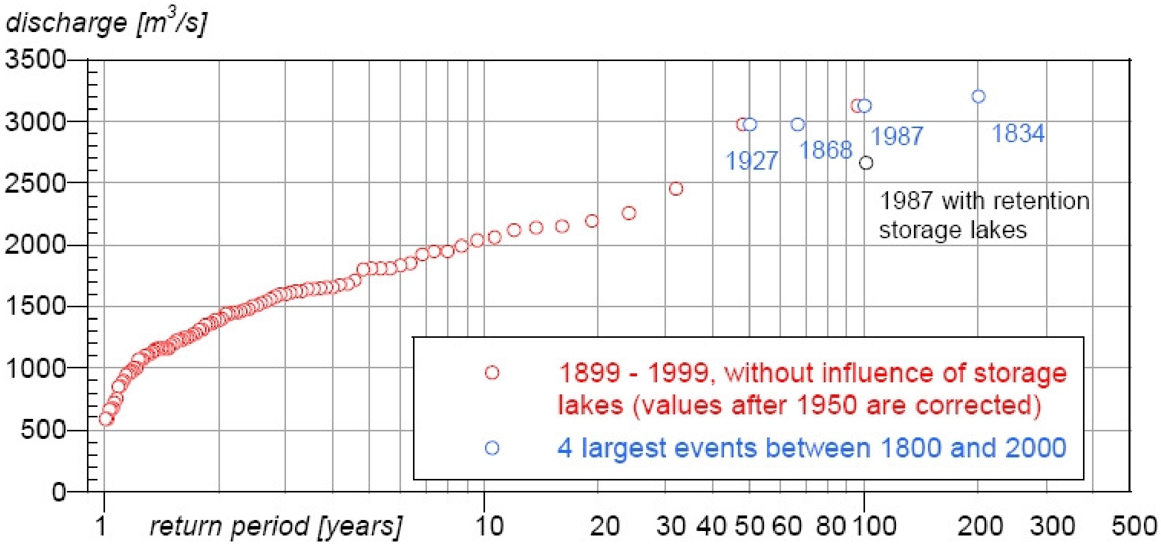


Fig. 89: Statistics of annual peak discharge after Gumbel for the lowest reach of the Alpine Rhine (gauging station Diepoldsau). The data after 1950 are adjusted by the influence of the storage lakes (Zarn, 2005)

Morphology

The morphology of the Alpine Rhine is shaped strongly by the extensive river training, which started in the middle of the 19th century (Bergmeister und Kalt, 1992). The aim of the river training was a stable river bed and a sufficient discharge capacity. For that purpose, the river bed was confined and provided with high flood embankments. In addition the Alpine Rhine was shortened by nearly 10 km with the relocation of the mouth at Fussach (Fussach-cutoff, 1895 – 1900) and the cut off of the meander at Diepoldsau (Diepoldsau-cutoff, 1908 – 1923). The sedimentation of about 3 million m³ suspended load annually leads to a rapid growth of the delta (Fig. 90). With the extension of the Alpine Rhine on its delta the suspended load are channelled into deep lake areas, which delays the following processes: (1) the silting up or rather the cut off of the east part of the Lake of Constance and (2) the aggradation in the Alpine Rhine or rather the decrease in discharge capacity upstream of the delta.

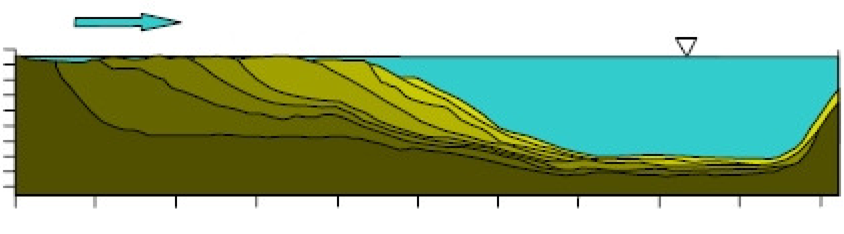


Fig. 90: Longitudinal profile of the Alpine Rhine delta in the Lake of Constance since 1885 (according to Lambert 1989). The relatively little growth of the sedimentation in this longitudinal profile after 1969 depends on the channelling of the Alpine Rhine on its delta (Zarn, 2005)

The slope of the Alpine Rhine decreases with increasing flow distance from Reichenau to the mouth of the River Ill, but not constant (Fig. 91). This is connected with the four block ramps Felsberg, Waffenplatz, Ellhorn and Buchs, the different river bed width or rather cross section geometry and the tributaries (Zarn 1999 and Hunziker, Zarn & Partner 2001). The geometry of the Alpine Rhine is variable. From Reichenau (km 0) until close to the mouth of the River Ill (km 65) the Alpine Rhine flows in a single channel, and in the following reach until Lake

Constance in a compound channel (Fig. 91). In this lower reach, the distance between the flood embankments is accordingly large. The width of the river bed, to which the channel shape is closely linked,, varies considerably. Between Reichenau (km 0) and the Maschänser Rüfi (km 14) as well as downstream of the mouth of the River Ill (km 65) the river bed is flat. Gravel bars can be formed in the remaining reaches. At Oldis (km 14-17) and particularly in the Mastrilser Rheinauen (km 20 23) the Alpine Rhine is braided and in the following reach until the mouth of the River Ill (km 65) alternate bars can be observed.

At river reaches with gravel bars the variability of different parameters as flow depth, flow velocity or grain size distribution of the bed material is considerably larger as in the case of a flat bed. Simultaneously with bars local hollows occur in the river bed, so-called scours, by which for instance the impact on the bank protection can be increased considerably. In the reach of the Alpine Rhine with the alternate bars and in the braided Mastrilser Auen scour depth of four meter and more can be observed.

Grain size distribution

For the morphology not only river bed width and slope are of importance, but also the grain size distribution of the bed material. It is described frequently by the two grain diameters dm und d901. With these two parameters the bed load transported (dm) and the resistance of the river bed against erosion (d90/dm) can be characterised approximately (Fig. 91). Along a river reach the grain diameter decreases. The reason for that is mass loss due to the mechanical impact during sediment transport (abrasion) and the fact, that larger grains are deposited earlier than smaller ones in sedimentation reaches (sorting). The bed load input from tributaries can coarsen the grain size distribution.

The river training caused an almost continuous monotonous channel, which resulted in a loss of natural sound habitats and a pauperisation of the aquatic biocoenosis. The daily water surface fluctuation due to hydro power production also affects the habitats still existing negatively.

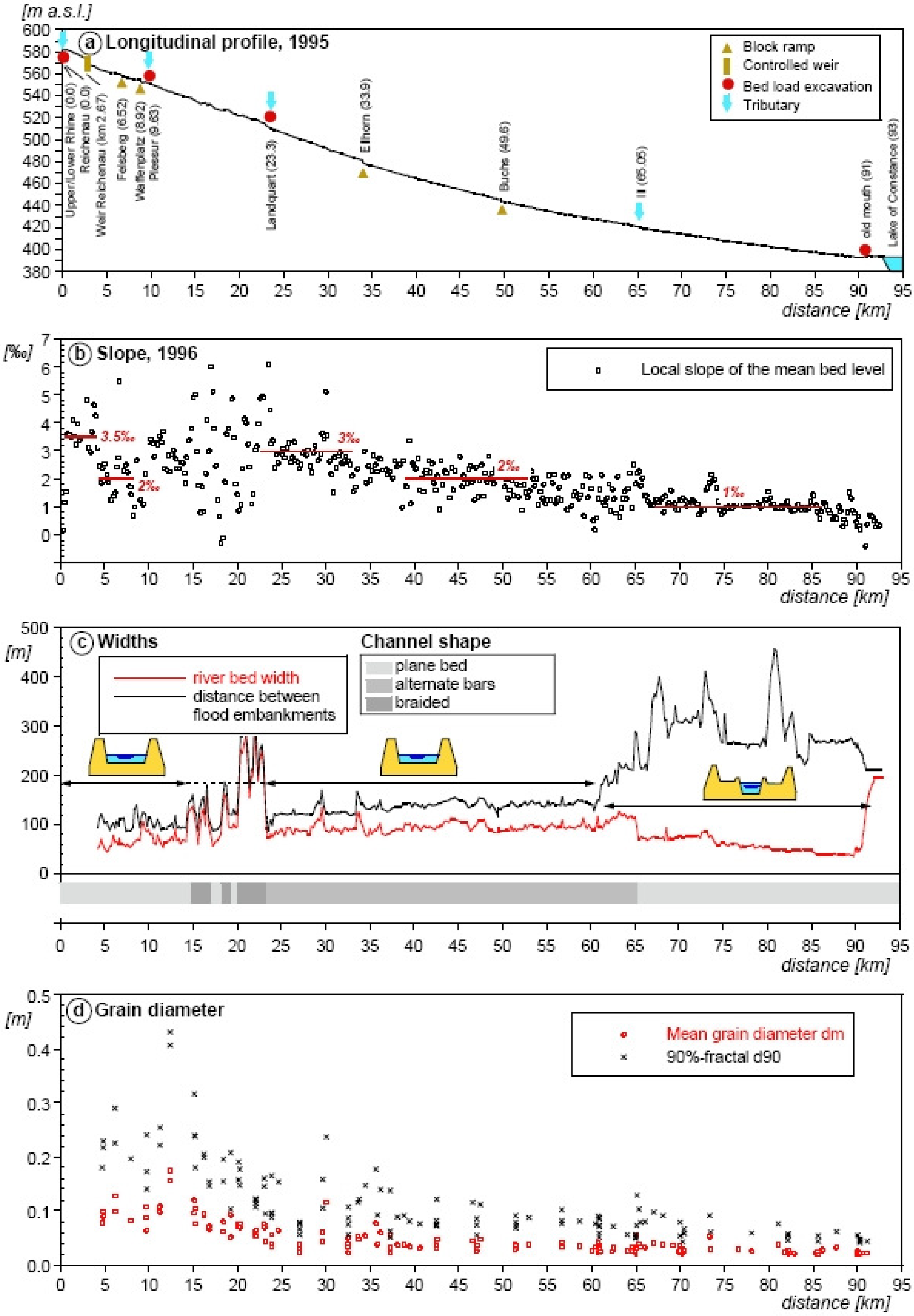


Fig. 91: Overview of the Alpine Rhine (according to Zarn 1999): longitudinal profile, slope, river bed width and distance between the flood embankments as well as characteristic grain sizes, which have been determined by line-by-number analyses (Fehr, 1987)

Alteration of the river bed since 1940

Before river training the Alpine Rhine presumably deposited bed load and aggraded nearly on the whole reach due to its slope and river bed width. Thus, the discharge capacity was reduced continuously and the frequency of flooding increased. The aim of the flood protection measures carried out and the bed load excavation were to prevent further aggradation and/or to initiate an adequate degradation of the river bed.

The erosion of the river bed in the 20th century was not gradual. Between 1940/41 and 1950 (difference zero line / black curve in Fig. 92) as well as between 1974 and 1995 (difference violet / red curve) the alteration of the river bed was substantially lower then between 1950 and 1974 (difference black / violet curve). Bed load excavation was the main reason for the erosion between 1950 and 1974. Although bed load excavation in the Alpine Rhine started in 1936, the main excavation took place in the period with the largest erosion rate especially in the reach between the mouth of the River Landquart and the River Ill (km 23.7 until km 65) as in Fig. 10 is shown. After the collapse of the bridge Buchs-Schaan in 1972, bed load excavation was forbidden in this reach.

The reasons for the extensive bed load excavation between 1950 and 1970 were the demand of the building industry and an overestimation of the bed load transport in the Alpine Rhine by a factor more than ten. In the past, the bed load transport was estimated to be 1.3 million m³ per year downstream of the mouth of the River Landquart and 0.35 million m³ per year downstream of the mouth of the River Ill (Zarn 1999). In fact there is today a maximum bed load transportation of 65'000 m³ bed load per year (below, Fig. 96a). Between 1936 and 1990 29 million m³ gravel was taken out of the Alpine Rhine, which is five times more than the bed load delivery from all the tributaries in a comparable period (Tab. 16). It is not surprising that for example the river bed at the Ellhorn (km 33.9) or at Buchs (km 50) eroded up to 5 m between 1950 and 1974 (Fig. 92, difference black / violet curve).

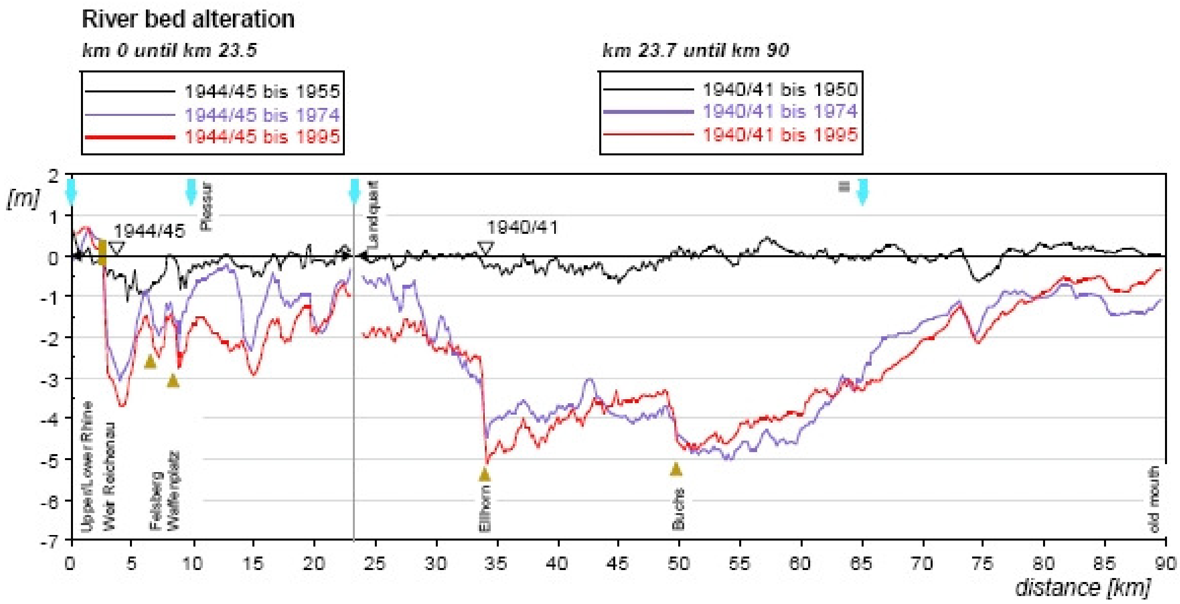


Fig. 92: River bed alteration of the Alpine Rhine between 1941 and 1995 (Zarn 2005)

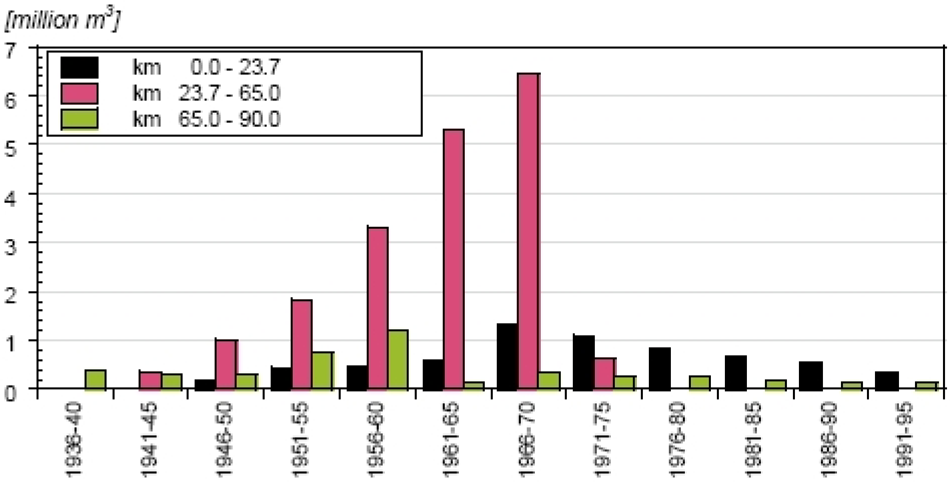


Fig. 93: Bed load excavation out of the Alpine Rhine since 1936 in different reaches. After the collapse of the bridge Buchs-Schaan in 1972 bed load excavation was forbidden between km 23.7 and km 65 (Zarn 2005)

Fig. 94: The bridge Buchs-Schaan collapsed in 1972 because of the erosion of the river bed. After the collapse numerous bed load excavations were stopped (Landesarchiv Vaduz) (Zarn 2005)

<u>Ground water</u>
The erosion of the river bed caused a lowering of the ground water table in the Rhine Valley and a decline of the quality and productiveness. Because more than half of the water supply for the 450'000 inhabitants originates from the ground water, this is of great importance (ARGE Rheinblick 2005). Ground water supplied inland water and wetlands are affected from a lower ground water table too. Water logging of agriculture land decreased to the benefit of the cultivation.

In the example of Fig. 95 the erosion of the river bed of about 5 m between 1953 and 1973 caused that water from the Rhine no longer infiltrated into the ground water, but ground water drained into the Alpine Rhine. With the stopping of the bed load excavation after 1972 sedimentation of about 1 m occurred until 1998 and resulted in a slightly higher ground water table close to the Rhine.

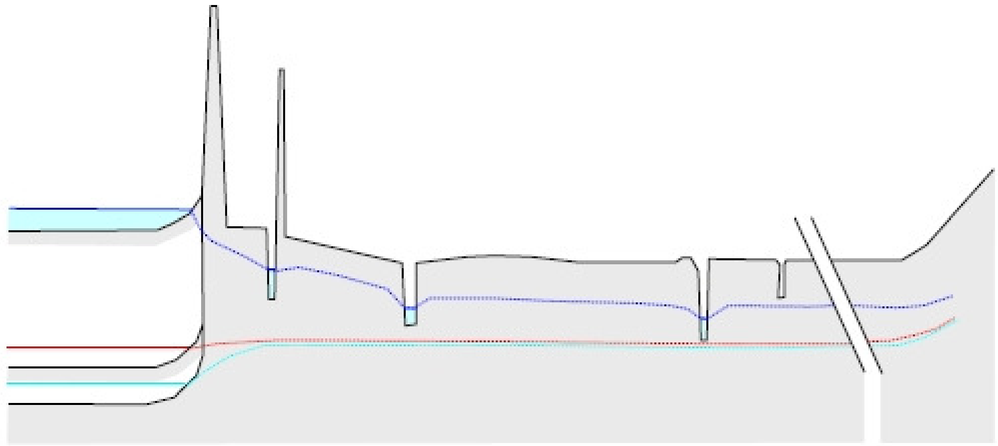


Fig. 95: Influence of the river bed on the ground water table in the case of the example of Ruggell in the Principality of Liechtenstein (km 58.4, schematic, strong excessive diagram, according to ARGE Rheinblick 2005)

<u>Current bed load sediment budget</u>

Methodology

For the analysis of the current bed load sediment budget and the prediction of future development, simulation models were applied, which are based on the program MORMO. The simulations were carried out between 1989 and 1999. In the course of the work the simulation models were being adapted to new knowledge. The simulation models were calibrated on river bed alteration in the period from 1974 until 1988 and from 1988 until 1996. Calibrating the models the river specific parameters (channel roughness, grain size diameter, abrasion, active river bed width) were varied as long as a sound agreement resulted between water surface and mean bed level observed and calculated. The parameters should be varied within the range of the observed values only. Afterwards with the model calibrated forecasting for 25 years was carried out. It was assumed that discharge regime, sediment input from the tributaries and bed load excavation do not change compared to the calibrating period.

The program MORMO is a one dimensional model. The flow resistance was calculated according to Strickler (1923) and the bed load transport according to Hunziker (1995), a modification of the procedure of Meyer-Peter and Müller (1948). The wide braided reach in the Mastrilser Rheinauen was calculated according to Zarn (1997).

Total bed load and river bed alteration

The bed load sediment budget can be explained by the total bed load transported and the river bed alteration. Fig. 96a shows the range of the mean annual total bed load calculated fort the period from 1974 until 1996. In fig. 96b and 96c the alteration of the river bed, which was observed in the periods from 1974 until 1988 and from 1988 until 1996 is compared with the ones calculated.

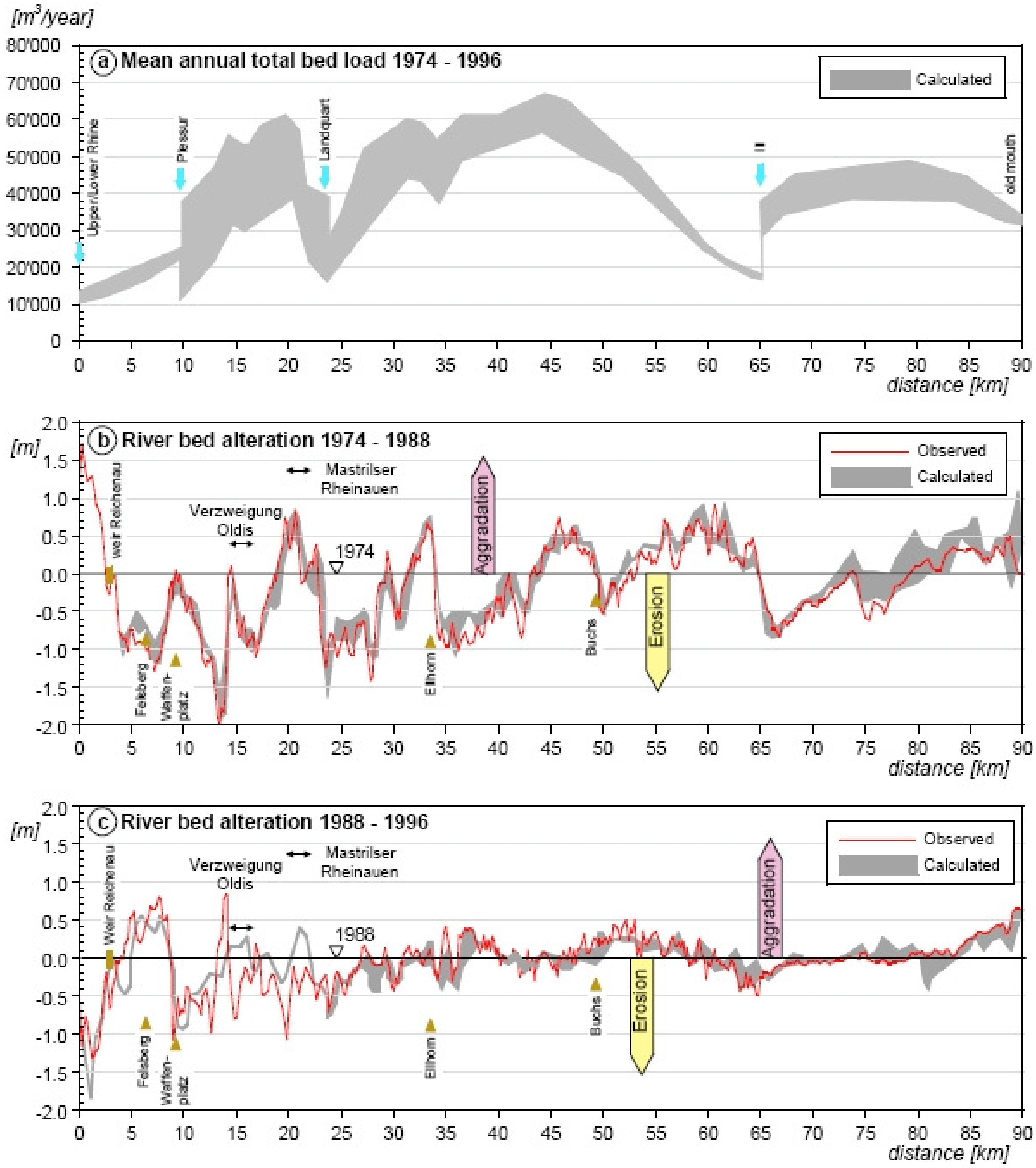


Fig. 96: Range of the mean annual total bed load which was transported in the Alpine Rhine between 1974 and 1995 (a), and the river bed alteration in the period from 1974 to 1988 (b) and from 1988 to 1996 (c) (Zarn 2005)

In the Alpine Rhine reaches with erosion follow reaches with deposition, but nowhere an equilibrium is obtained. Between the weir Reichenau and the Mastrilser Rheinauen the river bed eroded, whereas the block ramps at Felsberg and at Chur (Waffenplatz), the braided reaches at Oldis and the Mastrilser Rheinauen limited the erosion. The next reach between the mouths of the River Landquart and the River Ill is dominated by the block ramps at Ellhorn and at Buchs and the 15 km long deposition zone upstream of the mouth of the River Ill. The construction of the block ramps Ellhorn and Buchs between 1970 and 1972 mainly resulted in bed load deposition in the headwater in the first period. The deposition was limited to reaches of a few kilometres only. In the other reaches the Alpine Rhine partly eroded heavily. In the lowest reach between the mouth of the River Ill and the Lake of Constance the mountain river eroded until the Diepoldsau-cut-off (km 74.5 until km 79.6), followed by a deposition reach until Lake Constance.

Different reactions in the two periods

The alterations of the river bed in the two periods analysed are very different (Fig. 96b and 96c). Among other things, this depends on the construction of the block ramps, the different duration of the periods as well as the fact, that the discharge was higher in the first period than in the second period.

Mean annual total bed load

The mean annual total bed load in Fig. 96a illustrates how strongly erosion and deposition affect the bed load transport. Especially worth mentioning is the general increase of the curve between km 0 and km 45, which corresponds to the heavy erosion in this reach. In the area of the Matrilser Rheinauen there is a decrease of bed load transport calculated only, which indicates deposition in the floodplain. Downstream of km 45 the decreasing curve corresponds to the deposition upstream of the mouth of the River Ill. These depositions are linked to the reduction of the slope between km 45 and km 65, which is partly a consequence of the massive bed load excavation between 1940 and 1972. Upstream of the block ramp Buchs the bed load transport reaches 55'000 up to a maximum of 65’000 m³ per year. 55 to 75% thereof is caused by the river bed erosion between km 23 and km 45.

Comparison with the bed load excavation at the Lake of Constance

To avoid deposition in the channel extension on the Alpine Rhine delta, all bed load is excavated at km 90. In the period from 1974 to 1996 the mean excavation amounted up to 36’000 m³ per year. The mean annual total bed load calculated at the discharge into Lake Constance to be 32'000 to 34’000 m³ agrees well with the excavation observed.

Bed load input from the tributaries

With the calibration of the model and with the help of additional simulation in the tributaries, the bed load input into the Alpine Rhine could have been contained (Tab. 16).

Tab. 16: Overview of the annual bed load input from the main tributaries into the Alpine Rhine and the bed load excavation at the Lake of Constance in the period from 1974 to 1996 (Zarn 2005)

Tributary	Range of bed load input [m^3/year]
Upper River Rhine	24'000 – 32’000
Lower River Rhine	3'500 – 4’500
River Plessur	13'000 – 25’000
River Landquart	25'000 – 35’000
River Ill (incl. River Frutz)	10'000 – 20’000
Excavation at the mouth of Lake Constance	36'000

Prediction of the bed load sediment budget

The future bed load sediment budget and the connected alteration of the river bed can be predicted by numerical simulation. With the model calibrated and the same bed load input from the tributaries, and bed load excavation and discharge hydrograph as in the period from 1974 to 1996 the forecasting was performed (Fig. 97). In the same river reaches as between 1974 and 1996 erosion and deposition is predicted. However, the alteration of the bed level per year reduces and so also the values over the 25 year simulation period. The reason for that is the change of the slope due to erosion and deposition, which leads to a more balanced bed load transport capacity along the Alpine Rhine. Because less erosion are predicted with respect to the whole Alpine Rhine, less bed load is mobilised and transported as in the calibration period from 1974 to 1996. For example downstream of the mouth of the River Landquart erosion of more then 1.5 m was observed between 1974 and 1996. For a period of the same duration in the future, erosion of "merely" 1.2 m is predicted. If the discharge is larger in the future than in the years between 1974 and 1996 an acceleration of the processes is anticipated, and in the case of lower discharges, a delay.

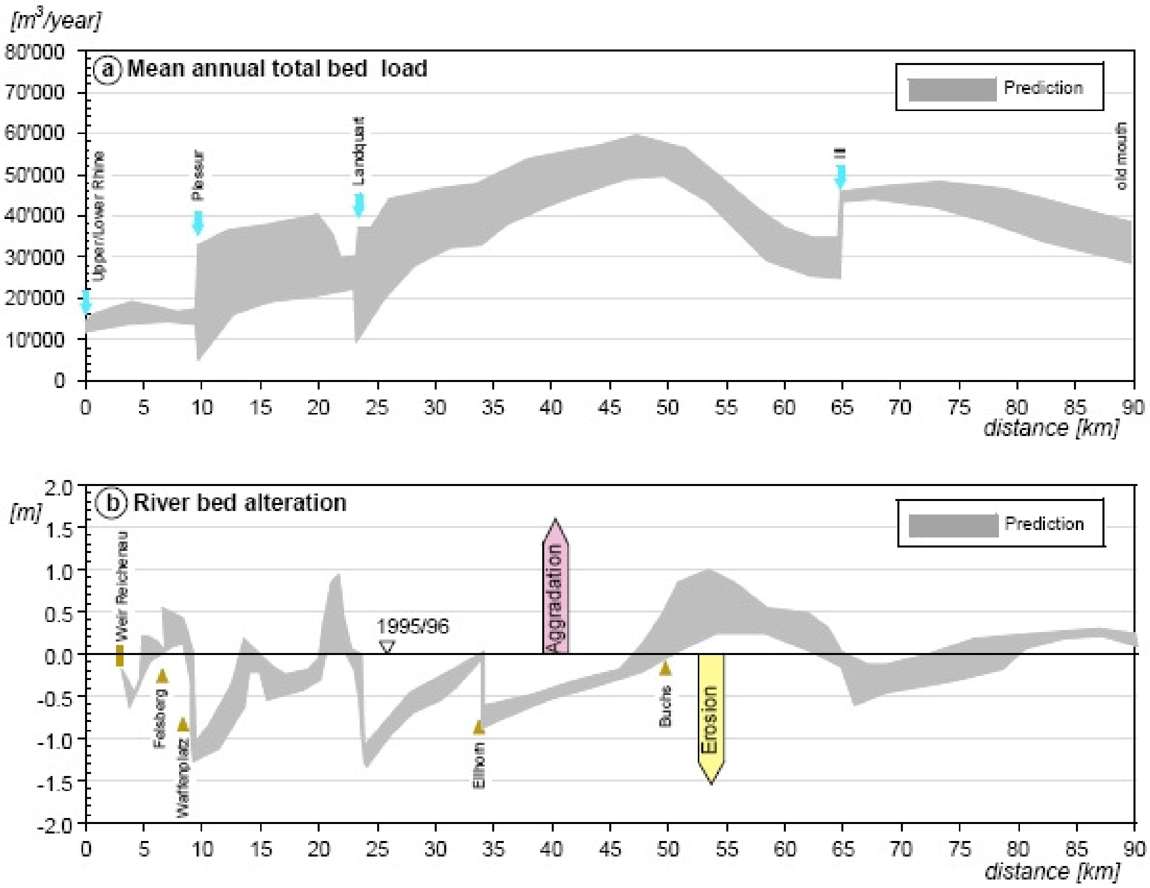


Fig. 97: Prediction of the mean annual total bed load (a) and river bed alteration (b) in the next 25 years for conditions as in the period from 1974 to1996 (The results are from simulations with different models. Because of the usage of a moving average over 5 cross sections the bed level alteration is not zero at the block ramps.) (Zarn 2005)

Conclusion and outlook

The investigation of the bed load sediment budget of the Alpine Rhine shows that this mountain river is not in equilibrium. With the river training carried out and the bed load excavation the bed load sediment budget and the morphology was considerably changed. For the flood protection both the erosion and deposition are not wanted. Erosion endangers the stability of bridges or protective structures, deposition reduces the discharge capacity.

The river training increased the discharge capacity and therefore, the flood protection was improved. On the other hand, it caused a sever reduction of natural sound habitats, which affects the ecology adversely. As a result, the attractiveness of the Alpine Rhine as a recreation area was reduced. The influence is not restricted to the Alpine Rhine itself. Because of the interaction with the ground water table the whole Rhine Valley is affected.

In the Development Concept Alpine Rhine (ARGE Rheinblick 2005) several measures are proposed, which can reduce the existing deficits. Overall, more space is needed for the Alpine Rhine. The river bed enlargements proposed upstream of Buchs will reduce the continuous erosion and the ones proposed in the reach upstream of the Lake of Constance , where the damage potential is extra high, will increase the discharge capacity. The river bed enlargements affect the ground water favourably, increase the morphological and ecological diversity and create valuable recreation areas for inhabitants and guests of the Rhine Valley.

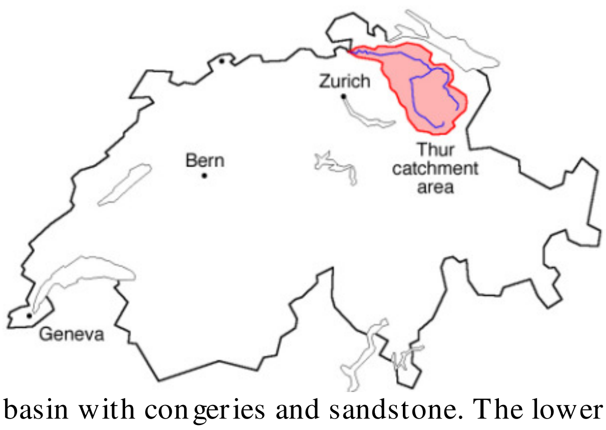
The knowledge about the bed load sediment budget was an important basis for working out the Development Concept Alpine Rhine. With the numerical bed load transport model an instrument exists to design measures for flood protection or for ecological improvement. Also the impact of bed load excavation or of a change in the discharge regime on the river bed level can be predicted. Forecasting of the bed load sediment budget and the development of the river bed level are important. Although the changes are slow, they are often irreversible and planning and realizing measures with respect to a large river takes time.

11.1.2 Sediment balance in the Thur catchment area

The Thur catchment area

The Thur catchment area is located in the north-east of Switzerland and comprises an area of 1720 km^2. The highest mountain (the Säntis) reaches 2500 m a. s. l. and the river Thur flows into the river Rhine at 340 m a. s. l. (Fig. 98).

The upper Alpine part of the catchment area is devided into four main valleys (Thur, Necker, Urnäsch, Sitter).
In the north-west follows the strongly subdivided Prealpine region with mountain ranges up to 1’500 m a.s.l.
Further north the region flattens out to the hilly countryside called Mittelland.
The upper steep catchment area consists of Helvetic nappes with hard limestone.



North follow the Subalpine and the molassic basin with congeries and sandstone. The lower part of the catchment area contains moraines and alluvial plains with local rockbeds.

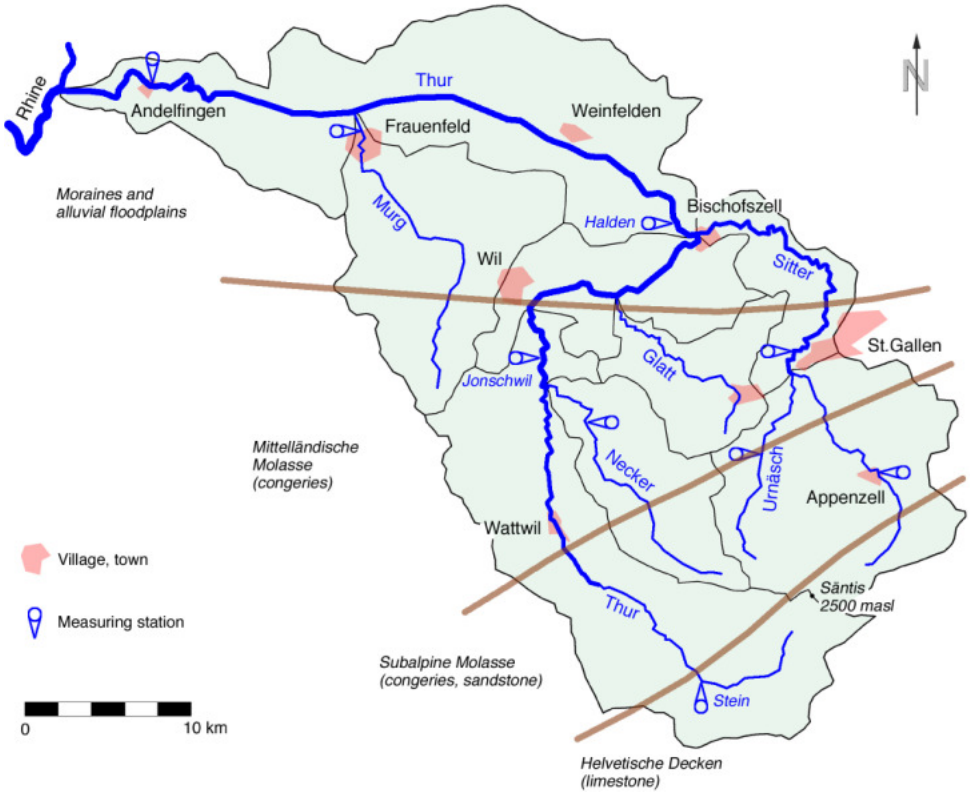


Fig. 98: Catchment area of the river Thur with the main channels, towns and the geological structure (Schälchli 2007)

The two main channels are the river Thur (length 130 km) and the river Sitter (length 48 km). The rivers Necker, Glatt, Urnaesch and Murg are also important channels. The longitudinal profile of the Thur (Fig. 99) shows stepped upper reaches with an average slope between 10 ‰ and 20 ‰, the middle reaches with a slope from 3 to 4 ‰ and the tailwater with a slope between 1 and 3 ‰. Die tributaries flow with a steeper slope into the river Thur.

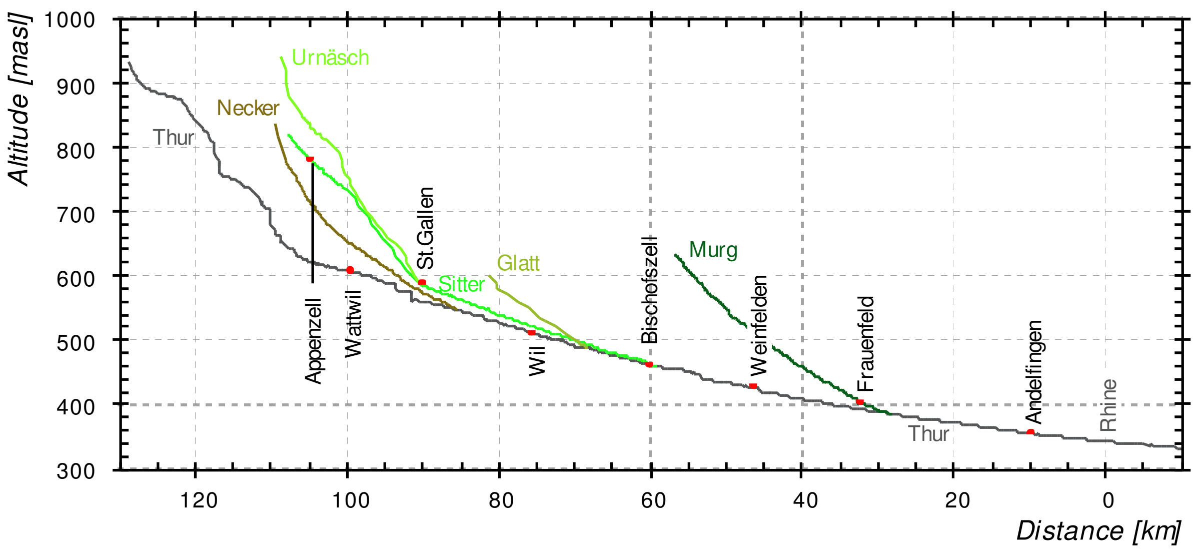


Fig. 99: Longitudinal profile of the river Thur and important tributaries (Schälchli 2007)

Precipitation and discharge

Precipitation is spread more or less evenly all over the year with highest values in summer. In the upper regions in winter, precipitation falls as snow. The average annual rainfall amounts in the upper reaches 2000 mm/a and in the low catchment area 1000 mm/a. Discharge is characterized by thaw and strong rainfall. The seasonal variation shows highest values in April (tailwater) to June (upper regions) and low values in autumn (Fig. 100). The annual average discharge at Andelfingen is 47 m^3/s.

High floods occur during extensive heavy rainfall. Thereby the flow rises in a few hours up to several 100 m^3/s. At Andelfingen flood peaks with 500 m^3/s occur annually. Fig. 101 shows the measured graphs of the flood event of August 12th in 2002 with a recurrence interval of about 20 years. Because the river Thur is canalized in the tailwater and the surrounding countryside is protected against flooding with high embankments, there is no significant retention of the flood peak. The flood with a recurrence interval of 100 years reaches at Andelfingen 1'400 m^3/s.

Fig. 100:
Average monthly flows at 4 measuring stations at the river Thur. Location of the measuring stations see Fig. 97. (Schälchli 2007)

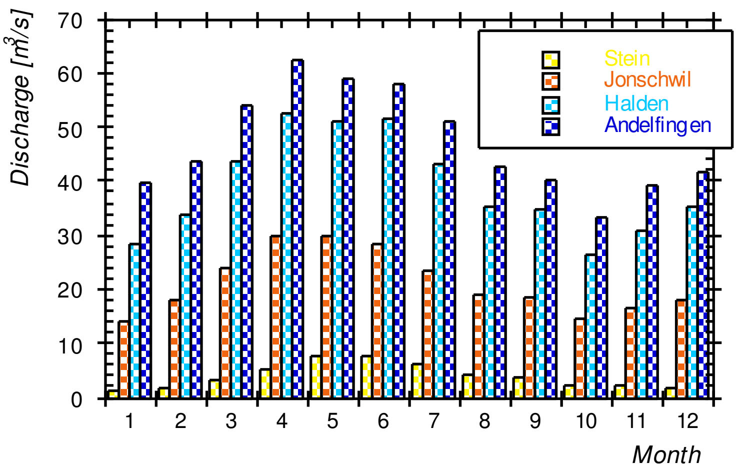
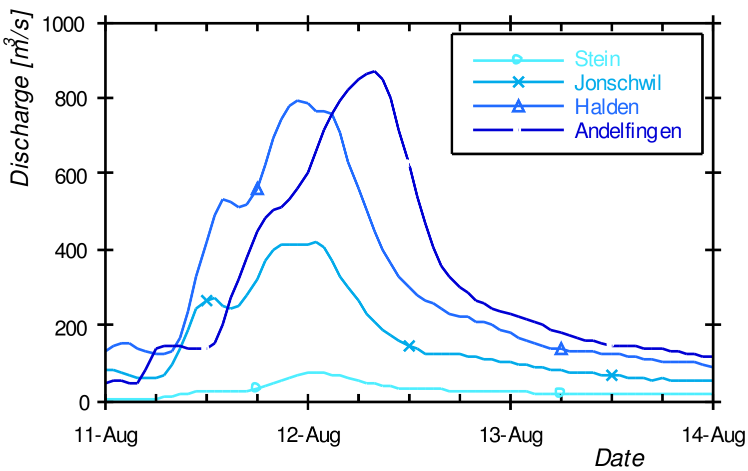


Fig. 101:
Measured graphs of the flood event of August 12th in 2002 at 4 measuring stations at the river Thur (Schälchli 2007)



River engineering

In the upper regions the river Thur flows in a V-shaped valley, with stepped slope, local rockbeds and short sections with low slope. In the middle regions follows a long section with incised meanders and in the tailwater the Thur naturally was braided or meandering.

In the upper and middle regions the villages are located in the sections with low slope. Here the banks are protected or the channel is fixed by river training works. In the sections with high slope and the section with incised meanders the Thur is still naturally.

Upper regions: Rock sill with the cascade Oberer Giessenfall.

The tailwater of the river Thur was straightened by river training works between 1870 and 1930. Thereby the cross section was narrowed and the banks were protected by riprap. The aim of the river training works was to gain land and to protect the countryside from inundation. With the constriction of the main channel the capacity of transporting sediment was increased significantly, so that the river bed degraded. The expected bed erosion reached 3 m between Wil and Bischofszell, what led to severe destabilisation of the riprap and the banks. To limit the bed erosion, in several sections the bed was fixed by riprap sills. The implemented river training works do not fulfil today's demands in many sections. The villages expand towards the channels, the aged embankments became permeable and the locally increasing bed erosion means a risk for the embankments. Bed erosion is intensified by dredging plants in the upper regions of the catchment area. The dredging is done for commercial purposes such as road works.

Middle reaches: Mouth of the river Necker (from left).

Apart from these technical aspects the moral concept of the society has changed. Rivers shall serve as habitats for the indigenous flora and fauna as well as for the recreation of the people.

Tailwater: Trapezoidal profile with forelands and a small widening.

Therefore the responsible authorities have started to restore various sections and to improve the flood protection. To provide a basis for these projects a study concerning the sediment balance of the river Thur was carried out. The studied sediment balance concerns exclusively the gravel which is transported as bed load. The finer suspended particles are completely transported downstream and are not relevant for bed alterations and flood protection. The study analyses the long-term development of the transported sediment and the alterations of the river bed.

Sediment delivery

In the upper and middle reaches the sediment delivery was estimated by field assessments, the geomorphology and the relief. In the field assessments the sediment storage, the potential mobilisation and the composition of the sediment was evaluated. Data of storage volumes behind barriers and dams or the extraction volumes of dredging were used for the calibration of the sediment delivery in defined catchment areas.

In Fig. 102 the specific sediment delivery of different small catchment areas is shown. The highest values between 300 and 400 m^3/km^2a are found in the higher region of the molassic basin, congeries and steep relief. In the lower region of the molassic basin the values range between 20 and 60 m^3/km^2a. In the hilly and even regions the specific sediment delivery decreases below 20 m^3/km^2a.

Not all the sediment recovered reaches the main channel. During high flood bed load is deposited in sections with low slope and on debris cones. The sediment output of the catchment area at Wil amounts in total to 40'000 m^3/a. 50% of this reaches the river Thur, where as a result of abrasion the bedload at Wil is reduced to 12'400 m^3/a. For this catchment area (500 km^2) a specific bed load of 25 m^3/km^2a results.

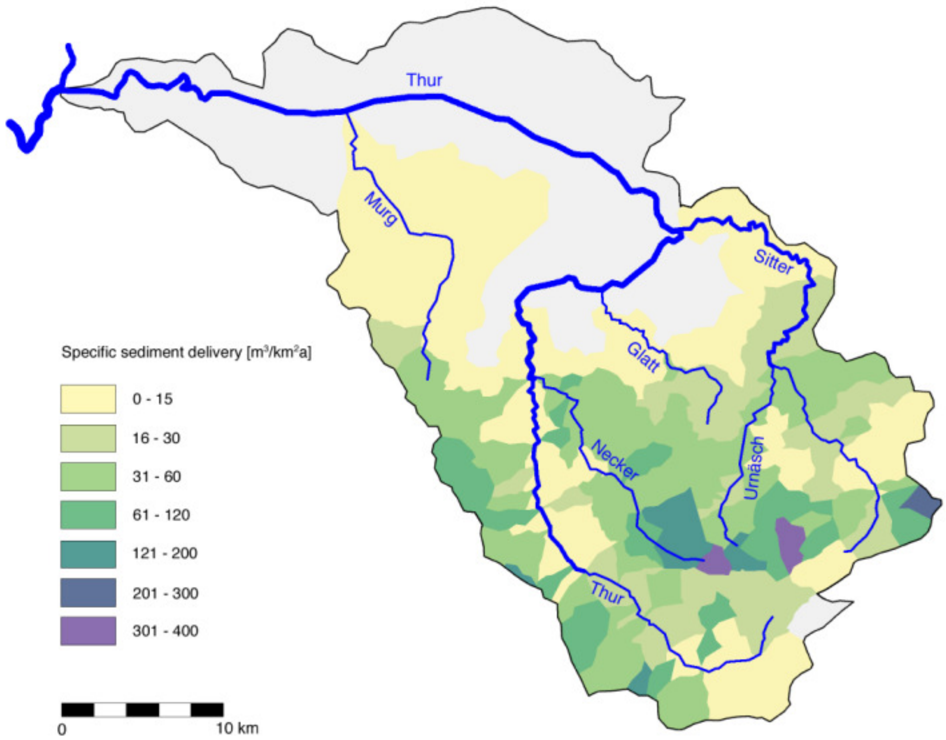


Fig. 102: Specific sediment delivery in different catchment areas of the Thur drainage basin (Schälchli 2007)

Modelling the Sediment Balance

In the river Thur, Sitter and sections of other channels the sediment balance was modelled by the program MORMO („MORphological MOdell"). The one-dimensional model enables the simulation of the alterations of the river bed considering different sediment inputs. The model computes for a given hydrograph for each cross section the bed load and the bed alteration in time. The model is calibrated by measured bed alterations. It enables the prediction of future bed alterations for different scenarios.

The model has been based on the input of measured cross sections. The shape of the cross sections and the roughness of the bed and the banks are dominant parameters of the transport capacity. In natural river sections beside alterations of the river bed also alterations of the river width are to be considered. In narrowed and canalized river sections the banks show a significant influence on the transport capacity. It is recommended to calculate the bed load in stripes where the flow depth (near the banks) is reduced by the discharge flowing on the banks (see Einstein).

The model takes the grain distributions of both the bed material and the bed load into consideration by the input of the diameters dm and d90 of both mixtures (4-grain model). In the upper and middle reaches the bed material is usually coarser than the bed load. In the tailwater the bed material and the bed load often are identical. Sills are benchmarks in the longitudinal profile of a river. Upstream of the sill the river bed is located at a certain amount, the offset of the sill, under the sill. The offset depends on the height, the shape, the roughness and the angle of the sill. During the calibration of the model the level of the sill was adjusted until upstream the calculated bed level corresponded with the measured bed level.

Sediment Balance of the Thur Tailwater

The sediment balance of the Thur tailwater between Bischofszell and the river Rhine was analysed for the actual state and the future development with unchanged input data and with increased sediment input. By the increased sediment input it was evaluated if bed erosion could be prevented when the dredging of gravel in the upper reaches would be stopped. Thereby the sediment input at Bischofszell increases from actually 14'000 m^3/a up to 19'000 m^3/a.

Fig. 103a to 103c show the longitudinal profiles of the averagely transported bed load (Fig.103a), the alterations of the bed level for periods of both 0 24 years and 24 – 48 years (Fig. 103b) as well as the difference between the bed levels for the forecast with unchanged and increased sediment input (Fig. 103c).

With unchanged sediment input (blue lines) between km 60 and km 50 slight bed erosion up to 0.5 m, locally up to 1.0 m, is detected. Between km 48 and km 40 the bed erodes downstream of sills up to 1.3 m. A pronounced and progressive erosion up to 2 m is detected between km 32 und km 28. After 48 years the erosive process has still not ceased. The widening Niederneunforn Altikon that was realized leads to a significant aggradation of the river bed in the widening up to 1.5 m and to a decreasing aggradation upstream until km 27. The aggradation process has not ceased after 48 years. With the deposition in the widening the bed load decreases downstream by averagely 10'000 m^3/a (see Fig.103a). At the river mouth the flow is influenced by the reservoir of the hydroelectric power station Eglisau. Here the bed load deposits and the bed level increases.

When increasing the sediment input by 36% up to 19'000 m^3/a between km 60 and km 50 the erosion diminishes and locally small depositions are expected (Fig. 103b and 103c). Because of the increased sediment input the bed raises about 0.2 m to 0.3 m compared to the scenario with unchanged input data. In the sections with a raising river bed as well as downstream the two scenarios show no significant differences. The aim to stop the bed erosion can not be reached only by cancelling the dredging.

Fig. 103a:
Longitudinal profile of the bed load for periods of 0 – 24 years and 24 – 48 years with unchanged (G=) and increased sediment input (G+) (Schälchli 2007)

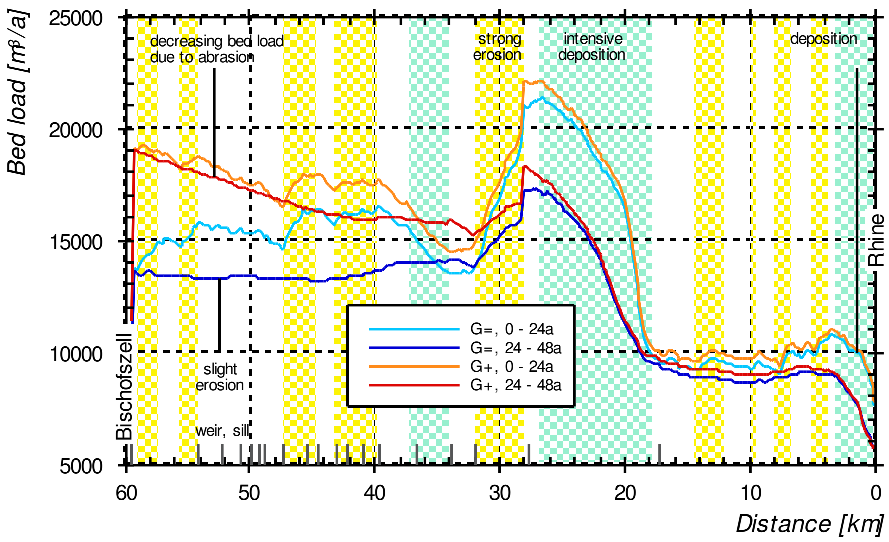


Fig. 103b:
Longitudinal profile of the bed alterations after 24 and 48 years for the scenarios according to Schälchli 2007

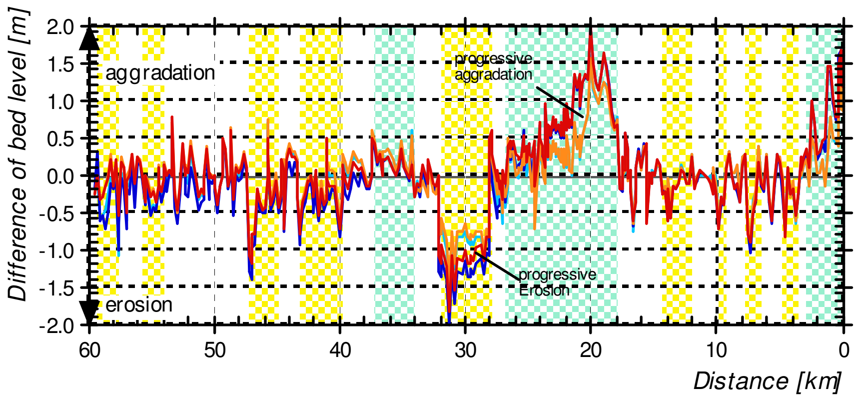
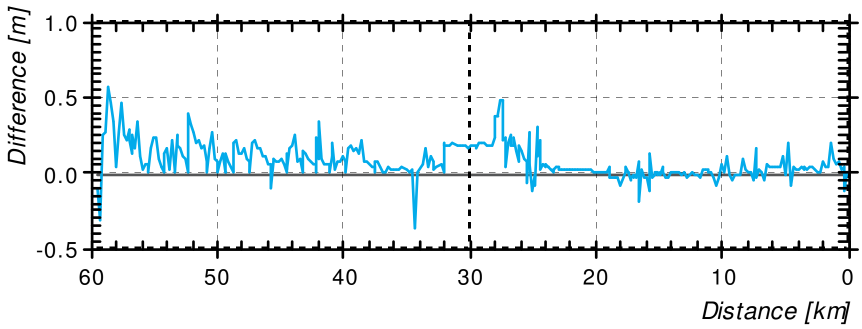


Fig. 103c:
Difference between the bed levels of the scenarios with unchanged and increased sediment input after a period of 48 years.



Sediment Balance of the Sitter Tailwater

The tailwater of the Sitter River is a mostly natural section with meanders. The bed load is significantly reduced because of dredging in the upper reaches of the catchment area. Near St. Gallen the average bed load with dredging is 3'400 m^3/a and without dredging 8'000 m^3/a.
In Fig. 104a and 104b the results of the mathematical modelling for the current and two increased sediment inputs is shown for a period of 22 years with high precipitation. For the current scenario (with dredging) there exists a significant deficit in bed load, which leads to pronounced bed erosion. Because of the erosion the bed load increases from 3'400 m^3/a up to 7'500 m^3/a. The bed erosion is limited by rock sills, weirs and the large channel width. If the Sitter would be canalized, the bed erosion would increase considerably. In years with low precipitation no significant erosion occurs and the sediment output in the river Thur reaches 4'000 m^3/a.

When the sediment input increases up to 8'000 m^3/a respectively 11'000 m^3/a sections with erosion and aggradation alternate. This all results in an even sediment balance. Local alterations of the bed level are the result of changing channel width due to bank erosion or accretion during high floods. These are natural processes in channels without bank protection.

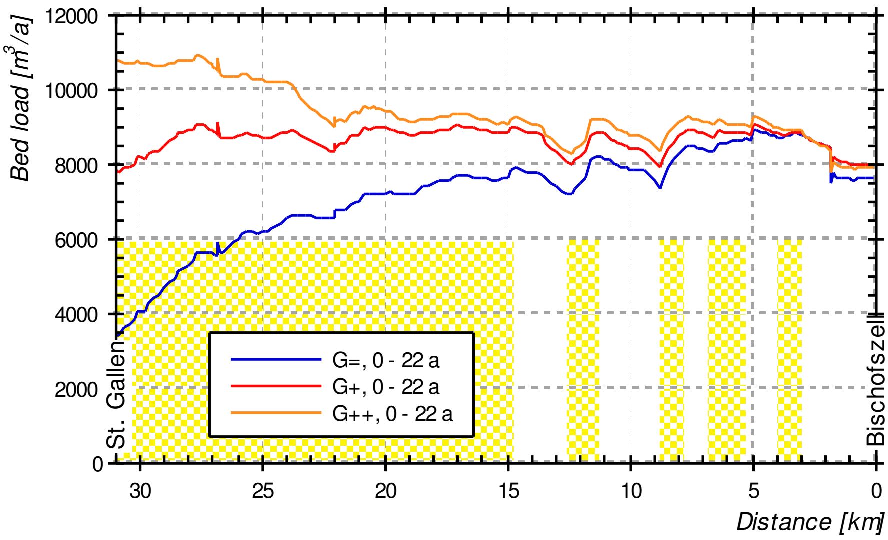


Fig. 104a: Longitudinal profile of the bed load for unchanged sediment input (G=) as well as increased sediment input (G+ und G++). The yellow areas mark the river reaches with bed erosion in the current state.

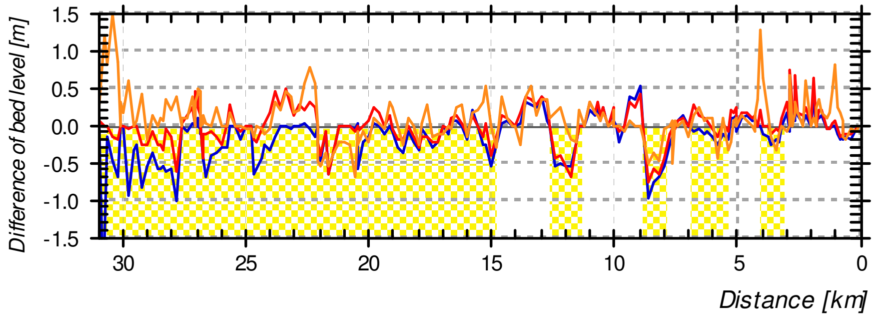


Fig. 104b: Longitudinal profile of the bed alterations for the scenarios according to Schälchli 2007.

<u>Summary Sediment Balance</u>

Fig. 105 shows the sediment balance of the river Thur and the main tributaries. Plotted is the transported bed load and reaches with significant erosion or aggradation in the current state as well as for the period 2030 – 2050 when the dredging is stopped (no additional widenings). In the current state in the upper regions the bed load increases slowly and reaches 3'500 m^3/a at Ebnat Kappel. In the canalized section near Wattwil the transported bed load increases as a result of bed erosion up to 6'100 m^3/s. With the inflow of the river Necker the bed load reaches 14'000 m^3/a. Downstream the bed load decreases because of aggradation upstream of a sill and abrasion until Bischofszell to 9'300 m^3/a. The input of the river Sitter reaches 4'000 m^3/a. Between Bischofszell and Frauenfeld as a result of the bed erosion the bed load increases up to 24'000 m^3/a. Downstream of Frauenfeld there are much gravel deposits both upstream and in the widening near Niederneunforn Altikon and the bed load decreases to 16'000 m^3/a. Near the river mouth the bed load depends on sporadic dredging which is undertaken for flood protection.

With the studied increase of the sediment input after 30 to 50 years the following processes can be estimated: In the canalized section near Wattwil the bed erosion stopped so that downstream the bed load decreases from 6'100 m^3/a to 4'800 m^3/a. Near Wil upstream of the sill no gravel is deposited and because of bank erosion (river restoration projects) the bed load at Bischofszell increases up to 11'500 m^3/a. When stopping the dredging in the upper reaches in the Sitter tailwater no bed erosion is expected and the sediment input in the Thur reaches 7'500 m^3/a. Between Bischofszell and Frauenfeld the bed load reaches 18'500 – 16'600 m^3/a. The decrease of bed load due to abrasion is compensated partly by continuing erosion. In the widening Niederneunforn Altikon the bed aggradates and the bed load decreases to 10'000 m^3/a. Downstream the sediment is transported without deposition to the restored river mouth, where all sediment is deposited (reservoir hydroelectric power station).

The study shows the following insights:

- The river training works at the river Thur resulted in an erosion process, which is not completed after 100 years. The initially intended erosion today leads to problems in river control.
- By only stopping the dredging the river bed can not be stabilized in the canalized sections of the river Thur.
- By stopping the dredging the bed erosion in the natural section of the Sitter can be prevented. The large channel width and local bank erosion are limiting the shear stress during high floods (compared with a canalized river section).
- The realisation of large river widenings lead to gravel deposition and bed aggradation, which is not completed after decades. These aggradations are acceptable concerning flood protection.

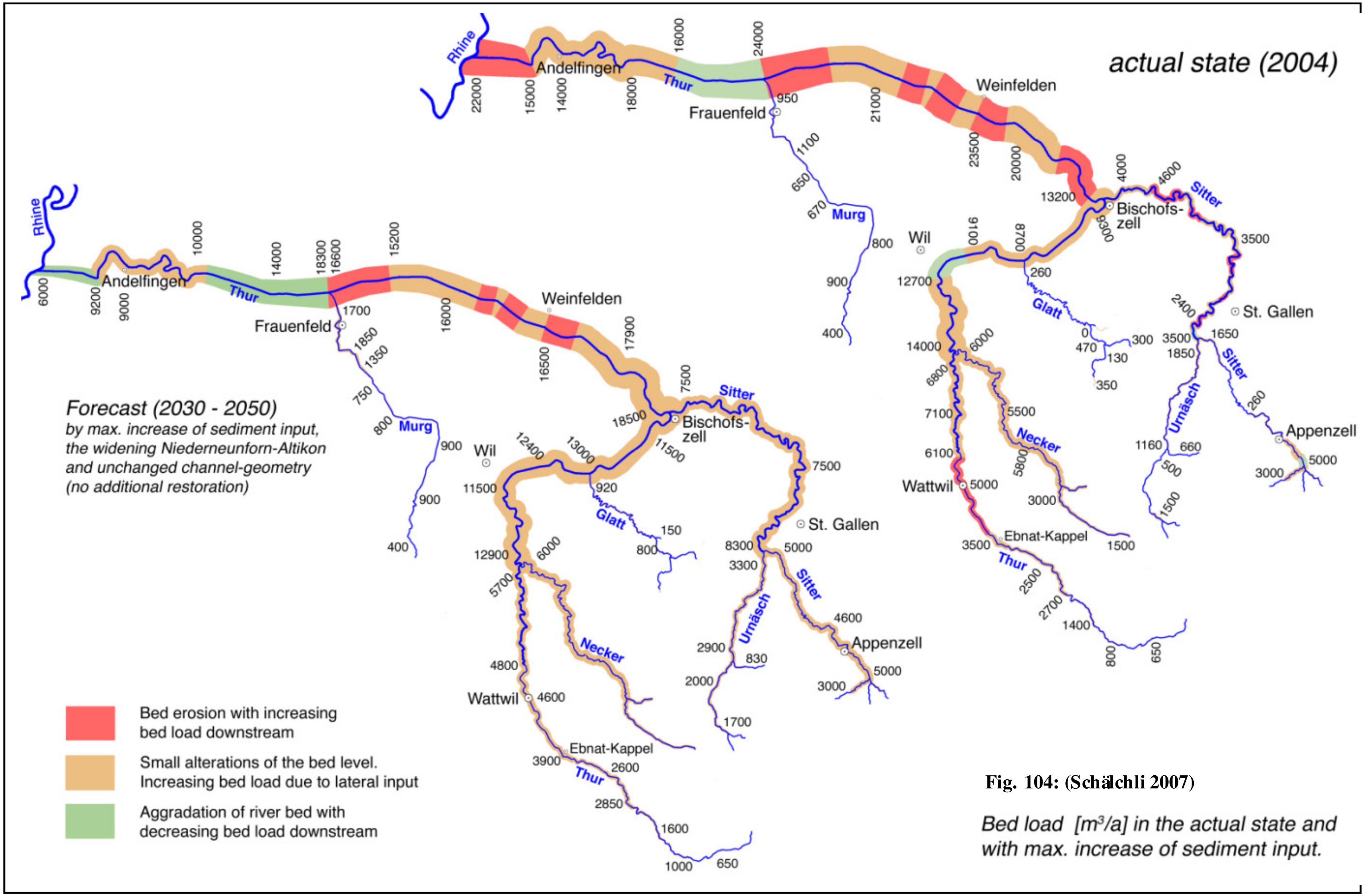


Fig. 104: (Schälchli 2007)

Bed load [m^3/a] in the actual state and with max. increase of sediment input.

Sediment Management
The study has shown that natural river sections often are in a dynamic sediment balance or may be restored by stopping dredging. In channelled river sections often exists a deficit in bed load, which leads to excessive bed erosion and thereby to problems in river control and water resources management. For this further measures in the canalized reaches are required to stabilize the river bed.

Up to now the river bed was usually stabilized by regularly implemented sills. When the interval of the sills is too large the bed erodes between the sills, what may result in scouring and destruction of the sills and bank protection works. To prevent these processes often additional sills were built. At the river Murg there exist 360 sills on a river section of 20 km, i.e. one sill on each 55 m. Such rivers are monotone and not natural.

As the example of the river restoration near Niederneunforn-Altikon shows, the river bed can be stabilized or even raised by widening the main channel. The impact on the upstream section is dependant on the dimensions of the widening. With the widening the river can be restored and a natural river meadow may develop.

When a widening is dredged, during high floods much gravel is deposited what amplifies the deficit of bed load downstream. Additionally the decreased water level (in the widening) leads to bed erosion upstream. These unwanted processes can be prevented, when no gravel is dredged and led away, but the widening is developed by self-acting bank erosion or by dredging and depositing the gravel in the main channel (as gravel banks).

To stabilize the Thur river bed between Bischofszell and Frauenfeld several river widenings are planed. The main channel may be widened form actually 50 m to 200 m. With this the implementation of further riprap sills can be prevented and the morphology of the river bed can be restored significantly. To protect the embankments additional measures are required. At the river mouth the bed load is deposited in the reservoir of the hydroelectric power station Eglisau. Here a sediment management concept has to be worked out to limit the aggradation of the river bed.

11.1.3 Reduction of erosion in the Emme river: Study „Emme 2050“

Introduction
In the last decades the Emme River had degraded, which endangered bank protections and check dams and lowered the groundwater level. As a result, there was a risk that ground-water supplies could decrease in the future modifying the quality of soil for agricultural use. Therefore a comprehensive investigation of erosion and sedimentation processes has been carried out.

Goal of the investigation "Emme 2050" was to propose suitable measures for a reduction of the erosion in the river bed of the Emme. For this, the overall system "Emme" had to be evaluated, if further measures were not to be limited to hydraulic measures. Therefore, a look back until 1880 (set up of the first project for hydraulic measures) was necessary. On the other hand, future developments in the main river and in the catchment area should be estimated. These estimations would serve to support decision making processes for a new concept of protection works. As a time horizon for the future evolution, the year 2050 was chosen from which the project name "Emme 2050" was therefore derived. Sediment transport in the

Emme River was computed and predicted with a purpose built computer program. The program "MORMO" ("morphological model") computes the development of the river bed as a function of discharge and sediment input. In this way, a longer river reach of 50 km of length could for the first time be computed and simulated.

The result of the study was a selection of measures which were proposed for the different river reaches down to the mouth of the Emme into the Aare. Additionally, basic principles for supporting measures in the catchment area were lined out (VAW/GIUB 1987)

<u>The Emme catchment</u>
The Emme River has its source at Riederund Brienzergrat and also originates from the Schrattenfluh. It flows for almost 80 km in northwest to northern direction into the Aare River. The catchment area is 963 km^2 (Fig.106).

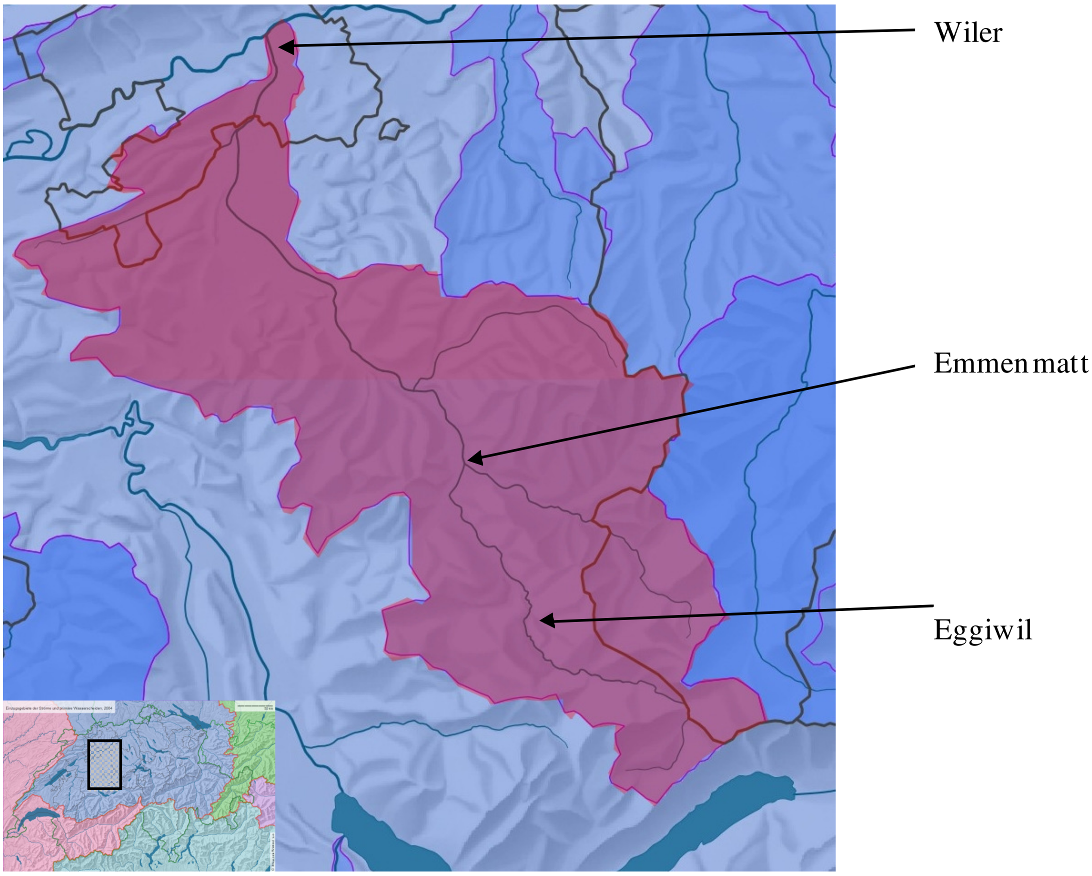


Fig. 106: The Emmental river basin. From south to north three gauging stations Eggiwil, Emmematt and Wiler indicated

Molasse covers more than 90% of the total catchment area while the rest of the underground consists of subalpine molasse, ultra helvetic Flysch and helvetic nappes. The development during quaternary can be described as follows:

- During the Mindel-Riss-Interglacial period, the Emme River eroded the main valley. The molasse rock is between 25 and 75 meters down of the valley surface.

- During the Riss glacial period, the main part of the Emmental was covered by Aare – and Rhone glaciers.
- The Würm glacial covered the Emmental marginally. But the Rhone glacier dammed the Emme River so that a lake all the way up to Langau and Signau was formed.
- After a Rhone glacier retreatment, lake accumulations were partly eroded again, and after a period of aggradation, the Emme river eroded again between 5'000 – 10'000 years before today, leaving the terraces system which can be seen until now.

In younger times, the Emme deposited some meters of material after flood events. In the last century, the Emme partially surmounted the bottom of a valley. Therefore, the problem then was the exact opposite of the problem today: because of lack of shear stress, the Emme bed increased constantly what caused the responsible authorities to intervene.

Selected climatic parameters of the Emmental are shown in Tab. 17:

Tab. 17: Climatic parameters in the Emmental

	Langnau	Affoltern	Burgdorf	Bern
Altitude a. s. l	695	802	525	570
Precipitation (mm/a)	1265	1165	1008	1000
Days with precipitation	140	139	128	126
Storm days	16	-	-	20
Days with snow cover	74	-	-	49
Annual average temp. (°C)	7.2	7.0	8.1	8.1

The Emme River has a "nivo-pluvial prealpin" flow regime (Fig. 107). Storms provoke sometimes extreme floods. The relation between the measured mean discharge and extreme floods can be up to 1:50. In Emmenmatt for example, mean discharge is approx. $12m^3/s$, however, high water maximum was already measured at 490 m^3/s, the extreme flood in August 2005 registered even 550 m^3/s, which corresponds to a specific discharge of 0.5 $m^3/s\ km^2$!
The chapters following now summarize the results of the study "Emme 2050".

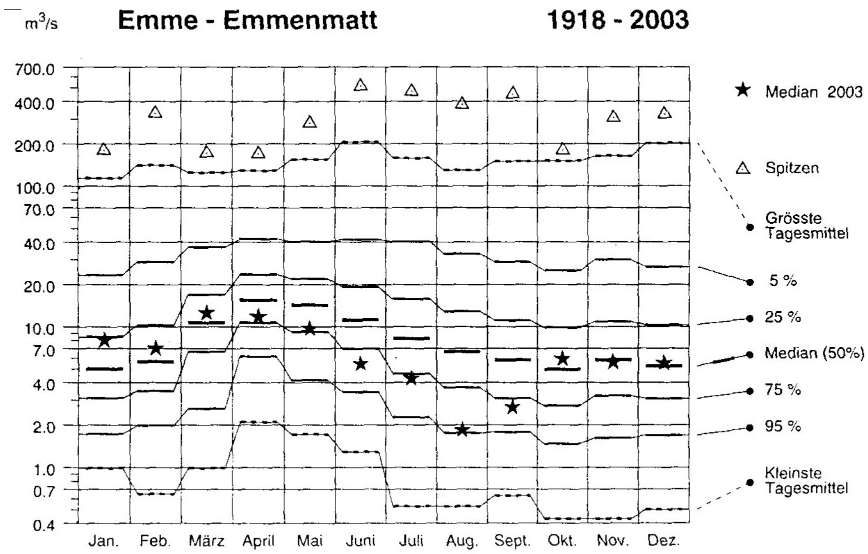


Fig. 107: Monthly distribution of mean daily discharge of Emme River

<u>Forests, drainages, precipitation and discharge</u>

Forests

The Emmental is today one of the most densely forested areas in Switzerland. Forest comprises 36% of total area in 1980, compared to the Swiss mean of 29% or the canton Berne of 25%. A forest inventory was carried out from 1752 to 1754 and contained information about the forest in the Amt Trachselwald, a sub region of the Emmental. A comparison of the forest areas of that time and now is shown in Tab. 18:

Tab. 18: Development of forest areas in the Emmental

Community	Total forest area in 1750	Total forest area in 1890	Total forest area in 1980
Trub	170 ha	2320 ha	3250 ha
Trubschachen	74 ha	560 ha	650 ha
Langnau	437 ha	1520 ha	1840 ha

However, the biggest clear cutting started only in1798, mainly for four reasons:

- Decline of government authority (loose of control of wood cutting) after the fall of the old Berne, and almost simultaneously increasing needs for wood.
- Increasing industrialization with corresponding wood requirement.
- Active construction activity by an increase in population in the first half of the 19th century.
- Wood export to foreign countries.

Later, an immense demand for wood resulted from the construction of railroads. The forest has an impact on runoff reducing flood peak discharge. In large catchments, influence of forest areas on discharge is difficult to conclude upon. Other influences like the ones described below play an important role, too.

Drainages
Drainages in the canton of Bern were institutionalized in 1897. Since the beginning of the 70's, the number of the drains has decreased, because federal authorities do not grant subsidies anymore since that time, because of agricultural overproduction. The effect of drainages on floods depends on the specific situation. Hill slopes in the upper catchment area of the Emme: grassland soils are little permeable. In drained areas, water can easily infiltrate into the drains filled with loose material, what increases the general velocity with which it reaches the receiving water. Flood peak might increase therefore.

In flatlands, however, water can not infiltrate undrained and saturated soils. After heavy rainfall, the water partially flows off superficially and can therefore increase the flood peak. On large drained grounds, which are dryer as the natural ones, rainfall water infiltrates until the ground-water level achieves the surface. Consequently, drained soils absorb strong rainfall and delay the drain into the receiving water.

Settlement and traffic
Buildings, forecourts and traffic routes are regarded from a hydraulic viewpoint as so called "sealed surfaces". In these areas, water can not infiltrate into the ground and flows off superficially. It reaches the receiving water relatively fast. Increasing settlement and traffic areas can also be observed in the Emmental, but the total areas of such surfaces are in the low percent range, so an influence on discharge, restricted to that factor only, can not significantly be registered.

Precipitation
For a 24 h rainfall with a recurrence interval of 100 years, the Emmental counts with approx. 120mm. In the case of the Emme River, it turned out that daily rainfall must exceed a specific threshold value for flood formation and sediment transport. Such threshold values were defined for the pluviometric stations at Bern, Solothurn, Langnau and Affoltern. Also, the monthly number of transgressions was computed for the period 1901 to 1980. On the basis of the calibration period for the MORMO model it was found that in certain cases a daily rainfall of merely 15 mm can result in a discharge higher than 170 m^3/s. Consequently, it sets up the question if threshold values modify themselves with time. In order to find a development trend the values were subjected to a regression analysis. The following results were obtained: The monthly frequency of computed threshold value transgressions hardly varied.

The number of precipitation days (precipitation of more than 0.1 mm) has rather decreased in the years of 1941 to 1980 compared with the period of 1901-1940. In all, a decreasing tendency was noticeable for the small daily precipitation, however, for the higher daily rainfalls an increasing, but only a partly significant tendency was observed. One can summarize after the statistical study that the precipitation in the Emmental is not subject to a modification. Possible changes of the discharge values in the Emme River do therefore not occur because of rain fall modifications.

Discharge
Besides the basics to be provided for the calibration of the MORMO model, the question about a possible modification of discharge was also tested. Within the framework of the project "Emme 2050", the discharge investigations were limited to those which are important for bed formation in the Emme River, what is the minimum discharge for sediment transport. However, this is only the case in midsize to high floods. Hence, discharges of 180'200 m^3/s were mainly studied. At these values, the armour layer of the Emme River is eroded. However, sediment transport already starts with 40 - 50 m^3/s. Consequently, investigations were concentrated on these minimum discharge values.

The model of MORMO had to be supplied with realistic discharge data in order to estimate erosion behaviour up to 2050. For this purpose, data from the discharge gauging stations of Eggiwil, Emmenmatt and Wiler were statistically examined over the entire measurement period. Among other things, evaluations of the annual maximum, flood volumes, frequency distributions of monthly maxima etc. were tested and finally plotted. So it was possible to read out maximum flood values, volumes and duration of floods with recurrence intervals of 1 month up to 100 years. It was then attempted to generate synthetic flood waves.

An operational and generally recognized procedure for the proof of discharge modifications does not exist. Numerous evaluations had therefore to be carried out including different aspects, as for example the coherence between rainfall and discharge as well as the behaviour of the flood peaks. The qualitative effect of various parameters on discharge is shown in Tab. 19.

Tab. 19: Effects on discharge by selected impact changes

Type of intervention	Effect	Tendency to peak discharge	Tendency to base flow
Increase of Settlement and traffic	Surface sealing	++	-
Increase of forested areas	Loosening of soil	(-)	?
Intensive farming	Soil compaction	+	-
Drainage of fields	Soil drainage	+	+ +
Hydraulic works	Abolishing of water retention	+	-

For the gauging stations of Eggiwil, Emmenmatt and Wiler (see Fig. 106) no significant modifications of the discharge volumes were registered on account of trend investigations for sediment transport. The frequency of larger floods did not increase. No more than an increase in peak discharge can be proved for Eggiwil. A slight trend exists in Emmenmatt only. In Wiler on the other hand, an increase in peak discharges was proved. The order of magnitude of modifications will range about 3 per mil per annum. For an extrapolation to 70 years, an increase in midsize floods would result by 20%.

Flood history in the Emme River and in the side catchments
Written reports about flood damage events in the Emmental already exist in the 14th and 15th century. For the time between 1901 and 1985, 118 events of damage were evaluated. Floods stayed away in only 31 of 85 registered years. Several events occurred for example in 1927,

1931, 1932, 1936, 1953, 1968 and 1970. The events of 1927 and 1931 concerned large areas of the Emmental. By means of the distribution of the number of events of damage to the individual decades, two important facts can be established:

- The concentration of the events of damage during the thirties. In that decade, the Emmental was affected by 35 damage causing floods. With the available data, it was not possible to clarify this issue in a satisfactory way. An accumulation of special circumstances in the meteorological environment (humidity period of the thirties) would form an explanation.
- Explicit decrease to about 50% of the former value of the flood damage events during 1971 to 1980. But one must warn against a fallacy: although an apparent decrease can be listed from 1981 to 1985 compared to the seventies: the two floods which concerned the region of Berne in 1986 also affected the edge in the Emmental. The 1987 events in the Biembach are no more considered. If these events were added to the five damage cases registered since 1981, the decade since 1981 showed again an increasing tendency of the damage frequency.

A flood record for the Emme River since 16th century is shown in Fig. 108.

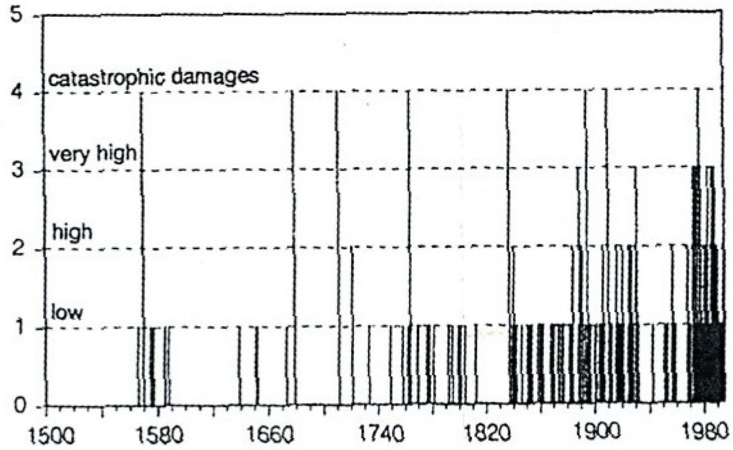


Fig. 108: Frequency and qualitative magnitude of floods in the Emme River between 1500 and 1995 (Gees, 1996)

<u>Hydraulic works</u>
Hydraulic works can influence discharge and sediment transport by means of transverse and longitudinal structures. Transverse structures reduce bed and bank erosion: especially by mounting several transverse structures in succession, the depth erosion can be suppressed. Behind the check dams, a widened retention space develops itself, now on a higher level than before. This retention space is broader as the one usually occupied by the creek. In this way, undercutting of the slope foot scarcely happens. Consequently, an extensive stabilization of the sediment sources can be achieved by these measures provided the sediment sources are within the area of influence of the construction.

Otherwise, the construction looses its effect as soon as material from the sediment source reaches the creek again. As a disadvantage, sediment retention at the backside of the check dam might form additional sediment potential in case of the damage of the structure. Modification of the sediment transport: check dams retain a certain sediment volume, which could achieve up to around 600 m^3 in the case of larger side valleys of the Emme. This material is possibly missing in the receiving water.

Modification of shear stress of the water: Slope reduction results by stepping back of the channel, decreasing itself the shear stress of the water, which finally results in a decrease of sediment transport capacity. Longitudinal structures serve above all for the reduction of lateral erosion. Moreover, it should be prevented in the case of a flood that the water submerges the neighbouring areas. However, longitudinal structures abolish natural water retention beside the river.

Longitudinal structures improve the hydraulic conditions in the channel, i.e. the water can possibly flow faster and shear stress of water increases. Discharge capacity is therefore increased, and consequently sediment transport capacity as well, with the positive effect for example in channels in the settlement: in the case of a flood, the transported sediment can flow off without causing damage. However, backwater problems might result in the receiving water.

Correction of the Emme River
During the middle of the 19th century, the Emme was a broad mountain river, with branches and meanders. Floods with inundations occurred often, and so did also sediment transport and occasional embankments. The Emme was constricted already at many places by means of dams and lateral weirs. All these were however single measures and influenced the floods only conditionally. The measures often pursued by the way the purpose of land reclamation. In a first construction period the river was checked only so that the room between old and new bank aggraded automatically by sediment deposits of subsequent floods. The new banks were increased only after this stage was completed. Therefore, one attempted a direct "cooperation" with nature in this way. In a later stage the flow section was completed with dikes by formation of a regular foreland. The work was done in accordance with the following list (Tab. 20):

Tab. 20: Constructions in the Emme River

Section	Technical report	Start of work	Completed
Kt. of Solothurn	1868	1871/72	1880/81
Section 1	1873	1874/75	1891/92
Section II	1884	1886/87	1901/02
Section III	1886	1897/98	1923/24
Section IV	1908	1909/10	1930/31

Situation after the corrections
At first the riverbed did erode so rapidly everywhere as had been expected. Later however, different causes supported the erosion strongly. Massive interventions became necessary therefore. Erosion was strong especially below the mouth of the Ilfis: within the first nine years after the correction it degraded up to 2.4 m. The first bed control had to be installed in 1897/98 already.

Since the mentioned correction stage, bed consolidation works had to be carried out at the Emme again and again. A generally increasing interest in flood security had to be satisfied, on the other hand, larger floods as the ones in 1910, 1949, 1953 and 1968 occurred, and damaged bank constructions. Moreover, with the continuous bed erosion the construction of more and more transversal structures became necessary.

Analysis of today's stage of the construction works
It soon became clear that nature would continue the introduced bed erosion by itself. The continuing degrading would have caused the collapse of the longitudinal structures, which were inserted for stabilization of the cross section. Above all the problem intensified itself at bridges and water diversion structures. Because the bed had to be held on a specific level, the first check dams had to be constructed. In such a way, the problems concerning erosion and bed development included above all the stability of the hydraulic structures in younger times. Check dams reduce natural bed slope, and meanwhile they reduced the Emme slope already for about 2/3 of the total height difference.

Control works in side catchment areas do also influence the receiving waters. At the beginning of the 20th century, efforts for punctual measures in neuralgic places of the side waters were made. The main goal was to protect in this way the adjacent land against flood damage. Between 1931 and 1940, a high construction increase was provoked mainly in connection with the depression and the frequent flood damage events since 1927. Certain saturation in theses activities, presumably because of financial circumstances (Second World War) and less frequent floods decreased the demand for subsidized protective measures in the two following decades. The second sudden rise of the subsidized hydraulic engineering projects can be observed since the beginning of the seventies: the number of projects increased to 38 from 20 (1961 1970) in the said decade, which corresponds to an increase of 90%! Floods can not be stated alone as a causal factor. The corresponding cases of damage did not increase until 1985. The granted subsidies achieved again a new absolute highest level between 1981 and 1985 (end of the observation period): 40 hydraulic engineering projects were granted, that is only one project less than in the period between 1890 and 1930!

It should however be taken into consideration that the younger subsidy projects involved not only a quantitative increase but also a qualitative one (substitute of old, break due measures).

<u>Sediment budget in the Emmental</u>
The sediment budget of the Emme is controlled by the following factors:

- Sediment input from the large catchment areas
- Sediment input from the smaller side catchment areas which connect directly to the Emme
- Erosion and accumulation of the Emme bed
- Dredging in the Emme

For an estimate of the natural sediment input and the dredging, specific basics had to be provided for entering data into the MORMO model. Moreover, the sediment input during the calibration period from 1969 to 1982 was used for the examination of the model and served furthermore as input parameter for the prognosis computations.

Method of evaluation
The sediment budget of the Emme can be expressed by means of a simple relationship:

$$G_{Output} = G_{input} - G_{BW} - \text{Abrasion} \pm \text{River bed}$$

G_{input}	Natural sediment input into the Emme: Control elements are the sediment sources in the side catchment areas from which ones sediment reaches the channels as well as the transport capacity of the side channels to take this sediment into the Emme.
G_{BW}	Sediment management: It contains all human measures into sediment budget like dredging, management (emptying) of sediment deposits, the effect of hydraulic measures on the sediment budget.
Abrasion	Roundoff and fining of gravel during transportation by water
River bed	Modifications i.e. increase (accumulation, deposit of material) or degradation of the bed (erosion) mean a reduction or an increase respectively the for sediment budget the considered section.
G_{output}	Sediment output from the considered river stretch considering the components mentioned above. The respective sediment volume goes as sediment input into the subordinate river section, in which the same elements are again considered. The lowest sediment output corresponds to the volume which finally leaves the system "Emme" at the mouth into the Aare River.

For the sediment budget estimation of the side channels, the following had to be considered:

a) Sediment production:

1. Qualitative evaluation of the sediment sources in question and of the erosion processes.
2. List of the known annual sediment transport of selected catchment areas which have preferably sediment deposits with data of the emptying including the corresponding cubature.
3. Estimate of the bed load of total sediment, considering granulometry: any grain size above 0.5 cm of diameter is regarded as coarse material; it is forming the river bed of the Emme.
4. Calculation of particular bed load in cubic meter per annum and square kilometre.
5. Calculation of bed load volumes for those areas of the catchment, from which bed load is to be expected (=bed load relevant areas)
6. Evaluation of the processes which progress within the bed load relevant areas by means of a comparison with the other examined catchment areas.
7. Derivation of the bed load volumes as a function of geological and geomorphological factors.
8. Transfer of corresponding volumes to all side catchment areas of the Emme.

b) Sediment management:

1. Estimating of dredged sediment volumes on the basis of official information and field observations.
2. Quantification of influence of hydraulic measures. List of the measures in the temporal and spatial context with the corresponding valuation. Verification in the field.

Sediment production
Sediment production, essentially the transformation of rock into individual rock fragments by decomposition, strongly depends on lithology of the prevailing rock formations. In the Emmental, this is above all the tertiary molasse deposits of Nagelfluh, Sandstone and Marl. From the Nagelfluh formations of the molasse, rounded components result in the creek bed. Nagelfluh is normally badly consolidated so that the conglomerates might quickly fall apart in single components. Sandstone will mostly be comminuted after few meters in the channel and therefore rarely appear as bed load. Marls are often even more sensitive and fall apart already before they achieve the creek bed.

In areas with frequent alternations of quantitative characteristically firm and too firm rocks, the Nagelfluh is laid open by the intense decomposition of marls by which it is also subjected to an accelerated decomposition. Marl layers often form so-called "glide horizons" on which other rock or the ground can slip off.

The weathered material then reaches, following the force of gravity, the receiving water. This can be by means rock fall, by means of slips or in small channels (creeks). In this way, a material deposit will be formed in time, which in the case of a flood will be washed away.

Annual bedload volumes
On account of information about the management of the sediment retention basins, first estimates about annual sediment outputs from different side catchments of the Emme could be made. The results allowed a first characterization of the catchments concerning their average bed load volumes. For 20 small sediment retention basins (Tab. 21), the average annual bed load could be determined. The values however are estimated and not measured, what always brings certain insecurity into the results. However, the sediment retention basins do not absorb all material. An unknown part of fine components is rinsed by the water and can not be registered anymore. This is partly compensable with surcharge calculations. Mistakes resulting in this case play a role where the total sediment volume inclusive fine material is the subject of discussion. The bed load part at total sediment volumes is very different in the Emmental and ranges between 30% and 70%.

Tab. 21: Small retention basins and average annual bed load

Catchment	Size (ha)	Sediment volumes (m^3/y)	Annual deposition rate (m^3/km^2 y)
Hübeli	14	25	179
Himperg	19	50	263
Löffel	24	50	208
March	31	30	97
Hälig	35	40	114
Bäänli	36	50	139
Schachen	38	100	263
Branntenegg	42	80	190
Habbach	49	20	41
Sperbel	54	50	93
Rappen	60	100	167
Schützen	92	200	217
Folz	94	80	85
Obermatt	160	550	344
Nidermatt	175	650	371
Talgraben	480	350	73
U. Frittenbach	635	650	102
Biembach	860	500	58
Goldbach	2190	600	27
Rüegsbach	2230	550	25

Sediment transport during flood events

The reconstruction of the sediment transport during flood events was only possible in few cases. A detailed analysis could be carried out in case of the by July 1st, 1987, event in the Biembach (Tab. 22).

Tab. 22: Sediment budget in the Biembach during the event of Juli 1st, 1987

	Erosion	Accumulation	
Channel erosion incl. banks	9000		1500 in main channel
Landslides directly to the channel	600		
Accumulation in channels		5500	1400 in main channel
Accumulation out of channels		600	
Total	9600	6100	

The importance of the internal relocation of material was clear here.
For other storms, the bed load cubatures could be estimated approximately (Tab. 23).

Tab. 23: Bed load volumes for storm events in the Emmental

Creek	Catchment area (km2)	Volume (m^3)	Recurrence interval (years)	Specific volume (m^3/km^2)
Löffel	0.4	2000	50	5000
Schachen	0.4	400	10	1000
Sperbel	0.5	100 - 130	10 50	200 300
Rappen	0.6	400 - 1300	10 50	700 2200
Steinen	0.7	700	10	1000
Folz	0.9	350	10	400
Blinden-bach	1.0	900	10	900
Schmitten	1.5	700	50	500
Büetschli	2.4	900 – 5000	10 50	400 2100
Biembach	5.5	3500	50	600

The flood events in the creeks in the Emmental are of minor importance for the Emme River, because they often consist of relatively small slopes and have accumulation possibilities in the plains. Bed load only reaches the Emme River occasionally.

Tab. 24: Sediment and bed load volumes in 23 small catchments of the Emmental

Creek	Catchment area [ha]	Annual solid matter$^!$/J	Deposit rate rn^3/km^{5}y	F/B %*	Bed load m^3/y	Bed load rate rn^3/km$^!$J
Hübeli	14	25	179	30	8	54
Himperg	19	50	263	30	15	79
Löffel	24	50	208	60	30	125
March	31	30	97	40	12	39
Hälig	35	40	114	50	20	57
Baanli	36	50	139	50	25	69
Schachen	38	100	263	60	60	156
Bagischwand	41	55	134	30	17	40
Branntenegg	42	80	190	60	48	114
Habbach	49	20	41	50	10	20
Sperbel	54	50	93	70	35	65
Rappen	60	100	167	60	60	100
Schützen	92	200	217	30	60	65
Folz	94	80	85	50	40	43
Obermatt	160	550	344	70	335	241
Niedermatt	175	650	371	70	455	260
Büetschli	236	500	212	70	350	148
H. Geissbach	275	900	327	80	720	262
Talgraben	480	350	73	50	175	36
U Frittenbach	635	650	102	30	195	31
Biembach	660	500	56	30	150	17
Goldbach	2190	600	27	30	180	8
Rüegsbach	2230	550	25	30	165	7

*Percentage of fine material to bed load

Mean annual sediment delivery rates

One of the main conditions of sediment delivery is the existence of sediment producing rock formations. Therefore, the different geological conditions are distinguished in a simple classification. The part of the bed load forming formations within the bed load relevant areas (Nagelfluh, limestone) is subdivided into four classes:

Category	Pecentage of area
1	< 25%
2	25 - 50%
3	50 - 75%
4	> 75%

The area percentage was determined by the layer thicknesses of the sediment forming formations within the slope. In this way, the following conclusions could be drawn:

- In areas with less than 50%, Nagelfluh bed load from the bed load relevant area amounts to about 250 m^3/km^2

- In areas with a lot of Nagelfluh but also alternating with ***marls and ***silicate brick the respective amount is about 550 m^3/km^2
- In areas with exclusively Nagelfluh in the decomposition resistant areas the value is about 200 m^3/km^2 amp, in all other areas approx. 400 m^3/km^2 a.

Development of sediment retention

Fig. 109 shows that the hydraulic measures carried out until after the first world had already a very strong effect on sediment retention. They took mainly place in the broad main channels, where high amounts of sediments are retained.

All check dams in the side channels retained approximately 170'000 m^3 of sediment until 1985 (Fig.109). No doubt, a considerable part of this material would have reached the Emme without these check dams. The mentioned bed degradation of the Emme is therefore also the result of the hydraulic measures in the side catchment areas. If sediment is permanently taken out of the water, sediment shortage in the main river will support erosion of the bed.

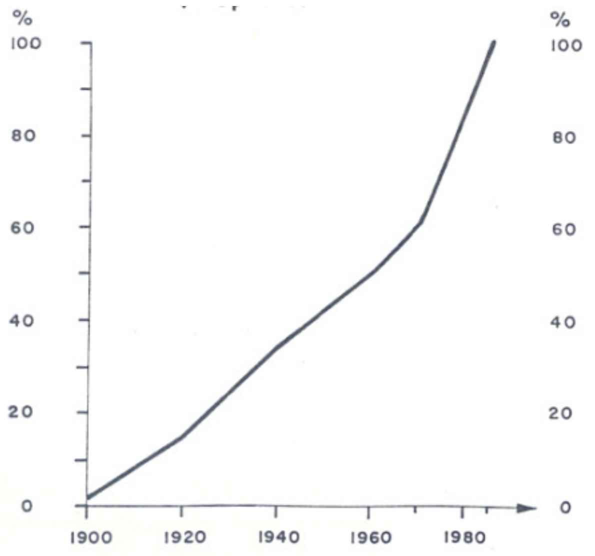


Fig. 109: Check dams constructed in the three side catchments of Trub, Gruene, Roethenbach and in all other catchments ("Gesamteinzugsgebiet" of the Emmental) (100% = 5000 check dams)

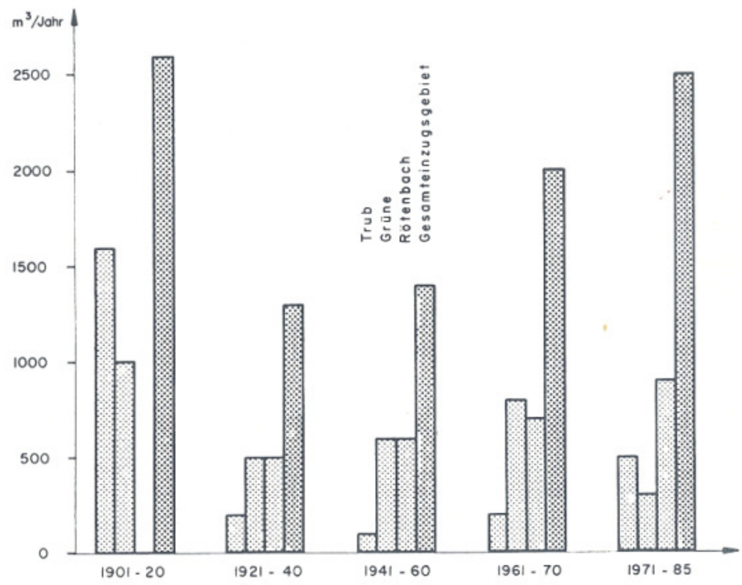


Fig. 110: Annual retention volumes by check dams

Sediment management

Sediment management in the Emmental is, apart from hydraulic engineering, mainly dredging (Tab. 25).

Tab. 25: Dredging volumes (m3) from Emme and Ilfis rivers at indicated time periods

	1961-1965	1966-1970	1971 - 1975	1976-1980	1981 - 1985
	7800	5900	6200	6000	3200
EI	19800	15300	11100	10100	8500
EII	400	200	-	-	-
EIII	11400	7700	9300	6700	1700
E III/IV	8300	8300	9100	5600	2400
Ilfis	2500	2000	1900	1500	-
In total	49800	39200	37600	29900	15500

EI to EIV are the Emmesections one to four respectively: Eggiwil – Emmenmatt, Emmentmatt – Burgdorf, Burgorf mouth of Limpach, Limpach – Aare river.

Today, there is no more dredging in the Emme, since no approvals are given any longer.

The MORMO Model computations

With the aid of the morphological model MORMO, it was now attempted to predict the future bed development in the Emme considering the variables mentioned in the preceding chapters.

The calculated river section starts at km 44 and ends at the sediment retention basin at the mouth into the Aare. The decisive unknown parameter was the sediment input at km 44, which is the result of the sediment input from both upper Emme catchment area and the Röthenbach as well as the one from the Ilfis River. All other small side catchments could be neglected because of their small sediment input volumes. The deposited cubature in the sediment retention basin at Luterbach was known. At this point, due to the hydraulic conditions by the power station Flumenthal no further sediment transport is possible. Consequently, the calculations could be controlled and the model adjusted if required. The determination of the annual sediment volumes occurred by means of a sediment function, which was set up for every river stretch. With this function, the corresponding sediment transport can be determined for every discharge value. The bed level changes were in this way computable.

Tab. 26: Mean annual bed load volumes during the calibration periods. Differences in the volumes at the point of sediment output from the calibration stretches are model induced

Calibration stretch	**Eggiwil - Emmenmatt.**	**Emmenmatt - Burgdorf**	**Burgdorf - Limpach**	**Limpach - Aare**	**Emmenmatt - Ramsei**
river-km	43.9-34.3	34.3-18.5	18.5-2.5	2.5-0.6*	33.4-25.7
Calibration period	1973-1983	1969-1982	1969-1982	1969-1982	1900-1930
GE (m^3)	4700	12000	20100	7400	29100
ES (m^3)	3900	7600	10100	5800	28500
AS (m^3)			5600		
A (m^3)	700	3700	5100	1000	5200
GESB (m^3)	700				
KE (m^3)	6000	4200	12100	5900	
GA (m^3)	2900	20300	7600	7500	52400

GE: bed load input into the calibration stretch
ES: erosion of river bed
AS: bed aggradation
A: abrasion
GESB: bed load input from side catchments
KE: dredgings
GA: bed load output at lower end of calibration stretch

For the prognosis computations it was in particular assumed that no structural measures would be taken and that the contemporary structures will hold the corresponding supplementary loads. The average annual cubatures for the four calculated river sections are shown in Tab. 27. In the section Eggiwil – Emmenmatt, the average annual erosion will be smaller than during the calibration period. Because there will be no more dredgings, the sediment output into the lower section will be larger. In the section Emmenmatt – Burgdorf, the eroded sediment volume is smaller in the future than during the calibration period. The sediment input corresponds to the one during the calibration period. At the beginning of the period, erosion provokes an essential increase of sediment transport, but in the year 2042 almost an equilibrium stage will be achieved. The average mean annual erosion of this period is very large with 400 m^3/km/a, however, decreases strongly until 2042.

Tab. 27: Annual bed load volumes in the Emme river betweeen 1982 -2042

River stretch	River-km	GE (m^3)	ES (m^3)	A (m^3)	GESB (m^3)	KE (m^3)	GA (m^3)
Eggiwil - Emmenmatt	43.9-34.3	6100	1500	1000	700		7400
Emmenmatt - Burgdorf	34.3-18.5	12500	3500	3300	4000		16900
Burgdorf-Limpach	185-2.5	16900	6400	3900		10000	9400
Limpach -Aare	2.5-06'	9400	1500	1200			9900

GE: bed load input into the calibration stretch
ES: erosion of river bed
AS: bed aggradation
A: abrasion
GESB: bed load input from side catchments
KE: dredgings
GA: bed load output at lower end of calibration stretch

Mouth of Limpach to the Aare:
Mean annual erosion is in the future essentially smaller than today (approx. 180 m^3/km a and 700 m^3/km a respectively). At the lowest kilometres the tendency to erode will hold on.
The results of the computation have been compared with field investigations and show a good agreement (Fig. 111).

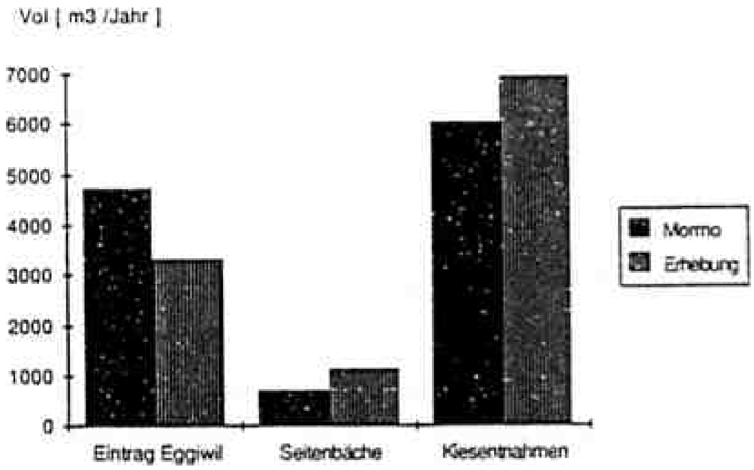


Fig. 111: Comparison of cubatures for the section Eggiwil - Emmenmatt

Measures to achieve an equilibrium stage of bed level in the Emme River
The question was now which basic possibilities do result in the stabilization of the Emme River bed?

Transverse structures
In stead of check dams, block ramps which would have ecological advantages (migration possibilities for fish and microorganisms) can be planned.

Bank protection
A change of the engineering methods at the banks often results in a modification of bank structure (bank roughness), which influences flow behaviour of the water. Both parameters, slope inclination and bank roughness, have a certain influence on discharge and therefore on transport capacity. Extreme modifications in this sense would for instance be vertical bank protections or allowing bank vegetation, where this did not yet exist up to now.

Variation of cross section and line management
A possibility is the variation of the bed width. Modifications of the cross section and of the line management can not be considered in an isolated manner but must be subject to an overall concept. An enlargement of the river bed becomes possible, where space is available to modify the contemporary cross section. However, this should be planned carefully because a trend reversal could be caused by a cross section enlargement, which could provoke bed aggradation.

Three variations were finally focused upon:

1. Regular River widening
2. Irregular widening with local ramifications
3. Widening for a meandering

Recommended measures
Several propositions were now selected from the many possible measures and recommended in a summarized manner for after treatment. The analysis of the catchment area yielded different results which were to be considered in the sense of supporting measures. They shall all reduce flood peaks and increase the sediment input into the Emme River.

The main measures concerned the Emme. In the side creeks, the following action was recommended:
The sediment input into the Emme has to be supported. Local dredging should be suppressed or at least be limited at its scale. This concerns above all the side creeks whose sediment naturally reaches the Emme. The management of sediment retention basins and the mounting of debris sorting dams make sense.

Further on, for the side creeks, protection concepts should be planned. Many of the protection measures in the upper reaches support only temporary sediment retention. Sufficient sediment transport into the receiving waters has to be guaranteed. However, measures against bed erosion in the Emme River are most important. But such measures may not lead to a trend reversal, i.e. bed aggradation. Therefore, the following points have to be considered:

- Every further bed narrowing has to be avoided.

- The approval practice for dredging from the Emme and the most important affluents has to occur very restrictively. The most important withdrawal place near Utzenstorf is to be abolished on a long-term basis.
- The bed can be held virtually on its contemporary level by regular cross section enlargement of 10 to 35 m. With local widenings a morphologically branched stage is achieved. However, such ramifications must alternate with constricted sections, in order to satisfy flood security requirements.
- A meandering section is possible at different places. However, this leads to a greater modification of the contemporary channel. For this, further clarification is required.
- If erosion should be fought by the construction of check dams, up to 80 of them would be necessary.
- Comprehensive measures in the channel (e.g. laying of boulders) only are eligible for consideration sporadically.
- At existing check dams, the fall height can be enlarged with block sills or an array of check dams.
- Future hydraulic engineering concepts must be designed for the smallest possible sediment retention.

The local widening measure

After finishing the project "Emme 2050", the different possibilities for implementation were evaluated. A local widening was planned as one of the first concrete measures. The project planned for the local widening is approx. 8 km north of Burgdorf.

Experiments in laboratory

Since the flow morphological contiguities can not be clarified in practice in detail, laboratory experiments have to be carried out. A flume was available for the experiments. Some adaptations had to be made compared to the natural circumstances (more stretched run and partly shortened stretches than in reality), which however should have no greater influence on the result. Topography was copied with the aid of the cross-sections from 1982. Longitudinal protections were simulated by means of a specific rip rap. The sediment employed for testing purposes was entered by means of a specific and precise charging machine at the upper end of model.

Results

In order to stop the expected bed erosion the local widening must show a width of 65 to 85 meters and a length of 460 meters. A branched river section resulted. The experiments would show moreover, that the lateral erosion will continue more and more without artificial limit and will endanger the existing flood control dikes in time. Therefore, four training structures were recommended in the forelands. Between the training structures and the flood control dikes about 20 m of foreland would remain as a buffer zone for the protection of the dikes. The widening itself should occur to a large extent by lateral erosion of the Emme, what would be accompanied by considerable cost savings.

The evolution of the local widening up to the final stage will last some years. Calmer development phases can alternate with progressing faster ones. Little measures such as the vegetation elimination can accelerate the development.

Implementation

Between November 1991 and March 1992 the first construction phase of the local widening was carried out. On May 7th, 1992 the structure was inaugurated by the authorities and institutes involved.

The flood of December 23rd, 1991 with a discharge of about 370 m^3/s already washed away approx. 8000 m^3 of sediment. The said material removal and the fill of small islands with excavation material of the training structures divided the Emme into two channels. However, different floods must still add their part up to reaching of 65 to 85 m of the final width. Until now, the reduced sediment transport capacity caused a bed aggradation of 70 cm as an average, which corresponds with a bed level in 1949 (Fig. 112).

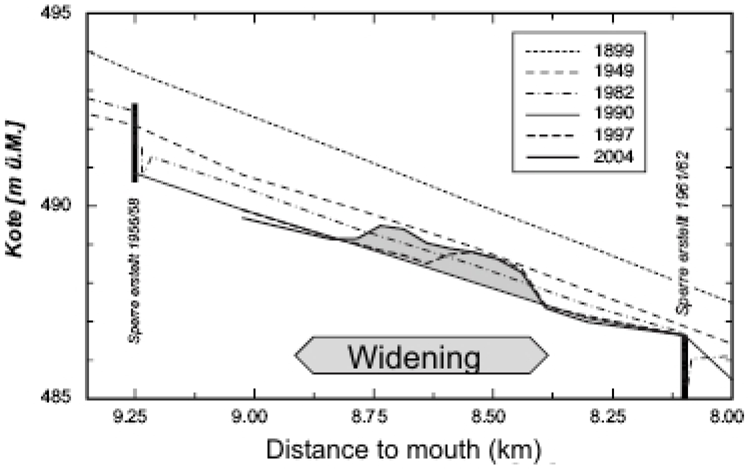


Fig. 112: Changes of bed level at the local widening

In August 2005, a large flood of about 550 m^3/s covered the widening completely. This was by far the largest flood since the implementation of the local widening, with unknown effects until now (Fig.113).

Fig. 113: The local widening during the flood of August 22, 2005 (Photo: C. Lehmann)

Socio-economic and ecological effects
A rich fluvial structure has already formed itself with several river branches, several gravel bars and scours. This piece of alluvial landscape represents a new niche for a number of rare plants. After several studies that have already been carried out to accompany the self formation of a near natural landscape, general experience for a few years in some widenings in Switzerland shows the following:

- The widenings promote the re-establishment of pioneer habitats, mainly gravel bars and softwoods.
- River widenings increase habitat diversity. However, habitat diversity is lower than in corresponding near-natural reference sites due to the limited spatial extent of the widenings.
- River widenings show a more complex habitat mosaic than near-natural sites.
- River widenings provide habitats for riparian plant species, for example, Phalaris arundinacea and Epilobium fleischeri.
- Restoration success depends mainly on the spatial extent of the widening, distance to near natural species pools and bed-load transport.

Although the bed has risen, due to larger bed width the water levels are not as high as before during floods. The Emme river widening has also gained great popularity as a recreation area for the local population (Fig. 114), who call the widening "pear" because of its outline form. Since the widening occurred within the existing flood control dikes, the flood safety is still guaranteed.

Fig. 114: The "Emme pear" as recreation area (Photo: C. Lehmann)

11.1.4 Assessment of sediment yield in the Weisse Lütschine, Canton of Bern

Assessment studies in small watersheds are mainly carried out for the following reasons:

- design of protective works
- sediment yield into receiving waters
- delineation of danger zones

The assessment study Lütschine mainly was done for the first two reasons.

In October 2000, a large flood event transported some 20'000 m^3 of material to the reaches of the small village of Stechelberg. Before taking some countermeasures, a study should investigate sediment yield in each of the tributaries and sediment transport of large flood events in the Lütschine River (Fig. 115). The main question was if an event like the one of October 2000 could easily repeat itself and what the river behaviour would be in the future, especially in view of climate change.

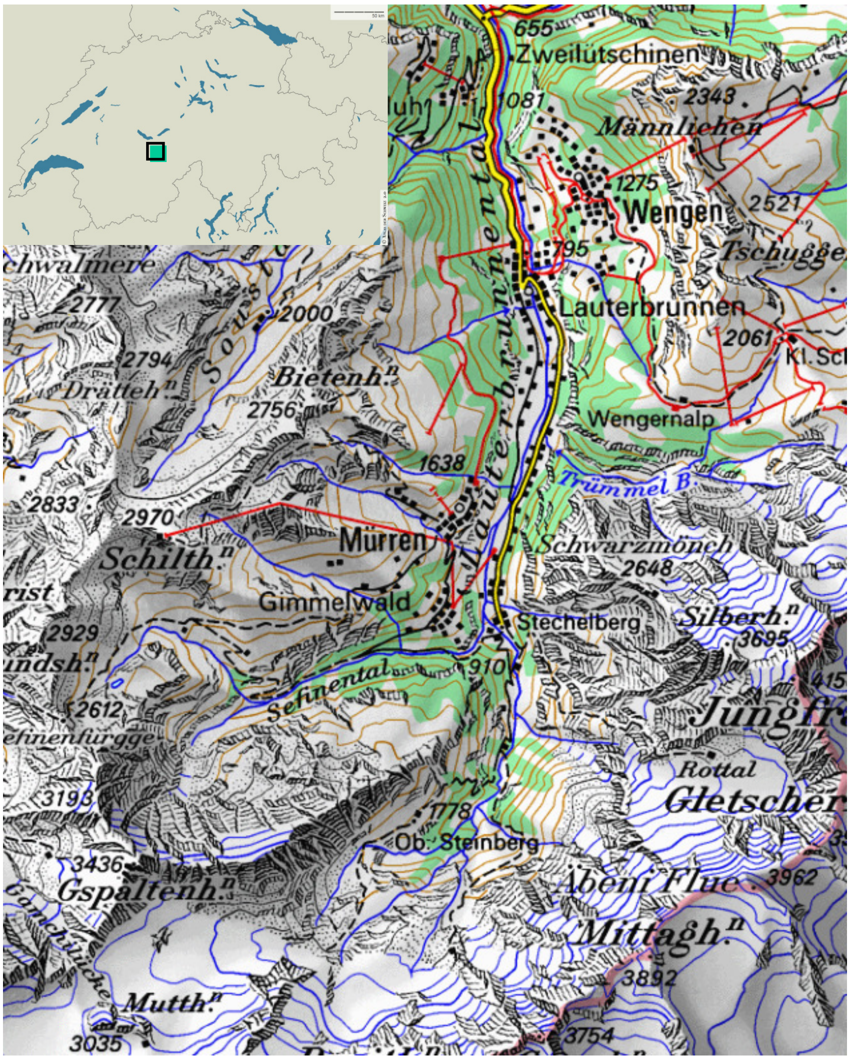


Fig. 115: Investigation site of the Lütschine study

The sediment yield into the Weisse Lütschine is primarily caused by the torrents south of Stechelberg, depending on the distribution of local storms. A scenario which causes flood discharge at rare recurrence intervals in all torrents simultaneously into the Weisse Lütschine is rather unrealistic on the basis of the findings of this study.

The greatest sediment load occurs when the two largest tributaries simultaneously transport material into the Weisse Lütschine. Therefore, one must take into account for the future that large sediment transport comparable to the one of the fall 2000 event will occur again, but not every 10 to 20 years. A recurrence interval is difficult to derive from the available data, especially given the effects of climate change. But events of a recurrence interval of about 50 to 100 years depending on the scenario will probably transport 20 30'000 m^3 of material or even more. On account of glacier withdrawals (uncovered debris cones), the frequency of the corresponding events would however increase in the future.

On account of the small transport capacity of the Weisse Luetschine, a high sediment load induces deposits by force. These deposits occur in different places along the Lütschine. Bed elevations caused by the deposits provoke flooding of neighbouring settlements and cultivated land (Fig. 116). Besides retention areas, which alone are not sufficient as protection measures, it was planned to support some natural deposit places in the river by application of technical measures, such as a reinforced local river widening, serving as a periodic sediment retention place.

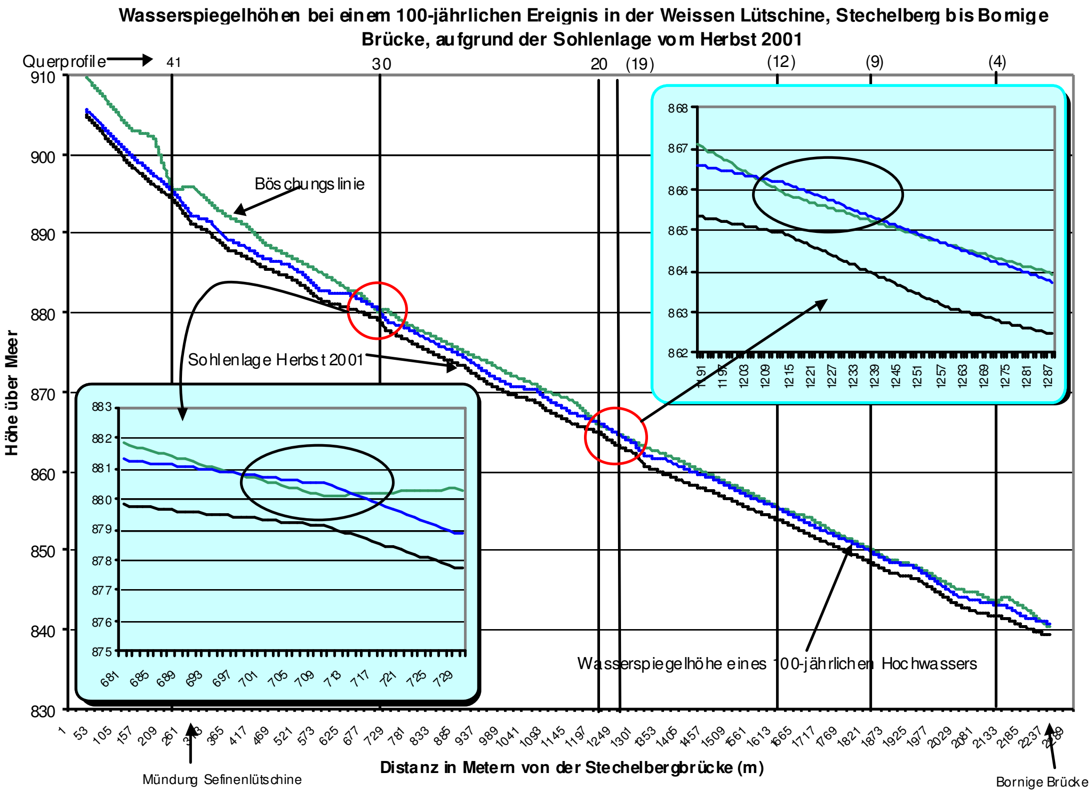


Fig. 116: Bed- and water level in the case of an event of 100 year recurrence interval indicating potential places of river outbursts (Lehmann 2001)

11.2 Germany

Two comprehensive studies on sediment transport and sediment management in the German Rhine were carried out on behalf of the Federal Ministry of Transport (BMV): "Abfluss- und Geschiebeverhältnisse des Rheins" (Discharge and bedload conditions of the Rhine River), carried out in 1987. Ten years later this was followed by the study: „Sohlengleichgewicht am Rhein" (Bed equilibrium at the Rhine River).

Two more recent studies of the Federal Institute of Hydrology (BfG) deal with the relocation of fine grained, contaminated sediments of the Iffezheim impoundment and with the gravel supply downstream of the barrage respectively: „Ergebnisse aus dem begleitenden Untersuchungsprogramm für die Umlagerung von Baggergut in die fließende Welle unterhalb der Staustufe Iffezheim" (Results of the accompanying research programme for the relocation of dredged sediment into the tailwater of the Iffezheim barrage/Rhine) and „Tracerversuch Iffezheim" (Tracer test Iffezheim). The most important results of these studies are summarized in the chapters 10.2.1 to 10.2.3

A Dutch/German study is "Bed level changes and sediment budget of the Rhine near the German-Dutch border" in 2001. The results of this joint study are described in chapter 10.3.

11.2.1 Bedload management at the Rhine River

<u>Introduction</u>
The river Rhine is the most important inland waterway in Europe connecting Switzerland, Eastern France, and Western Germany with the North Sea. Canalization of the main channel, fixing of embankments, reclamation of floodplains and flood control measures have forced the river into an even smaller channel and have changed the naturally existing hydraulic and morphologic processes. In addition, the sediment flow has been drastically disturbed, especially after construction of impounding dams. Today the free flowing parts of the river Rhine are characterized by a general bedload deficit and a non-uniform bedload distribution. This leads in large parts to severe bed degradation whereas other reaches are stable or slightly aggrading. As water levels tend to follow bed level trends (Dröge et al.1992, Brinke ten and Gölz 2001) ecological damage in the flood plane, serious navigation problems in the main channel, and economic disadvantages for water management, agriculture and forestry are well known negative consequences.

To avoid these disadvantages a strategy has been developed which allows to stabilize the river bed by combining conventional training measures with measures of bedload management (Gölz 1994). The latter are meant to balance the bed load budget of the river by artificial bedload supply as well as by dredging and redumping of bed sediment. Additionally, local river training works and scour prevention measures have to support this sort of dynamic bed stabilization.

<u>Morphological and nautical conditions</u>
Between Basel and Mainz the Rhine flows through the vast tectonic valley of the Upper Rhine graben before entering the Rhenish massif. The uplift of the Rhenish massif forced it to cut a deep and rather straight gorge into the rising block, whereas in the adjacent Lower Rhenish embayment the Rhine shows the characteristics of a lowland river with large meanders before diverting into the individual branches of the deltaic area of The Netherlands. Es-

pecially crucial for navigation is the transition zone between the Upper Rhine graben and the Rhenish massif (Fig. 117). Here in the Mainz basin the river is very wide and the resulting small water depth at low flow is further restricted by the development of large dunes.

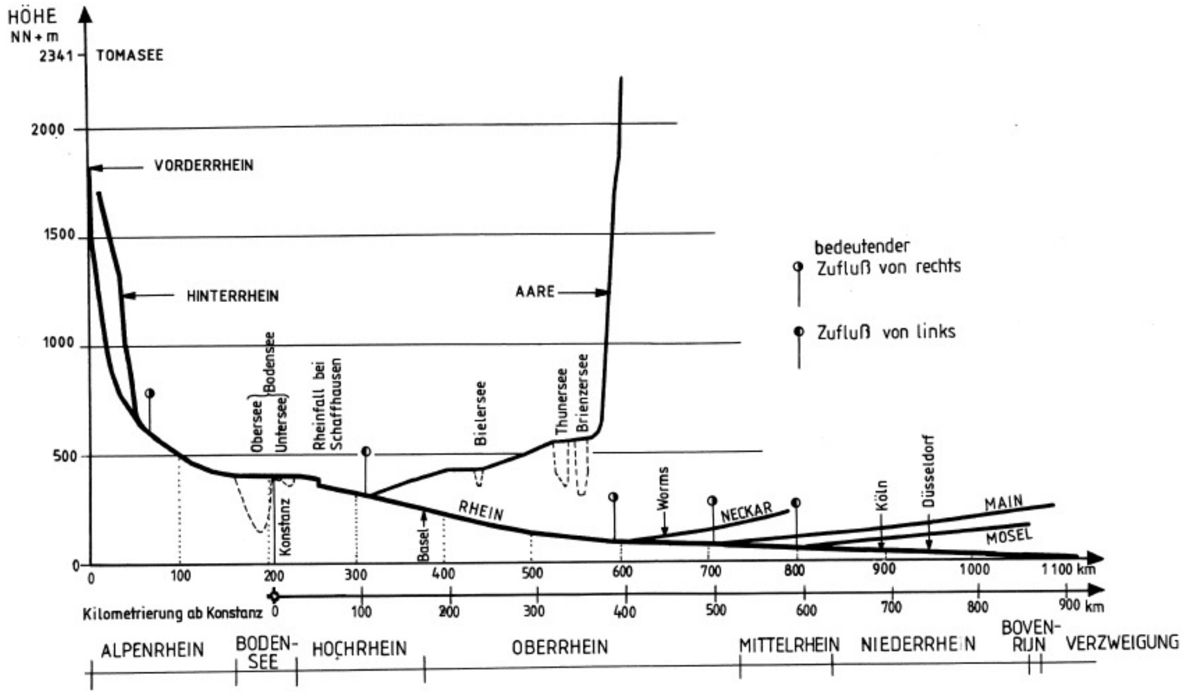


Fig. 117: Hydrological longitudinal section (CHR 1993)

To enable navigation in the Southern part of the Upper Rhine the river has been impounded in the course of the 20th century beginning after World War I near Basel in the South and ending in 1977 with the construction of the Iffezheim barrage some 150 km further North. Although heavily changed by correction and training works the Northern Upper Rhine has remained a dynamic gravel-bed river with a mean annual bedload of about 180'000 m^3. To avoid bed degradation immediately downstream of the Iffezheim barrage the river has been supplied with gravel since 1978 when the weir was put into operation (Kuhl 1992). Stabilization of the riverbed and of water stages immediately downstream of the impoundment weir is the primary aim of this measure, as the unhindered access to the ship locks of the impoundment must be ensured (Fig. 118). Moreover, this bedload supply at Iffezheim is the only major source of the free-flowing Upper Rhine since the impoundment weirs upstream and the dam regulation of the main tributary, the Neckar River, inhibit the natural supply of bedload to a high degree. In the long-term an average of about 180'000 m^3 of gravel are dumped each year.

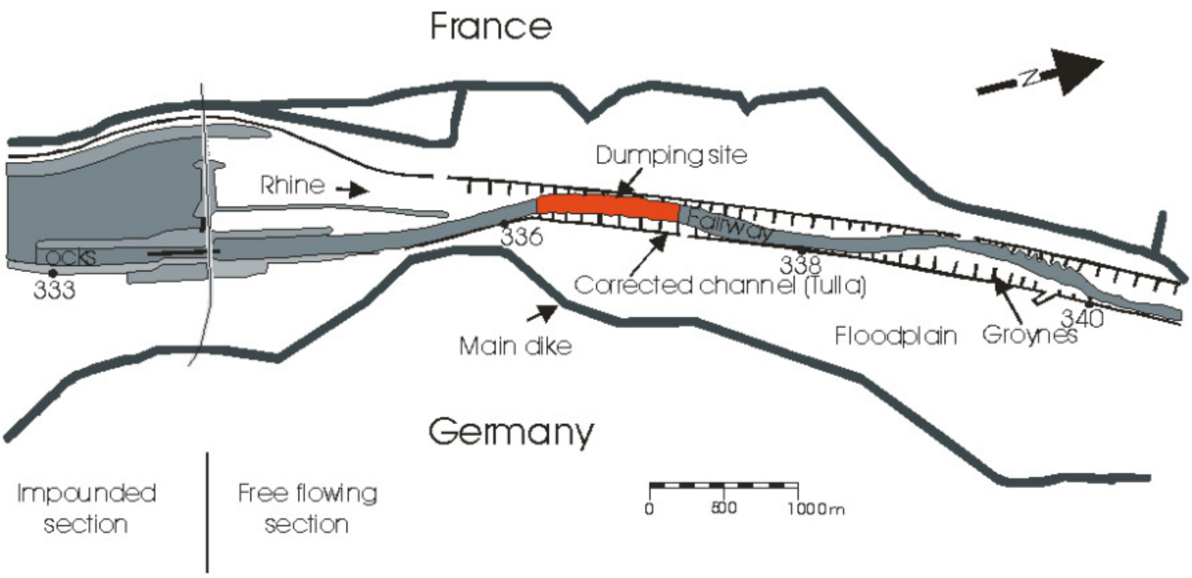


Fig. 118: The Upper Rhine near the Iffezheim barrage (BfG, 2008)

Artificial bedload supply

Artificial supply of bedload material for the dynamic stabilization of river reaches has become an accepted method in river engineering and is being increasingly applied to German Federal waterways. The material to be added is dumped from hopper barges forming a thin mobile gravel carpet on the river bottom (Fig. 119). The dimension of the amount of material and its grain-size composition is mainly aimed at the transport capacity of the reach to be stabilized and the grain-size of the natural bedload there. Additional stabilizing effects or a reduction of the material to be added is expected from using coarser material, e.g. in an Austrian bed-stabilization project downstream of Vienna (Zottl 1999). Conversely, also the addition of finer material may be appropriate as well, if the aim is a quick stabilization of reaches further downstream (Gölz 1990).

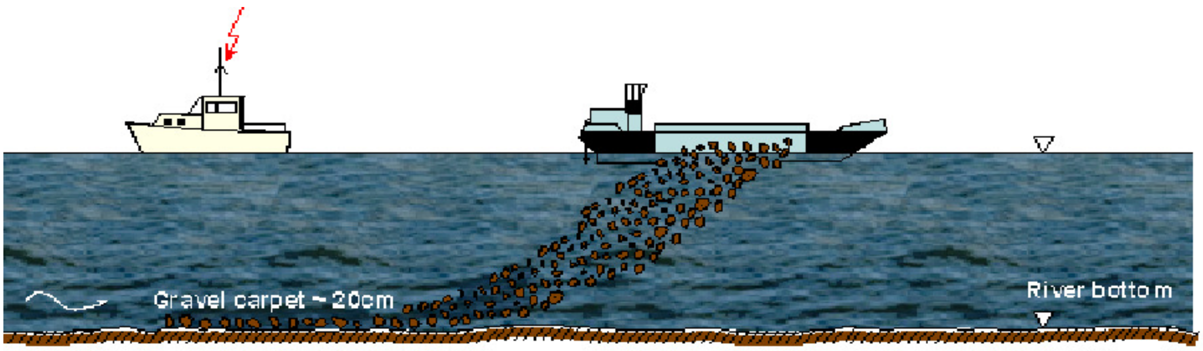


Fig. 119: Artificial bed load supply (BfG, 2008)

In order to have a better scientific basis for bedload supply measures, field tests with petrographic tracers have been carried out, which give not only information about sedimentological processes like hydraulic sorting, mixing and abrasion but also show how the material supplied will spread over the reach which needs to be stabilized (Gölz 2002, BfG & WSA Freiburg 2006 and chapter 10.2.2 of this volume).

Bedload withdrawal
Some 160 km downstream of the Iffezheim barrage the hydraulic conditions of the river have drastically changed. Between Mainz and Bingen water-level slope and flow velocity reach a minimum with the consequence that bedload transport slows down. The sandy sediment delivered from the Upper Rhine tends to form large dunes which obstruct shipping traffic especially at the time of low water conditions.

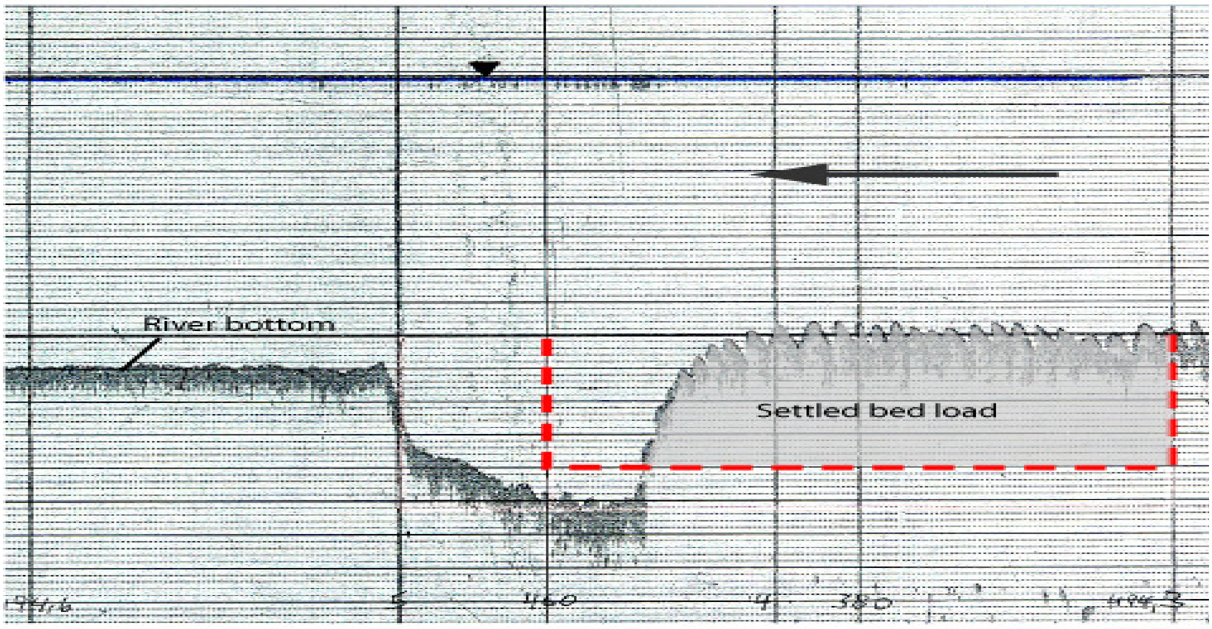


Fig. 120: Bed load trap near Mainz (longitudinal section) (BfG, 2008)

Due to their mobility and limited dimensions, these obstacles are difficult to dredge. Thus other solutions had to be found to cope with the problem. In 1989, a huge bedload trap was implemented near Mainz. A trench 160 m wide and 1.4 m deep was dug widthways into the bed. The sudden widening of the cross section forces the bedload to settle in the trench (Fig. 120). From there it can be easily removed by dredging. On an average basis, about 100'000 m^3 of sand and fine gravel are dredged in the bedload trap near Mainz each year. Due to this measure navigation conditions have been markedly improved during the last decade.

Overall concept for the River Rhine
Based on the positive experience with the artificial gravel supply at Iffezheim and the bedload withdrawal at Mainz an overall concept for the free flowing section of the River Rhine was established by a working group appointed by the German Federal Ministry of Transport aiming at establishing a dynamic equilibrium of the river bed (BMV 1997).

Concept
A reach by reach analysis was the basis for formulating a catalogue of actions for achieving a dynamic equilibrium along a section of 530 km length between Iffezheim and the Dutch-German border (Tab. 28). To avoid aggradation and erosion sediment transport must be controlled in such a way that transport capacity and bed load are in harmony, both locally and at a

large scale. Accordingly, the concept must rely on mutually complementing measures of river training (improving or construction of groynes, guide walls, etc) and measures of bed load management (supply and withdrawal of bedload material). Generally, large scale deficits and excesses of sediment should be compensated by measures of bed load management, whilst local imbalances should be counteracted by river training measures.

Certainly, the intended state of the riverbed will be achieved by the proposed actions only in the very long run. Hence, supplementary local actions like dredging and redumping of dredged material will be needed over a long period. For compensation of the general bed load deficit besides the supply at Iffezheim additional bedload supply measures with a bulk volume up to 300´000 m^3 per year are conceivable (Tab. 28).

Tab. 28: Overall concept Rhine

No.	Reach	Measures
1	334.0-352.1	Bed load supply (170'000 m³/a) Adaption of LW-groynes
2	352.1-402.6	Adaption of LW-groynes Temporary dredging
3	402.6-423.0	No
4	423.0-444.4	Maintenance dredging (15'000 m³/a)
5	444.4-493.5	Redumping of dredged material from reach 4 Groyne adaption
6	493.5-529.0	Bed load withdrawal (60'000 m³/a) Training works Temporary dredging (1998-2002)
7	529.0-585.6	Bed load supply (70'000 m³/a) Training works Temporary dredging (1998-2007)
8	585.6-640.0	Bed load supply (30'000 m³/a) Local training works Temporary dredging (1998-2008)
9	640.0-703.6	Maintenance dredging (60'000 m³/a) Local training works Temporary dredging (1998-2006)
10	703.6-768.0	Bed load supply (100´000 m³/a) Maintenance dredgings (30´000 m³/a) Local training works Temporary dredging (1998 – 2008)
11	768.0-800.0	Maintenance dredging (30´000 m³/a) Static bed stabilisation and training works Temporary dredging (1998 2001)
12	800.0-865.5	Bed load supply (100´000 m³/a) Maintenance dredging (20´000 m³/a) Local training works Bed coarsening Temporary dredging (1998 2003)

Economic considerations

For the design of the overall concept a scenario analysis was made comparing different planning options with the reference case. The latter describes the present day situation and serves as a basis for subsequent calculation of the economic efficiency of the overall concept. Among the variants of the planning scenario the most cost-efficient and most practicable variant was selected.

Based on the estimates of 1997, the economic efficiency of the overall concept was calculated. For the calculation of the benefit/cost ratio, the loss of benefit resulting from the economic damage in the reference case was compared with the difference of the costs in the planning scenario and the costs in the reference case. The highest loss of benefit in the reference case (61% of the whole loss of benefit) results from the reduction of loading depths due to falling water levels (BMV 1997).

Tab. 29: Benefit/cost ratios

Reach	Upper Rhine	Rheingau reach	Lower Rhine	Whole free-flowing section
Within next 10 years	3.3	1.4	1.0	1.2
Within next 50 years	22.6	13.7	2.2	3.4
Within next 100 years	39.3	25.0	2.6	4.6

Tab. 29 shows benefit/cost ratios calculated for different periods and different reaches of the inland waterway Rhine. It becomes clear that the benefit-cost ratios of the individual reaches differ very much but that all of them increase with the length of the period considered. This calculation does not take into account the ecological damage resulting from erosion, because it cannot be quantified in monetary terms yet. However, the resulting lost benefit would certainly improve the benefit/cost ratios to a high degree.

Preconditions
Apart from the financial resources, the implementation of the overall concept based on artificial bedload supply presupposes a series of organizational, logistic, and scientific-technical requirements. The latter comprise fundamental investigations of the exchange of bedload material and suspended sand, of the spreading behaviour of the material supplied, and of the possibility of bed stabilisation by coarsening of the surface layer. These investigations have been largely accomplished and the results are available in the form of scientific reports (Frings and Kleinhans 2006; BfG and WSA Freiburg 2006).

The most important precondition for long term bedload management, however, is the availability of suitable material. The Upper Rhine is fed with a mixture of sand and gravel from adjacent gravel pits. In the long run there is the possibility to use gravel, which will accumulate in connection with flood defence and rehabilitation measures at the Southern Upper Rhine. At the Middle Rhine, where gravel exploitation is very limited, broken material from quarries has to be supplied. The suitability of broken material as a substitute for gravel has been proved by several investigations (Gölz et al. 1995; Herrmann 2001). Furthermore enquiries made at the German quarry managers and at the appropriate construction companies showed that enough broken material can be provided in the long term.

Realization
In order to ensure the functionality of the inland waterway Rhine in the future, the proposed measures had to be implemented without delay. Usually, delayed investments have merely the consequence that the expected benefit will be achieved later. In the present case, however, additional damage will occur until the overall concept is implemented, so that existing disadvantages will intensify. Once negative developments have begun as a consequence of erosion they can hardly be reversed. Bearing this in mind, the German Water and Navigation

Authorities started a bedload management program in 2000 according to the outlines presented in Tab. 28.

Besides the gravel supply at Iffezheim and the bedload withdrawal at Mainz, meanwhile four additional supply measures have been implemented, one at the Middle Rhine and three at the Lower Rhine. Altogether, along the 530 km long free flowing German Rhine a total amount of 360'000 m^3 of bedload material is supplied annually, half of which originates from gravel pits and the other half from quarries.

By implementing the overall concept at the free flowing Rhine the German Water and Navigation Authorities entered a partly unknown technical terrain. Therefore a continuous performance review is indispensable. In this context guidelines were elaborated, containing a package of hydrological, sedimentological and morphological measurements by which water and bed levels are continuously checked (PGEKG 2005). Based on the measuring results every two years a status report is prepared describing the developments of bed and water levels and identifying undesirable changes, so that the individual management measures can be corrected or adapted in time.

Outlook

At the German Rhine large scale bed level changes proceed with low rates of about 1cm /year (Gölz 1994). As could be shown recently by a tracer test, the migration rates of gravel supplied at Iffezheim vary between two and six kilometres per year (BfG and WSA Freiburg 2006). Due to the slow reaction of the system the effects of bed-load management measures on bed and water levels might be recognized only in the course of several years or decades. Therefore the positive impact of the overall concept, whose individual measures have been implemented step by step since 2000, will appear mainly in future. Nevertheless the system has to be permanently monitored, in order to recognize both positive and negative developments and to make corrections where necessary.

11.2.2 Selective transport and dispersion along the Upper Rhine – results of a long term field test using a petrographic tracer

<u>Introduction</u>

Artificial supply of bed load material for the dynamic stabilization of river reaches affected by erosion has become an accepted method in river engineering and is being applied increasingly to German Federal waterways (BMV 1997, Gölz 1999).

The Southern part of the Upper Rhine has been impounded in the course of the 20th century. To avoid bed degradation downstream of the last weir at Iffezheim the river has been artificially supplied with gravel since 1978 (Kuhl, 1992). Stabilization of river bed and water stages immediately downstream of the impoundment weir is the primary aim of this measure, as the unhindered access to the ship locks of the impoundment must be ensured.

Moreover, this bedload supply at Iffezheim is the only major source of bedload material for the free-flowing Upper Rhine since the impoundment weirs upstream and the dam regulation of the Neckar River inhibit the natural supply of material to a high degree. In the long-term average about 300'000 tons of gravel are dumped each year. The quantity may vary between 120'000 tons and 580'000 tons. The latter amount had to be added in the year 1999 that was characterized by two subsequent flood events, of which the second one had a recurrence period of 100 years (Fig. 121).

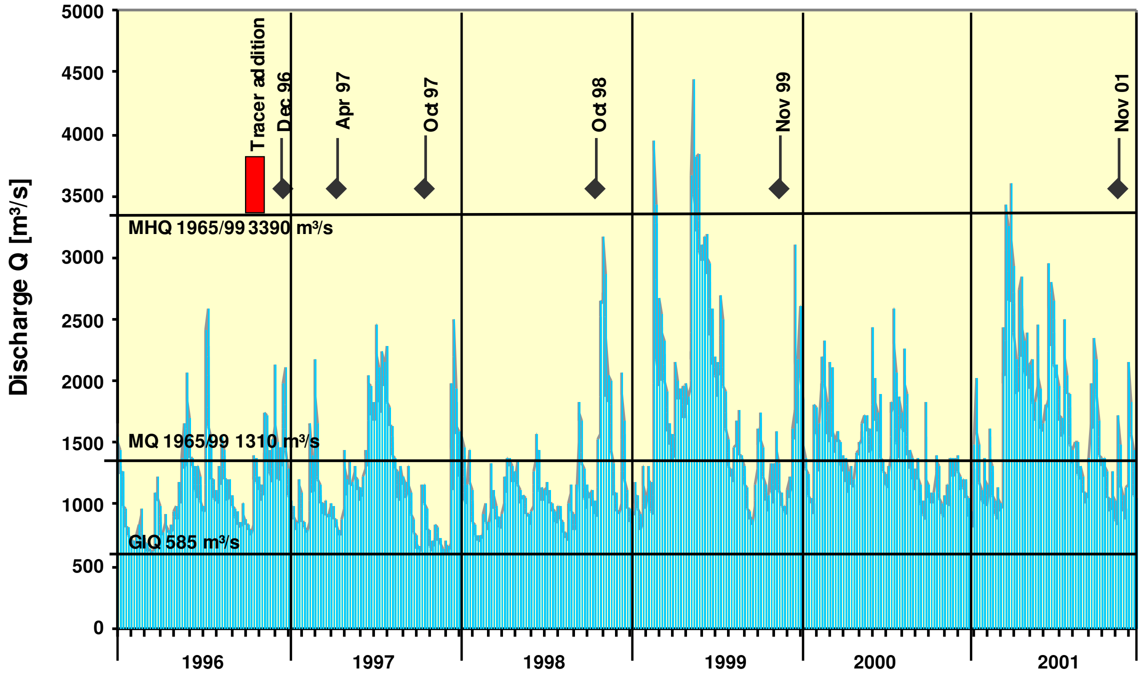


Fig. 121: Hydrological conditions and sampling schedule (BfG, 2008)

Although artificial bedload supply has been practised at the Upper Rhine over more than two decades now, it was not yet known how fast the material dumped at Iffezheim moves downstream and how it spreads on the riverbed or mixes with subsurface material. Meanwhile some 30 kilometres downstream of the dumping site aggradation of the river bed is noticeable, whereas on the first kilometres downstream of the barrage bed degradation can be compensated only by great efforts especially at high discharges. Therefore it is necessary to optimize the artificial bedload supply. Against this background, the German Federal Institute of Hydrology together with the Federal Waterways and Shipping Office Freiburg devised a field test to provide a better scientific substantiation for future bedload supply practice (BfG and WSA Freiburg 2006). To gain more knowledge about transport and dispersal of the material supplied a petrographic tracer was used consisting of conspicuous rock material that can be easily distinguished from natural bed material by colour, structure and shape, but has a similar grain-size composition as the material intended for artificial bedload supply.

Experimental Procedure

In October 1996, the Federal Waterways and Shipping Office Freiburg organized the dumping of 28’000 tons of gravel-sized broken granite from a quarry in the Black Forest into the River Rhine between riverkm 336.2 and 337.1 within four weeks. The grain-size of the tracer material was adjusted to the grain-size composition of the gravel that used to be dumped in the past few years. Repeated echo-sounding surveys in the following months showed that the granitic tracer had been entrained by the current and has been transported downstream. Spreading of the tracer was registered by several sampling campaigns in intervals of 2, 6, 12, 24, 36 and 60 months after dumping. The samples were collected by means of the diving-bell vessel "Carl Straat", what allowed direct sampling at the river bottom down to a depth of 0.5 m below bed surface. Sampling was done at five points within one cross section.

In order to examine the influence of floods on mixing and exchange processes, after the floods of 1999, at certain points additional samples were taken down to a depth of 1.5 m below bed surface by means of a special freeze-core equipment. All samples were split by sieving into five fractions and the percentages by mass of the tracer in each fraction were determined by selecting the granite grains. Thanks to its special structure and colour, the tracer could be identified reliably and quickly. Only the fraction 4-8 mm was more difficult to analyze as this grain size already meets the size of the individual minerals of the granite. Because of sampling along 10 to 12 cross sections with five vertical profiles a time, each campaign comprised several hundred petrographic analyses.

Results
The following results are based on the evaluation of about 1'000 grain-size analyses and 4'600 petrographic analyses distributed over a reach of 65 km, a width of 120 m, and a depth of 1.5 m below bed surface. Additionally 35 samples, collected in the groyne fields, were sieved and petrographically analyzed.

Plotting the mean tracer concentration of the sampled cross-sections along the course of the river gives for each fraction a longitudinal distribution that reflects the status at the time of sampling. As can be seen from Fig. 122, i.e., 24 months after dumping, the tracer had been removed nearly completely from the dumping site and had spread according to the fraction considered over 8 to 21 km of the downstream reach. As expected, due to hydraulic sorting the coarser fractions remained clearly behind the finer ones. The finest fraction of 4-8 mm, however, is not the fastest one, but has nearly the same migration velocity as the fraction of 8-16 mm and is only slightly faster than the medium-sized fraction of 16-31.5 mm. This is due to "hiding", what means that fine grains are sheltered from entrainment by coarser grains or are trapped in the voids between those. Even if the fronts of the individual fractions have already rather far advanced, the mass of the tracer characterized by the centre of gravity of the distribution curve lags notably behind. Fig. 123 illustrates the advancing of the "mass centres" of the individual fractions by means of a travel-time diagram. They move at an average velocity of merely 2.2 to 5.5 km per year downstream, whereas the fraction heads proceed at a rate of 6 to 11 km per year.

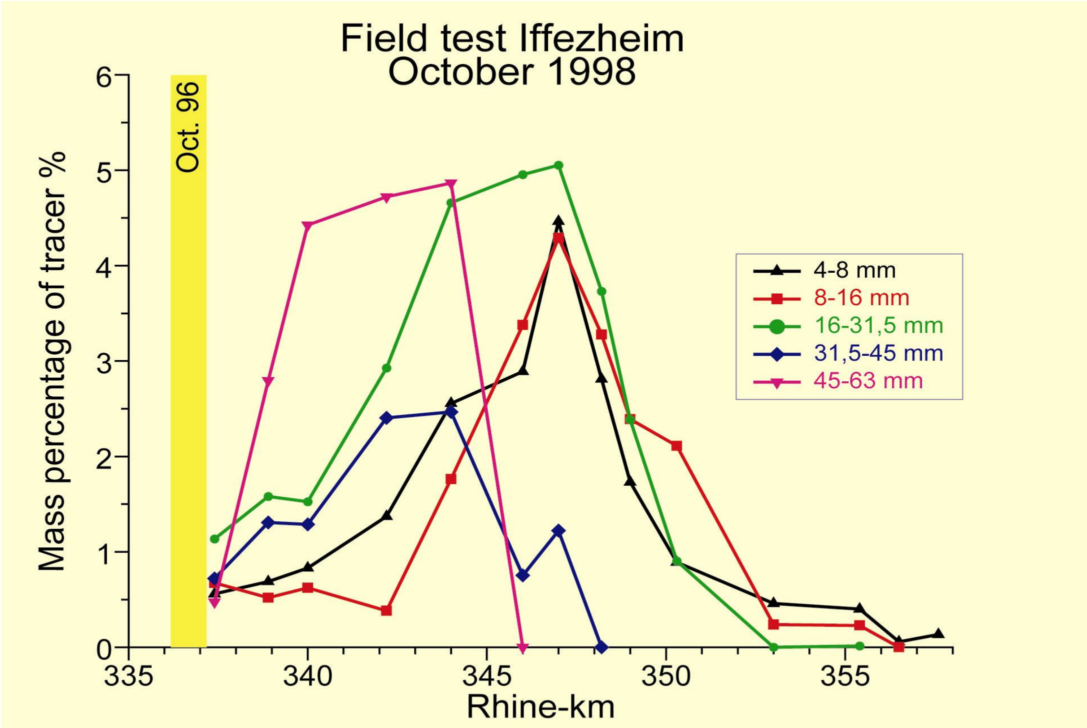


Fig. 122: Longitudinal tracer distribution 24 months after dumping (BfG, 2008)

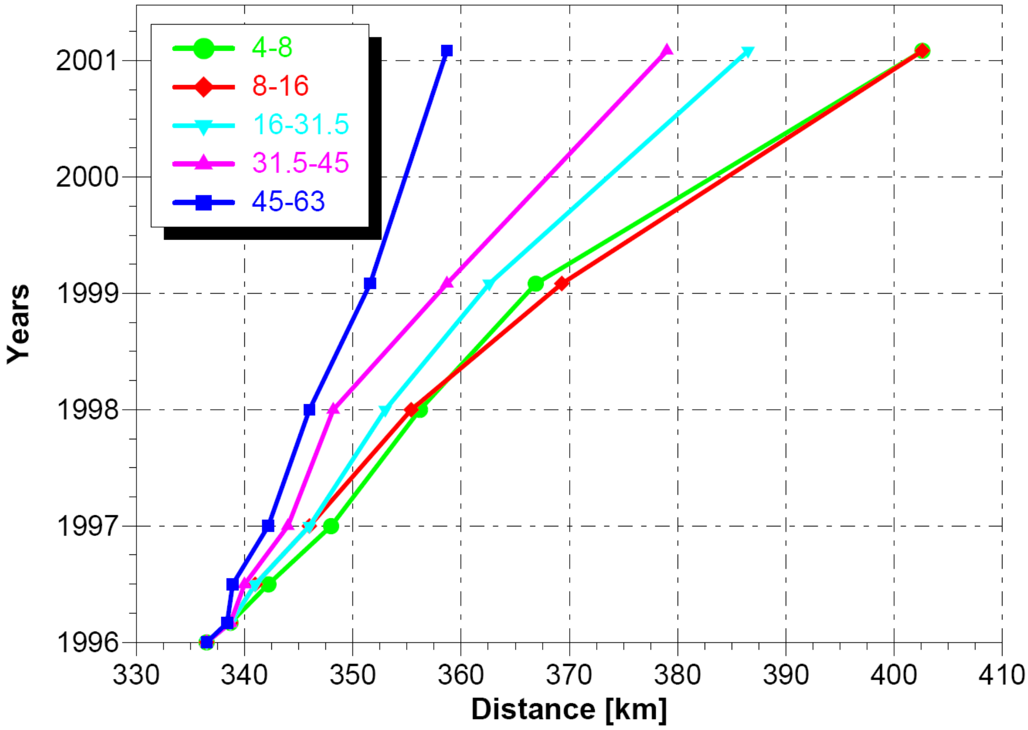


Fig. 123: Travel time diagram 1996-2001 (BfG, 2008)

It is also interesting to watch the behaviour of a single fraction. Fig. 124 presents the longitudinal distribution patterns of the fraction 16-31.5 mm, as they were observed 2, 6, 12, 24, and 36 months after dumping. Two months after starting the experiment a part of the tracer material is still present in the dumping reach, and the distribution curve shows a very sharp peak with a maximum tracer concentration of nearly 40%. In the following time concentrations notably decrease, and the distribution curves flatten more and more, until in October 2001, i.e., five years afterwards, the distribution curve stretches over 65 km but is still "rooted" in the original dumping area. One can conclude that the tracer will disperse more or less evenly over the whole migration reach in the course of time.

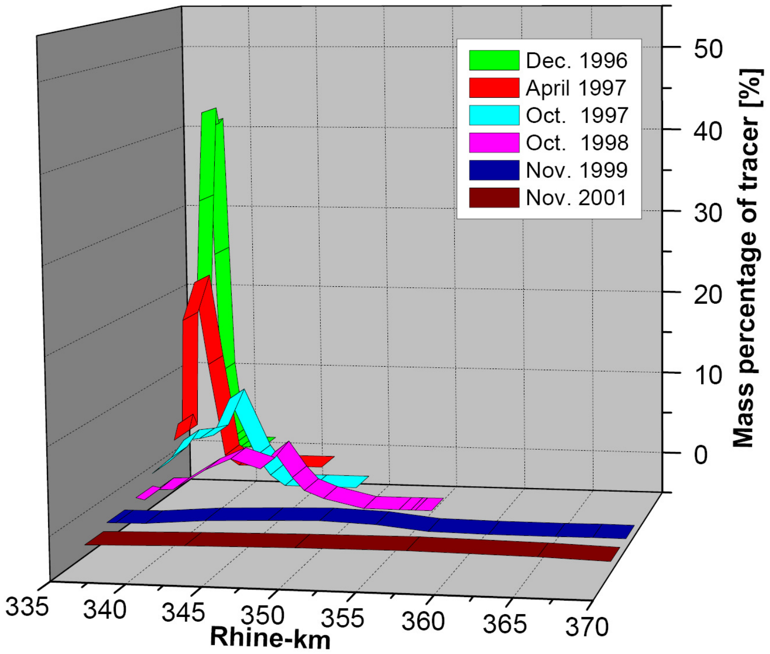


Fig. 124: Longitudinal dispersion of fraction 16-31.5 mm (BfG, 2008)

The stretching of the distribution curve shows the degree of dispersion which the tracer has reached during transport. In this paper the term dispersion is used for the combined effects of a couple of sedimentological processes which cause spatial scattering of particles of the same size in the course of transport. However, dispersion also has a lateral component and a vertical one. The lateral dispersion of the tracer has not yet been examined, but the vertical dispersion was studied by means of freeze-core samples. These samples were taken at some selected sites in November 1999, i.e. after the two major flood events, and in October 2001. They gave essential insights into the depth of mixing of the tracer with sediments of the subsurface. Tracer material was found in the freeze-cores down to a depth of 1.3 m below bed surface. The minimum depth was 0.35 m. On average, a mixing depth of 1 m may be assumed. Two sedimentological processes could explain such great mixing depths. On the one hand, bed forms may contribute to mixing when tracer material rolls down the lee slope of a dune: The tracer pebble is then covered by the proceeding bed form, and is later not involved in the transport process again, especially when the height of the bed form decreases due to changing hydraulic conditions. A second explanation might be simple deposition of bedload material in aggradation reaches. Moreover, a combination of these two effects seems possible.

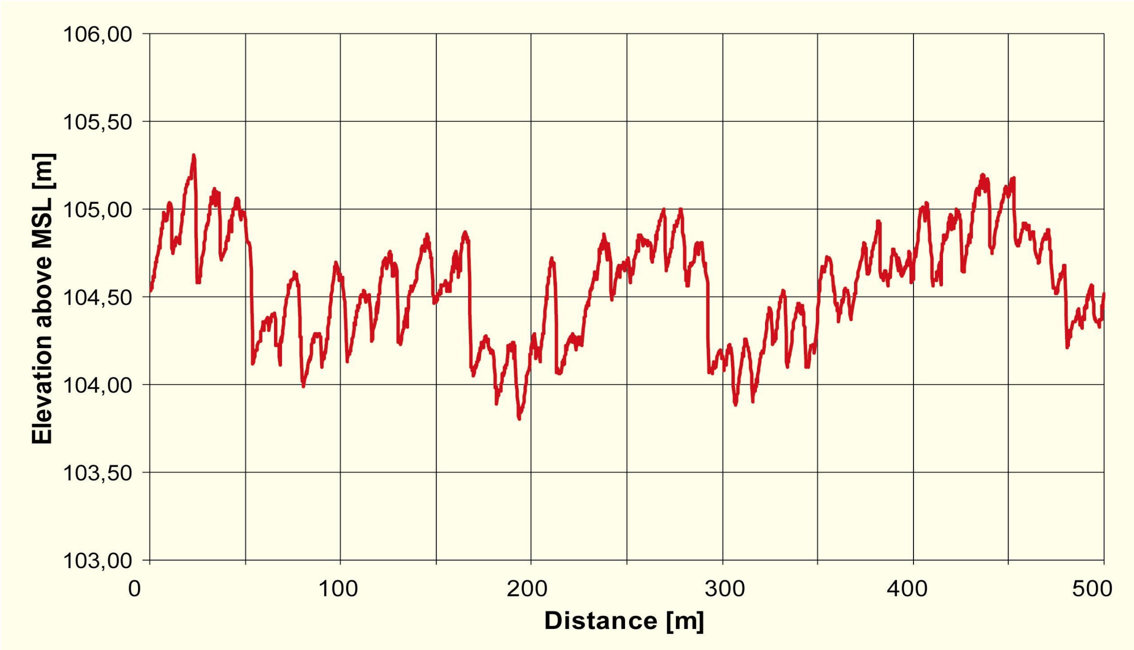


Fig. 125: Bed form development (gravel dunes) at high discharge (BfG, 2008)

As could be proved by cross-sectional echo soundings there was no evidence of bed aggradation at the sites of freeze-core sampling. However additional longitudinal soundings, carried out at a discharge of 3'000 to 3'500 m^3/s, established the presence of large gravel dunes with heights up to one meter and more (Fig. 125). So bed form development at high floods is responsible for the mixing depths observed.

Mass balance

The quality of a tracer experiment can be tested by establishing a mass balance comparing input and output of tracer. This seemed possible for the tracer experiment at Iffezheim too, although only a simple approach was applied. For simplification at first a three layer model of the river bed was chosen with a variable length and a standard width of 120 m, assuming a thickness of 0.1 m for the first layer, and 0.2 m for the second and third ones. The results are presented together with the initial mass in Fig. 126. One can see that during the sampling campaigns in October 1997 and October 1998 the tracer could be found for the most part, even if the portions of the individual fractions have slightly shifted in the balance. This might be due to the simplification used for computing and to the fact that tracer concentration of the third layer was derived from one sample within the cross section only. Thus, a certain distortion is inevitable. Nevertheless, it may be concluded that in 1997 and 1998 the tracer was recovered nearly completely by sampling down to a depth of 0.5 m below bed surface, whereas this was certainly not the case in the sampling campaigns of 1999 and 2001, when only 50% and 35% respectively of the original tracer mass were found. One could assume that the material was transported further downstream without being noticed, that it has invaded deeper layers and/or that the tracer was transported into the groyne fields at flood stage.

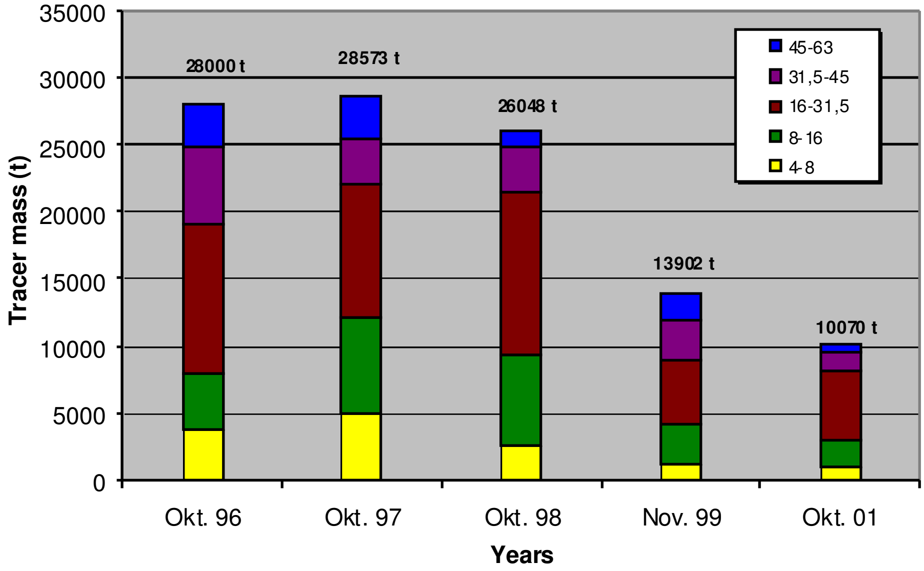


Fig. 126: Tracer input and mass balances for the years 1997-2001 (BfG, 2008)

These questions could be solved by analyzing the freeze core samples and the samples collected in the groyne fields. Although the number of samples was not sufficient for an exact quantitative determination of the tracer portions in the groyne fields and in the deeper strata, the results allowed a rough estimation of the tracer masses being deposited beyond the borders of the simplified model described above (BfG and WSA Freiburg 2006).

Using, in addition, the results of abrasion experiments (Herrmann 2001), an equated mass balance could be established (Fig. 127), showing that five years after dumping the tracer has spread over a reach of 65 kilometres length. Only 36% of the original tracer mass was found in the layer 0-0.5 m below bed surface. About the same quantity was transferred during large floods down to a depth of 0.5-1 m below bed level. About 10% have been deposited in the large groyne fields and around 15% of the original mass was lost by abrasion.

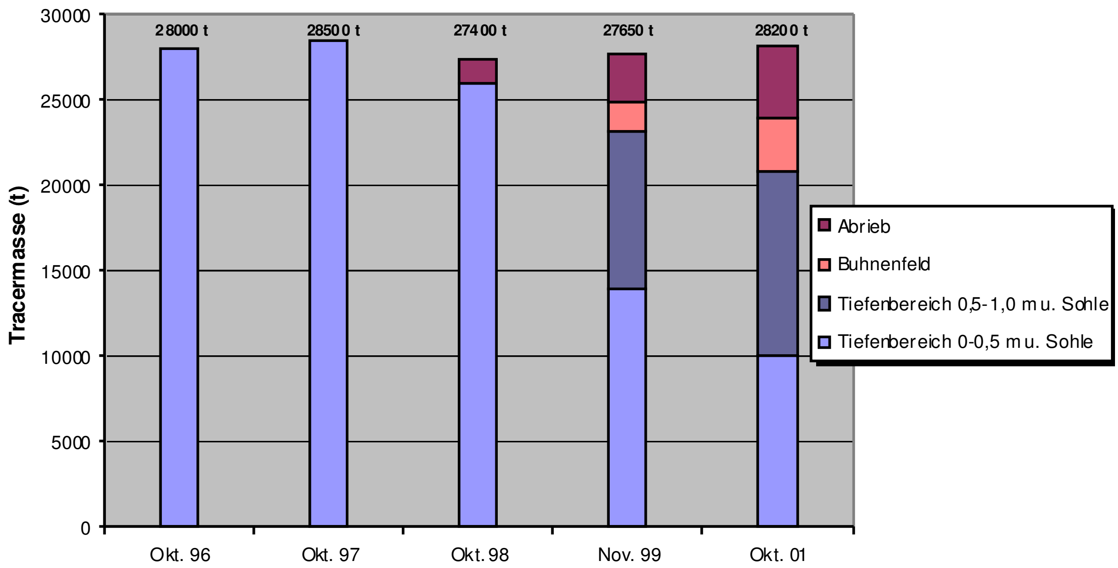


Fig. 127: Completed mass balance (BfG, 2008)

Conclusions
So far the field test Iffezheim has shown that it is possible to quantify transport and spreading of the petrographic tracer by an appropriate sampling and analyzing programme. The results obtained have been verified by mass balances, even for the flood year 1999 and the sampling campaign 2001. Preliminarily, the following major findings can be noted:

- The dumped material does not move downstream as a compact sediment wave, but is spread during transport over the whole distance (dispersion).
- This phenomenon is less due to delayed entrainment at the dumping site and the stochastic character of sediment transport than to mixing and exchange processes.
- After the floods in 1999, a maximum mixing depth of 1.3 m below bed surface was observed. The minimum mixing depth is 0.35 m; a mean mixing depth of 1 m can be assumed.
- Apparently flood waves do not increase mean migration velocity, but intensify bed deformation by the development of large gravel dunes which favours tracer transfer into deeper strata.
- Strong hydraulic sorting was observed for grain-sizes >32 mm. They clearly lag behind the fractions 4-8, 8-16, and 16-31.5 mm. The latter show relatively uniform transport behaviour.

The field test has provided a set of new findings about the spreading and the behaviour of the material supplied at Iffezheim allowing to enhance the existing empirically based supply concept to a more scientifically based one. In this connection numerical modelling will be an important tool, if the models take account of the sedimentological processes observed in the field. In addition the data collected in the course of the tracer experiment might be useful for calibrating and validating appropriate sediment transport models.

11.2.3 Suspended sediment transport and sediment management in the impounded section of the Upper Rhine

Introduction

The River Rhine is the most important inland waterway of Europe connecting Switzerland, Western Germany, and Eastern France with the North Sea. To enable navigation in the Southern part of the Upper Rhine the river has been impounded in the course of the 20th century beginning near Basel in the South and ending in 1977 with the construction of the Iffezheim barrage some 150 km further north. After World War I the French built a long side canal (Grand Canal d' Alsace) with four impoundments beginning downstream of Basel and ending near Breisach. The next four impoundments were constructed by diverting the river by an artificial loop for the locks and the hydropower station (the so called loop-solution). The last two barrages, Gambsheim (1974) and Iffezheim (1977), cross the whole river as one structure. They consist of two locks, a dam, the hydropower station, and a flexible weir. The two impoundments are laterally bordered by high dykes between whom the whole flow of the river has to be discharged.

Sedimentation in the impounded section of the Upper Rhine causes rising of bed and water levels. To ensure high flood discharge and the security of the dykes, the sediments have to be removed from time to time. Dredging and disposal, however, are a major problem as the sediments are partly contaminated by hexachlorobenzene (HCB). As has been shown by Witt et al. (2003), there is also the risk of remobilization of highly contaminated sediments during high floods.

In future, due to climate change, the frequency and magnitude of high floods could increase (Asselman 1997) and might influence sedimentation and remobilization in the impounded section. Thus the development of strategies both to reduce dredging of sediments and to dispose them in an ecologically friendly and economically acceptable manner is one of the important tasks of sediment management at the Rhine waterway. To achieve these goals the behaviour of the suspended load when entering, passing, and leaving the impounded section has to be studied. As a first step this has been done by evaluating the data of the permanent measuring stations for suspended load and by detailed monitoring of a flood event and of a major dredging exercise at the Iffezheim barrage.

Suspended sediment monitoring
Suspended sediment transport along the river Rhine has been monitored over more than three decades at 11 permanent stations by taking a 5 l water sample at a defined measuring point every working day. Suspended sediment concentration is determined by filtering the sample and weighing the solid residue. The influence of the tributaries and the retention effect of the impoundment-chain of the Upper Rhine on the suspended sediment budget of the river can best be seen in the longitudinal section of the annual suspended load (Fig. 128).

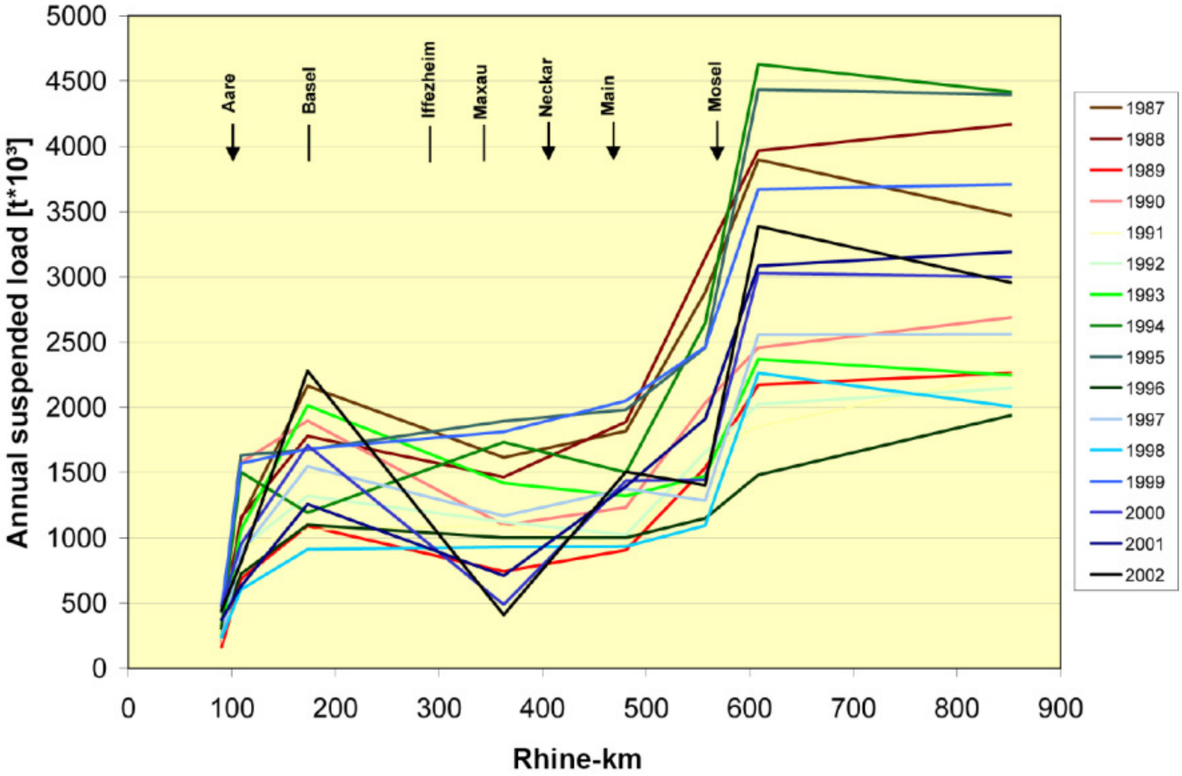


Fig. 128: Longitudinal section of the annual suspended load along the River Rhine (BfG, 2008)

The River Rhine leaves Lake Constance at km 0 nearly devoid of sediments. The first major sediment input comes from the Aare River draining the central Swiss Alps, the Swiss midlands and part of the Jura chain. Although only small tributaries join the Rhine within the next 70 km downstream to Basel (km 170) the annual suspended load increases by about 0.5 M t to about 1.5 M t. Passing the impoundment chain between Basel and Iffezheim, the Southern

Upper Rhine appears to loose about 300'000 t of suspended sediment by backwater deposition. The actual loss must, however, be significantly higher, because some smaller tributaries draining the Black Forest and the Vosges enter the main stream between Basel and Maxau. As shown by previous petrographic investigations, the Alsatian waste water channel supplies a considerable amount of suspended solids originating from the French potash mining industry (Gölz 1990). Further downstream the influence of the River Neckar is rather modest whereas the Rivers Main, Nahe, Lahn, and especially the Mosel cause a doubling of suspended load by about 1.5 M t to 3 M t on average. Down to the German-Dutch border (Rhine-km 865) the suspended load remains nearly constant. It is of interest to take a closer look at the monitoring station of Maxau. It is one of the oldest stations and it is located some 25 km downstream of the Iffezheim barrage. Monitoring of suspended load started in 1965, i.e. 9 and 12 years respectively before the barrages of Gambsheim and Iffezheim were put into operation. From Fig. 129 it is evident that both suspended sediment concentration and suspended load dropped by about 25% after the construction of the barrages.

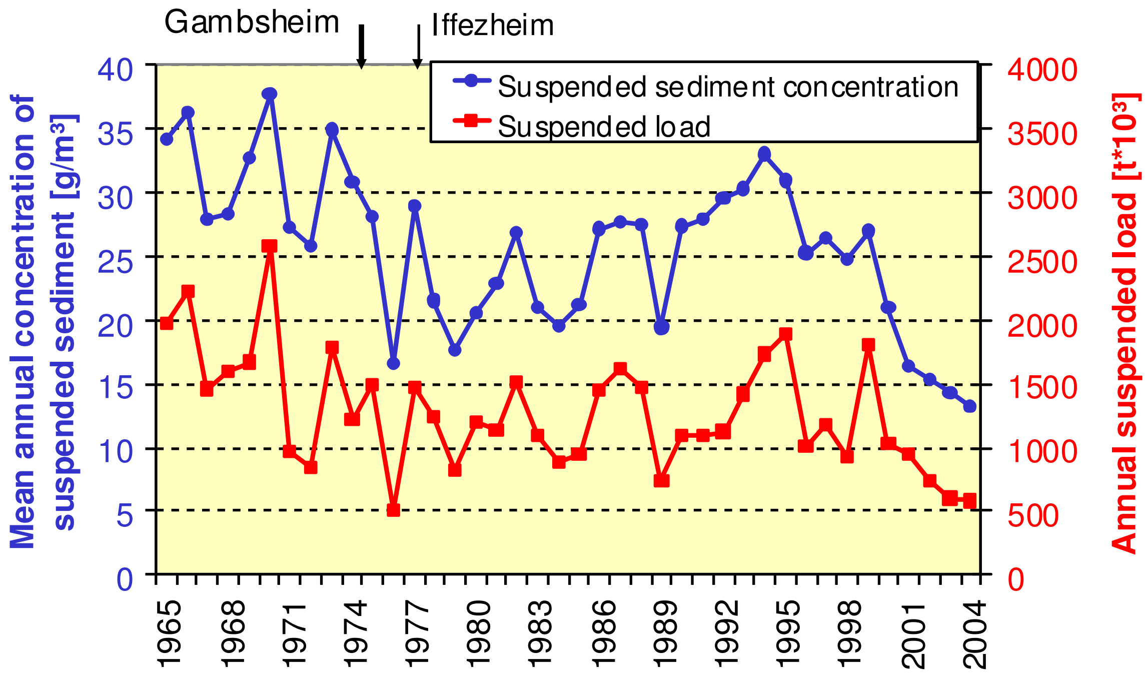


Fig. 129: Mean annual suspended load and mean annual concentration at station Maxau (Rhine-km 362,3) (BfG, 2008)

<u>Sediment management</u>

Dredging activities at the Upper Rhine are mainly concentrated on the sediment accumulations upstream of the weirs and on those forming in the outlet channels of the hydropower stations. Fig. 130 gives an overview of the annual amounts of dredged material during the last 15 years (Polschinski 2007).

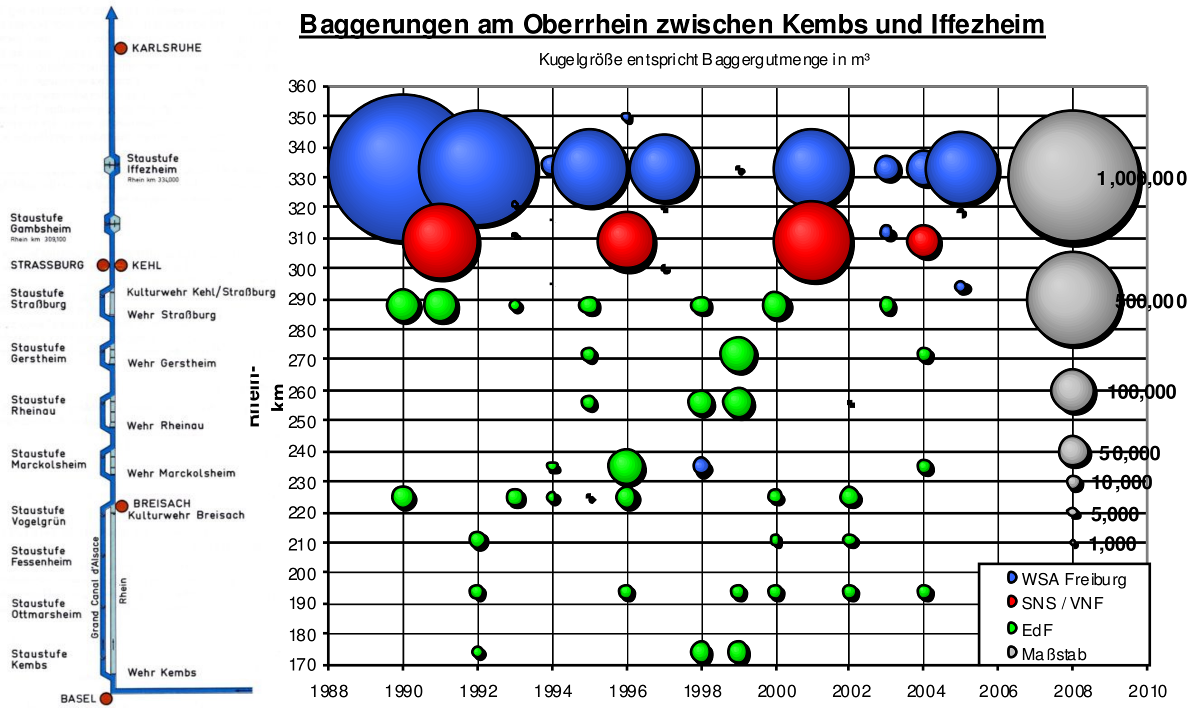


Fig. 130: Chain of impoundments at the Upper Rhine and annual amounts of dredged sediment between 1991 and 2004 (Polschinski 2007)

Within the group of the first eight barrages, which are all situated in side canals and do not impound the main channel, the annual volume of dredged material amounted to 100’000 m^3/a in former years. Now it has been reduced to about 50’000 m^3 per year by allowing a further narrowing of the cross sections (personal communication, Schittly 2005). About 160’000 m^3 are dredged at Iffezheim and 70’000 m^3 at Gambsheim, hence about 85% of the total dredging volume are assigned to these two impoundments. In the years after the construction the dredging volumes of the two final barrages were considerably higher but could be reduced by building moles in the backwater serving on the one hand as hydraulic structures and on the other hand as disposal sites for the dredged material. Meanwhile the capacity of these disposal sites as well as the capacity of an additional mole in the tailwater of the Iffezheim barrage is nearly depleted. Depending on hydrology it must be expected that every year about 150’000 – 200’000 m^3 of fine-grained sediment settle in the backwater of the Iffezheim barrage and have to be dredged to guarantee the safety of the dams and the discharge of floods. A further reduction of sedimentation by changing the weir operating mode was investigated, but could not be implemented because the area of sedimentation is too far away from the main hydraulic influence of the weir.

As all other dredged material handling options (e.g. treatment of dredged material, land disposal) would cost significantly more, the German Water and Navigation Authorities decided to relocate the dredged material downstream by flushing it through a pipeline across the barrage into the free flowing river where the separated flows from the ship-locks, the power station and the weir channel converge
(Huber & Polschinski, 2004).

From the chemical point of view, there is currently still a major problem left from the past. During the period 1960 1985, large amounts of hexachlorobenzene (HCB), released by illegal emissions, had been discharged into the Rhine. Although the main emitter of HCB has meanwhile reduced its inputs to negligible levels for many years now, HCB-contaminated sediments are still present in the impoundments and move downstream when they are resuspended by floods or mobilized by dredging operations (Koethe et al. 2004).

Thus contamination of freshly settled sediments in the backwater of the Iffezheim barrage is the result of mixing of recent, relatively clean, suspended matter with remobilised old, contaminated sediments. The detailed transport mechanisms of the HCB-load from one barrage to the next and finally to Iffezheim are very complex and are not fully understood yet.

The relocation of some 300’000 m^3 of fine grained sediments within some months has never been practised at the Rhine before, but it was clear that this measure would increase the concentration of suspended matter in the Rhine downstream of the Iffezheim barrage over many kilometres and for a long period. The river itself transports naturally some 1.2 M t of suspended matter per year but during flood events, some 500’000 t can be moved within only a few days, which leads to much higher concentrations of suspended sediment. Consequently, the river system and its biocoenoses are "accustomed" to high sediment discharges. Therefore, the scheduled sediment monitoring programme had to consider the situation that increased concentrations of suspended matter would prevail over months. This means that monitoring activities were concentrated, on the one hand, on the morphological responses in ecologically sensitive areas like groyne fields, side channels etc. and, on the other hand, on the dispersion of suspended solids in the river channel. The distribution patterns of suspended solids were determined at selected cross profiles before, during, and after the relocation operation. The influence of the relocation on sediment distribution is shown in Fig. 131 for a cross section located some 100 m downstream of the pipeline outlet. Altogether suspended sediment concentrations were measured at 13 cross sections between Iffezheim (km 334) and Worms (km 444) by means of sampling, turbidity measurements and Acoustic Doppler Current Profiling (ADCP). Additional information was provided by the daily records of the permanent measuring stations.

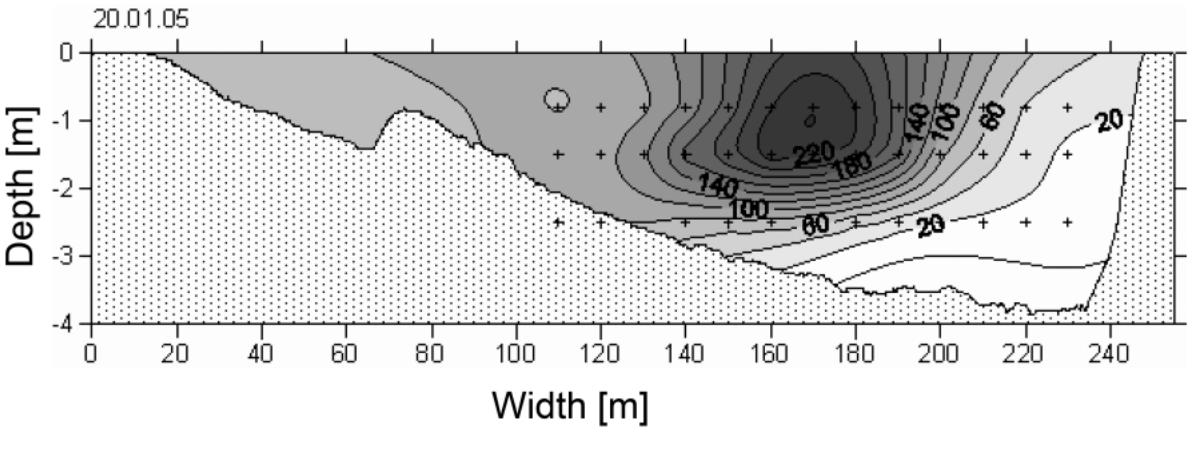


Fig. 131: Distribution of suspended material [g m^{-3}] in a cross section downstream of the relocation site (BfG, 2008)

The longitudinal section of Fig. 132 shows the range of cross-sectional averaged suspended sediment concentrations, measured during the relocation phase, in comparison to the long-term average concentration for similar discharge situations at roughly 1’000 m^3/s. Close to the relocation point, the concentration varies considerably due to changes of the flushing mode and to variations of discharge. Further downstream dispersional effects contribute to homogeneity and the variation of concentration becomes smaller.

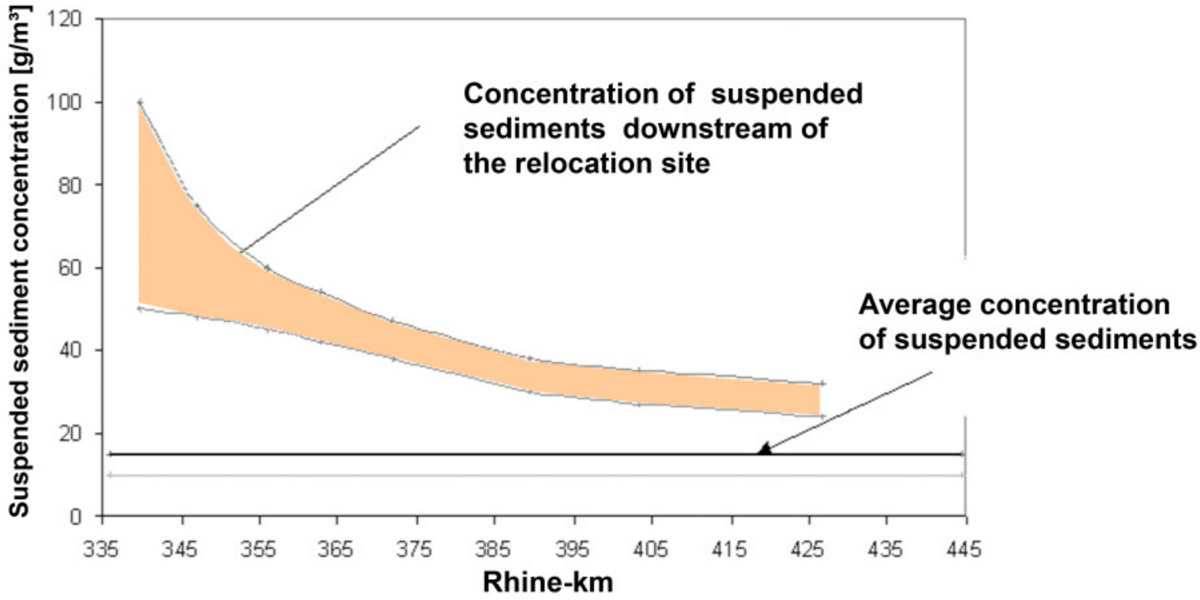


Fig. 132: Longitudinal distribution of mean suspended sediment concentration [g m^{-3}] downstream of the relocation site (BfG, 2008)

The strong decline of suspended sediment concentration within the first 20 – 30 km cannot be ascribed to dispersion and dilution effects but must be explained by temporary deposition because suspended sediment loads decrease by the same range. Concerning the fine grained nature of the relocated material and the high flow velocity of the Upper Rhine, the risk of settling of large amounts of sediment in the channel can be excluded, but it was expected that suspended solids might drift into groyne fields, bayous, harbour basins etc. Sediment sampling subsequent to the relocation measure confirmed that most of the fine sediment, which had been temporarily stored in such areas, was resuspended again by increasing discharge and transported further downstream. The temporal resolution of the turbidity records enabled calculation of the propagation velocity of distinct turbidity peaks and lead to ca. 4 km/h as the characteristic transport velocity for suspended sediment at discharges lower than the long-term mean discharge (MQ). This is in good agreement with the flow velocities determined by Van Mazijk (1996) by using a dye tracer ten years ago.

<u>Climate change impacts</u>
The extreme rainfall in the Swiss Alps from August 19th to August 22nd 2005 and the associated heavy soil erosion induced a very strong increase of suspended sediment concentration in the tributaries, in the lakes but also in the main river. The concentration measured on August 23rd at the station of Weil/Basel amounted to 2'689 mg/l, which was the highest concentration ever measured there since the beginning of the records in 1973. With the aid of the records of the permanent measuring stations along the Rhine and some supplementary recordings from turbidity sensors, the propagation of the turbidity peaks could be followed from Lake Constance down to the Dutch border (Fig. 133). Between Weil/Basel and Koblenz the mean velocity of the suspended sediment wave was 6 km/h both within the impounded upper reach and in the subsequent free flowing section. The flood wave with the highest discharge

of around 3’000 m^3/s (at Weil/Basel slightly greater and at Koblenz slightly less, see Fig. 133) propagated with the same velocity of c. 6 km/h downstream but the centroid of the turbidity cloud lagged typically some hours behind the discharge peak. The peak sediment concentration decreased within a few days, whereas the decline of the discharge took more than one week. The extreme precipitation event was due to a so-called Vb weather situation (Schmid et al. 2005).

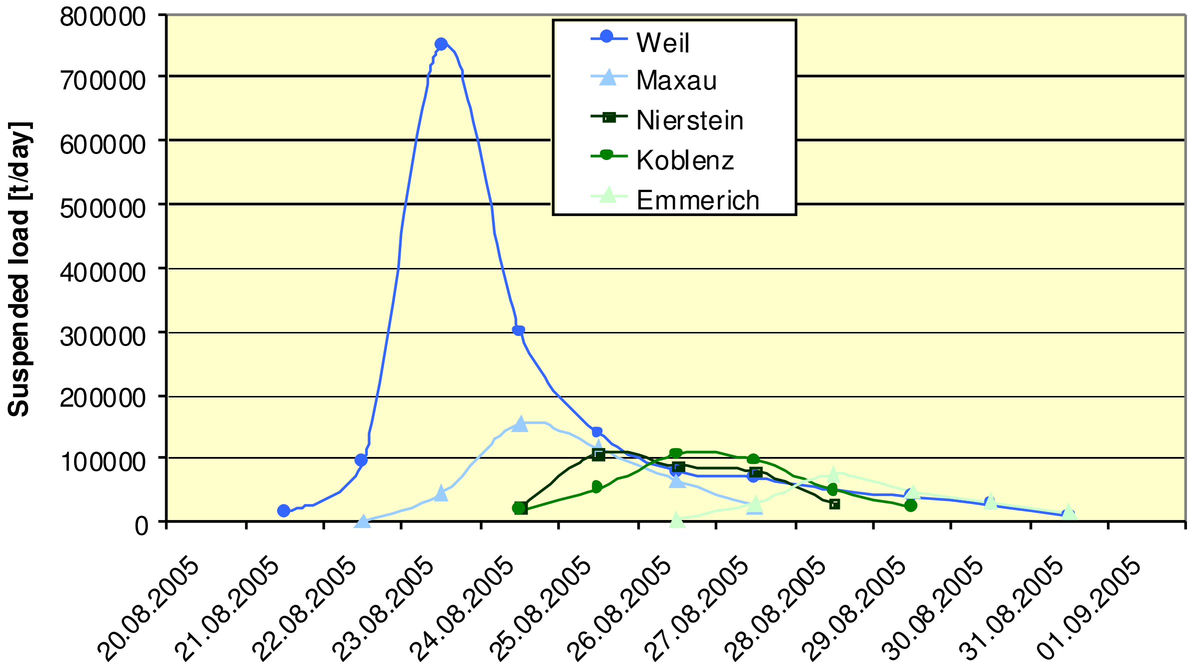


Fig. 133: Suspended load at the permanent monitoring stations during the flood event of August 2005 (BfG, 2008)

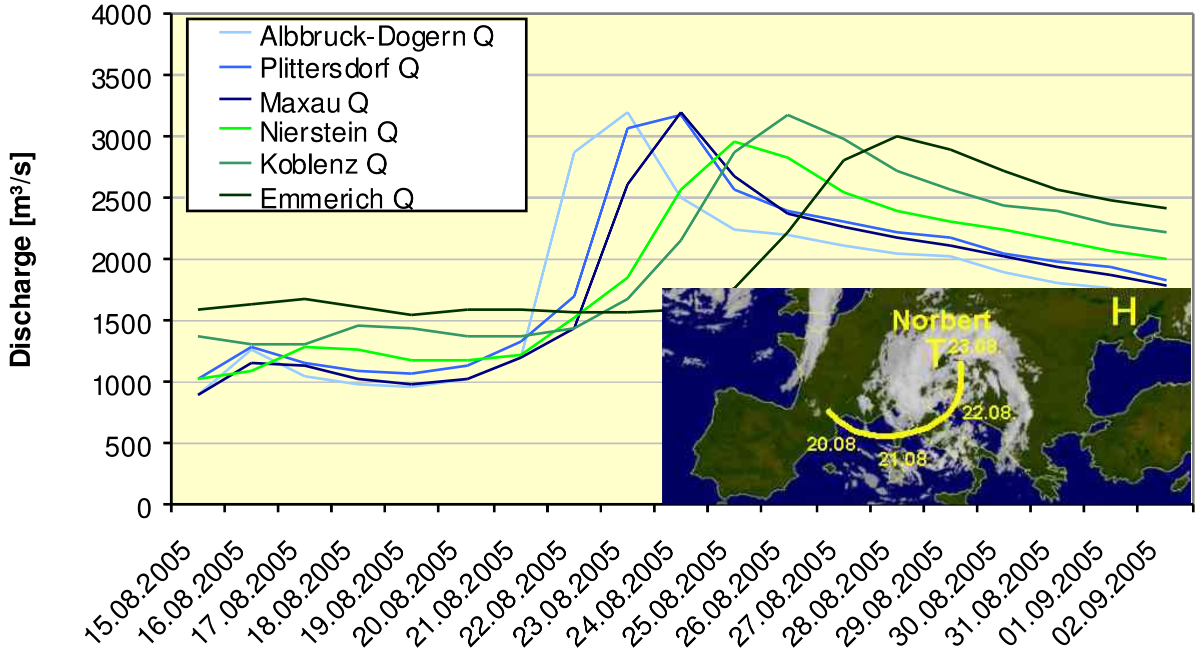


Fig. 134: Discharge at the monitoring stations during the flood event of August 2005 (BfG, 2008)

Aside from the discussion whether the more frequent appearance of such weather conditions is a consequence of climatic change, there is no doubt that the short but extreme event caused an extreme input of suspended sediment into the river system. Besides Weil/Basel another two permanent monitoring stations recorded maximum values of turbidity or sediment concentration respectively. Since sampling at some stations is discontinued on Saturday and Sunday, the graph in Fig. 134 contains curves that are partly fitted in order to give an overall impression of the suspended sediment transport in the River Rhine between Switzerland and The Netherlands during the August 2005 event.

A large amount of sediment must have disappeared in the impounded section of the Upper Rhine, as the deficit between the stations of Weil/Basel and Maxau amounts to about 1 M t of suspended sediment. It is not plausible that this mass has been deposited in the impoundments alone, in fact part of the sediment load might have been stored in the so-called "Restrhein", on the flood plain and the accompanying bayou system. Downstream of the impounded sections the suspended load decreases further. At first sight this seems surprising, because normally the suspended load increases significantly on its way down to The Netherlands. However, in this special case none of the numerous tributaries to the Rhine downstream of Basel offered either noticeable additional discharge or an appreciable sediment input. A kind of "frozen" sediment wave moved downstream with a quasi-steady profile and with a maximum discharge peak being only slightly reduced.

Conclusions

The permanent monitoring stations for suspended load provide an important database for the understanding of suspended sediment transport and sedimentation processes along the Rhine River. From the analysis of the prominent flood event of August 2005 it is concluded that sedimentation in the impounded reach is related to high discharge events rather than to mean or low discharge conditions. This is indicated by the strong reduction of suspended sediment load when the flood wave passes the impounded section. Although at flood stage part of the suspended load enters the "Restrhein" and might be stored on the flood plain and in the accompanying bayou system, considerable amounts of sediment are deposited in the impoundments of Gambsheim and Iffezheim. Both the long term records at Maxau and the dredging statistics substantiate that the backwaters of the barrages Gambsheim and especially Iffezheim are important sediment traps, which considerably reduce the suspended load in the subsequent free flowing section. Looking at the potential influence of climate change on sedimentation, it has to be considered that global climate change affects the frequency and intensity of extreme events (Kempe and Krahe 2005). Given that precipitation events like that of August 2005 will occur more frequently in future, the rate of sedimentation in the impounded section of the Upper Rhine might increase considerably necessitating enhanced dredging activities in the backwaters of the barrages Iffezheim and Gambsheim.

To secure high flood discharge and the stability of the dykes in the impounded section of the Upper Rhine, about 300'000 m^3 of fine grained sediments have to be dredged and relocated every year. Because of the contamination of the dredged material, relocation within the channel is problematic and has already caused some political disturbances. Monitoring of suspended sediment transport during the relocation of 100'000 m^3 of fine grained sediments from the backwater of the Iffezheim barrage into the free flowing river proved that, despite the temporary storing of sediments in groyne fields and side channels, no permanent silting affected the riverine ecosystem. To increase knowledge about transfer, storing, remobilization and mixing of sediments along the chain of impoundments, especially in the backwaters of the Gambsheim and Iffezheim barrages, two additional measuring stations for suspended sediment should be installed between Basel and Maxau. Furthermore the passage of suspended sediments during high floods has to be studied in detail and connected with the results of the chemical monitoring and echo-soundings carried out before and after the floods. Together with the data of the dredging and dumping activities it should be possible to establish a detailed sediment balance of the impounded section, which serves as the basis for improved sediment management along the Southern Upper Rhine.

11.3 The Netherlands

With respect to sediment management in The Netherlands several studies have been carried out over the last year. The most extensive studies are summarized below.

11.3.1 Study German – Dutch border

A project has been carried in close collaboration between the BfG and RIZA. In this project Dutch and German morphological studies of the Rhine have been integrated. These studies focused on changes in bed level and sediment budget that have been conducted simultaneously by German and Dutch researchers for parts of the lower Niederrhein and upper Dutch Rhine branches, respectively. The project aimed at quantifying riverbed development, water level changes and sediment budget changes of a part of the river Rhine, being 40 km of Niederrhein, Bovenrijn, Waal and Pannerdensch Kanaal, as well as analysing the influence of natural processes and human interference on riverbed development. It was shown that bed level degradation in the border area was already going on in 1934. Degradation increased in time, with a maximum in the period 1980-1990. Since 1990 degradation rate has reduced, but degradation was still going on in 1999. This degradation is only for a small part directly due to dredging. Dredging in other parts of the river along with the adjustment to normalisation works carried out in past centuries are the major causes behind the observed bed degradation. The German – Dutch study has been published in 2001 by Ten Brinke (RIZA) and Gölz (BfG) in RIZA-report 2001.044 entitled ‘Bed level changes and sediment budget of the Rhine near the German – Dutch border’.

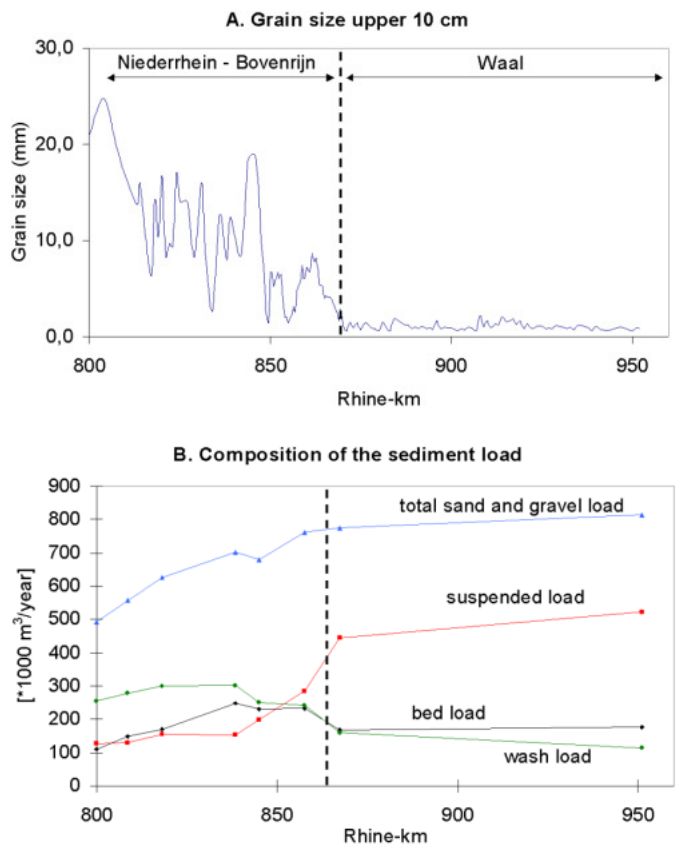


Fig. 135: One of the results of the study of the Rhine near the Dutch-German border is the composition of the sediment load at various positions along the Niederrhein, Bovenrijn and Waal. This downstream variation of the sediment composition follows from the combination of sediment transport data sets of Germany (BfG) and The Netherlands (RIZA).The figure shows the change in grain size of the riverbed (above) and the transport of sand and gravel (below) from the German Niederrhein via the Bovenrijn to the Waal (ten Brinke 2005)

11.3.2 Morphological behaviour of bifurcations in the Dutch Rhine river system

In The Netherlands the River Rhine bifurcates into three branches: the Waal, Nederrijn-Lek and the IJssel. Further downstream, the Lek and the Waal spread out in a complicated pattern of branches near Rotterdam. In this densely populated and low-lying country, management of river discharge over the Rhine distributaries, and thus a firm control on the behaviour of river bifurcations, is of utmost importance. This makes high demands upon the knowledge of sediment transport and morphological processes in these areas. Over the last years three research projects have been carried out, focusing on the three main bifurcations of the Dutch Rhine River system: Pannerdensche Kop, IJsselkop and the Kop van Oude Wiel. Pannerdensche Kop is the bifurcation of the Bovenrijn into the Waal and the Pannerdensch Kanaal. IJsselkop is the bifurcation of the Pannerdensch Kanaal into the Nederrijn and IJssel. Kop van Oude Wiel is the bifurcation of the Waal into the Boven- and Nieuwe Merwede. Research was aimed at sediment transport and morphological processes near these river bifurcations, thus contributing to the understanding of the morphological behaviour of these bifurcations and enabling numerical morphological modelling.

A lot of effort has been put into understanding and quantifying temporal and spatial variability of sediment characteristics and morphological processes in the study areas. The grain size of the upper layer of the bed has been mapped using new techniques (natural radio-activity of sediments; shallow seismic surveys). The grain size of the subsoil, including the so-called active transport layer, has been mapped based on borings and seismic profiles. Measurements have been carried out focused on the suspended and bed load sediment transport and the development of dune patterns during floods such that the spatial variation in sediment transport and dune characteristics is known quite well. Validation of formulations in the literature for bed roughness in the presence of dunes has been carried out based on measured dune characteristics and grain size, and simultaneous measurements on current velocity and water level gradient.

Along with processes within the study areas at a relatively small time and spatial scale, the study areas are subject to developments on a scale of the entire river system over several decades. At present these developments in the Dutch Rhine are mostly related to bed degradation of the upper reaches of the Dutch Rhine branches due to a variety of causes. In future decades the impact of climate change resulting in higher floods may become another significant driving force that affects the study areas. When investing in research for modelling morphodynamics of river bifurcations, these investments should be aimed at both detailed process-oriented studies, including spatial variability near the bifurcation, and processes on a much larger scale.

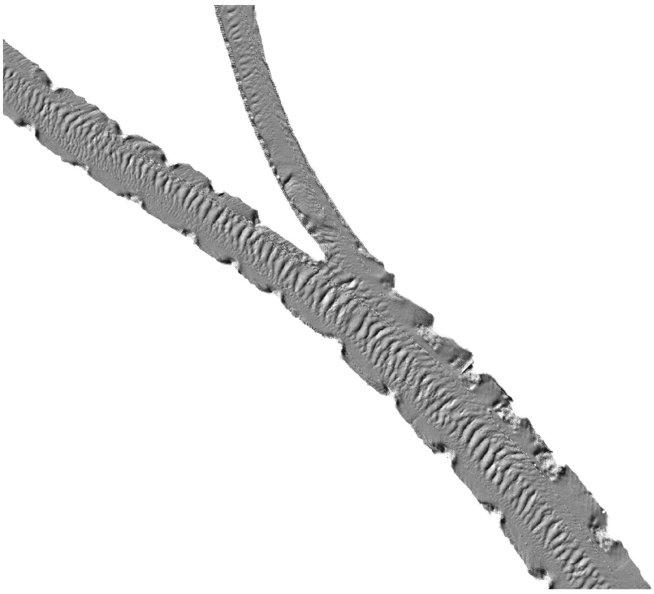


Fig. 136: Sand dunes on the bed of the river near the bifurcation of the Pannerdensch Kanaal into the Nederrijn and the IJssel (bifurcation IJsselkop), measured with a multi-beam echo sounder (Ten Brinke 2005)

The project near the Pannerdensche Kop has been carried out several years prior to the projects near IJsselkop and the Kop van Oude Wiel. Hence, results of the Pannerdensche Kop project have already been published in several scientific papers:

- Ten Brinke, W.B.M., A.W.E. Wilbers and C. Wesseling, 1999. Dune growth, decay and migration rates during a large-magnitude flood at a sand and mixed sand-gravel bed in the Dutch Rhine river system. Spec. Publs int. Ass. Sediment. 28: 15-32.

- Kleinhans and ten Brinke, 2001. Accuracy of cross-channel sampled sediment transport in large sand-gravel-bed rivers. Journal of Hydraulic Engineering 127, 258-269.
- Julien, P.Y., G.J. Klaassen, W.B.M. ten Brinke and A.W.E. Wilbers, 2002. Case study: bed resistance of Rhine River during 1998 flood. Journal of Hydraulic Engineering 128: 1042-1050.
- Kleinhans, M.G., 2002. Sorting out sand and gravel: sediment transport and deposition in sand-gravel bed rivers. PhD-thesis Utrecht University.
- Wilbers, A.W.E. and W.B.M. ten Brinke, 2003. The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. Sedimentology 50, 1013-1034.
- Wilbers, A.W.E., 2004. The development and hydraulic roughness of subaqueous dunes. PhD-thesis Utrecht University.

The first results of the other two projects have been reported in Dutch reports. The first scientific paper that focuses on all three bifurcations is being prepared. Besides, (some of) the results of these projects will be integrated in a PhD-thesis by Frings (Utrecht University) that is scheduled for 2008.

11.3.3 Sediment budget of the Dutch Rhine River system

For the Dutch Rhine River system a sediment budget (or sediment balance) has been made that presents the yearly flows of gravel, sand and silt for all three Rhine branches. This budget has been based on the cross-sectionally integrated sediment transport and on a time series of echo soundings. The sediment transport data were derived from other projects, such as those near the bifurcations (see above). From these data estimates of the yearly flows of gravel, sand and silt were made at the locations of the cross-sections of the measurements. These data, mainly referring to locations in the upstream reaches of the Dutch Rhine branches, were combined with data on sediment flows at cross-sections in the downstream reaches (made available by the Rijkswaterstaat Directorate in this area). The long-term morphological behaviour of the parts of the river in between these cross-sections was derived from echo-soundings: the yearly erosion or sedimentation of the riverbed was quantified from a time series of several years of echo soundings. The sediment budget of the Dutch Rhine River system is presented in a Dutch RIZA-report. The budget is also presented in the book “The Dutch Rhine – a restrained river” by ten Brinke (2005).

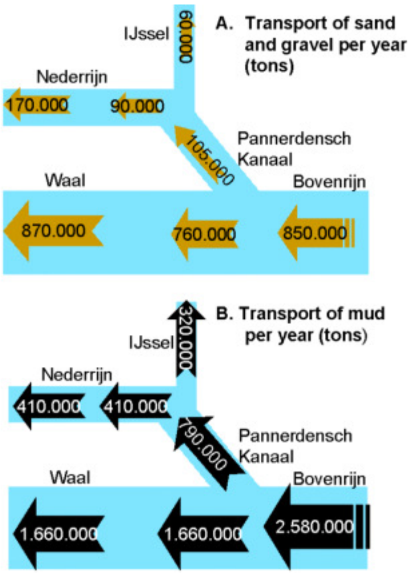


Fig. 137: The flows of sand and gravel (above) and silt (below) through the Rhine branches, per year (Ten Brinke, 2005)

12 Literature

APITZ, S.E., C. CARLON, A. OEN AND S. WHITE (2007): Strategic Framework for Managing Sediment Risk at the Basin and Site-Specific Scale. In: Heise S (Ed.), *Sediment Risk Management and Communication*. Elsevier, Amsterdam

ASSELMAN, N. (1997): Suspended sediment in the River Rhine - the impact of climate change on erosion, transport and deposition. PhD thesis, Utrecht University, The Netherlands

ARGE RHEINBLICK BESTEHEND AUS HUNZIKER, ZARN & PARTNER AG, EBERSTALLER-ZAUNER BÜROS, RUDHARDT+GASSER, ARGE LIMNOLOGIE, TK CONSULT AG (2005): Entwicklungskonzept Alpenrhein, Kurzbericht; Internationale Regierungskommission Alpenrhein und Internationale Rheinregulierung (Hrsg.)

BASSON G.R. AND A. ROOSEBOOM (1997): Dealing with Reservoir Sedimentation, Water Research Commission Report No. TT 91/97, Pretoria, 395 pp

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

BELZ, J. U. (2006): Abflussregimeänderungen im Rheingebiet, Vortragsmanuskript, Bundesanstalt für Gewasserkunde, Koblenz

BERGMEISTER, U. AND L. KALT (1992): Der Alpenrhein und seine Regulierung (Hrsg.): Internationale Rheinregulierung, Rorschach, Buchs Druck und Verlag, Buchs

DEN BESTEN, P, C.A. SCHMIDT, M. OHM, M.M. RUYS, J.W. VAN BERGHEM AND C. VAN DE GUCHTE (1995): Sediment quality assessment in the delta of rivers Rhine and Meuse base don field observations, bioassays and food chain implications. Journal of Aquatic Ecosystem Health, 4, 257-270.

BEYER PORTNER, N. (1998): Erosion des basins versants alpines par ruissellement de surface, PhD thesis, Communication 6, Laboratory of Hydraulic Constructions (LCH), Swiss Federal Institute of Technology, Lausanne, Switzerland.

BFG (1980): Die Herkunft des Rheingeschiebes. Ein geologisch- petrographischer Beitrag zum Geschiebeproblem. Report, Federal Institute of Hydrology, Koblenz, February 1980

BFG (1982): Mineralogisch-petrographische Untersuchungen an Schwebstoffen und feinkörnigen Sedimenten des Rheins. Report BfG 0034, Federal Institute of Hydrology, Koblenz, June 1982

BFG (1985): Untersuchung der Abfluss- und Geschiebeverhältnisse des Rheines. Summarizing Report BfG-0291, Federal Institute of Hydrology, Koblenz, November 1985

BFG (1993): Untersuchung und numerische Modellierung von subaquatischen Dünen im Rhein bei Niederwalluf (Rheingau). Report BfG-0774, Federal Institute of Hydrology, Koblenz, October 1993

BFG (2005): Ergebnisse aus dem begleitenden Untersuchungsprogramm für die Umlagerung von Baggergut in die fließende Welle unterhalb der Staustufe Iffezheim (Results of the accompanying research programme for the relocation of dredged sediment into the tailwater of the Iffezheim barrage/Rhine)

BFG, WSA FREIBURG (2006): Tracerversuch Iffezheim. Bericht BfG-1530, Bundesanstalt für Gewässerkunde und Wasser- und Schifffahrtsamt Freiburg, Koblenz, December 2006

BFG (2008): Unterlagen aus der Bundesanstalt für Gewässerkunde, Federal Institute of Hydrology, Koblenz

BMV (1987): Abfluss- und Geschiebeverhältnisse des Rheins (Discharge and bedload conditions of the Rhine River)
BMV, ED. (1997): Sohlengleichgewicht am Rhein. German Federal Ministry of Transport. Report, Muenster/Mainz, Dec.1997
BMV (1977): Sohlengleichgewicht am Rhein. Report of the working group Rheinsohlenerosion, Münster/Mainz
BITTERLI, T., P. AVIOLAT, R. BRÄNDLI, R. CHRISTE, S. FRACHEBOUD, D. FREY, M. GEORGE, F. MATOUSEK AND J.-P. TRIPET (2004): Grundwasservorkommen. Tafel 8.6. Hydrologischer Atlas der Schweiz. Bundesamt für Wasser und Geologie, Bern-Ittigen
BOILLAT, J.-L. AND P. DELLEY (1992): Transformation de la prise d'eau de Malvaglia, étude sur modèle et réalisation. Wasser – Energie – Luft, 84. Jhg. 1992, Heft 7/8, p. 145 – 151
BOILLAT, J.-L. AND G. DE CESARE, G. (1994): Dichteströmungen im Bereich des Grundablasses des Stausees Luzzone – Modellversuche. Tagungsband (proceedings) des Symposiums Betrieb, Erhaltung und Erneuerung von Talsperren und Hochdruckanlagen, pp. 183-192, Graz, Austria
BOILLAT J.-L. AND H. POUGATSCH (2000): State of the art of sediment management in Switzerland, International Workshop and Symposium on Reservoir Sedimentation Management, Tokyama, Japan
TEN BRINKE W.B.M., A.W.E. WILBERS AND C. WESSELING (1999): Dune growth, decay and migration rates during a large-magnitude flood at a sand and mixed sand-gravel bed in the Dutch Rhine river system. Spec. Publ. int. Ass. Sediment. 28, 15-32
TEN BRINKE W.B.M. AND E. GÖLZ (2001): Bed level changes and sediment budget of the Rhine near the Dutch-German border. National Institute for Inland Water Management and Waste Water Treatment (RIZA), the Netherlands and Federal Institute of Hydrology (BfG), Germany. Report RIZA 2001.044
TEN BRINKE W.B.M. (2004): De Beteugelde Rivier. Bovenrijn, Waal, Pannerdensch Kanaal, Nederrijn-Lek en IJssel in vorm. Diemen
TEN BRINKE W.B.M. (2005): The Dutch Rhine, a Restrained River. Diemen
BROWN, C.B. (1943): The Control of Reservoir Silting, United States Department of Agriculture, Miscellaneous Publication No. 521, Washington D.C., 166 pp
BULTOT, F., A. COPPENS, G.L. DUPRIEZ, D. GELLENS AND F. MEULENBERGHS (1988): Repercussions of a CO_2 doubling on the water cycle and on the water balance – A case study for Belgium. J. Hydrol. 99: 319-347
BULTOT, F., D. GELLENS, M. SPREAFICO AND B. SCHÄDLER (1992): Repercussions of a CO_2 doubling on the water balance – A case study in Switzerland. J. Hydrol. 137: 199-208
BUWAL (2000): NADUF. Messresultate 1977 - 1998. Schriftenreihe Umwelt. Nr. 319. Bern
CARLING, P.A., E. GÖLZ, H.G. ORR AND A. RADECKI-PAWLIK (2000): The morphodynamics of fluvial sand dunes in the river Rhine, near Mainz, Germany. In Sedimentology and Morphology. Sedimentology, 47, 227-252
CARLING. P.A., J.J. WILLIAMS, E. GÖLZ AND A.D. KELSEY (2000): The morphodynamics of fluvial sand dunes in the River Rhine, near Mainz, Germany. II. Hydrodynamics and sediment transport. Sedimentology 47, 253-278
CHELLA, M.R., J.J. OTA AND P.H. POVH (2003): Simulação física do transporte de sedimentos e assoreamento em reservatórios. XV Simpósio Brasileiro de Recursos Hídricos
CHEN, J. AND K. ZHAO (1992): Sediment management in Nanqin Reservoir. International Journal of Sediment Research, Vol. 7(3), pp. 71-84

COLLET, L.W., R. MELLET AND W. STUMPF (1916): Le charriage des alluvions dans certains cours d'eau de la Suisse. Annalen der Schweizer Landeshydrographie, Bd. 2. Bern

CHR/KHR (1993): Der Rhein unter der Einwirkung des Menschen – Ausbau, Schiffahrt, Wasserwirtschaft. Internationale Kommission für die Hydrologie des Rheingebietes (KHR). International Commission for the Hydrology of the Rhine basin. Report no. I – 11

CHR/KHR (1996a):Grosse Speicherseen in Einzugsgebiet des Rheins. Internationale Kommission für die Hydrologie des Rheingebietes (KHR). International Commission for the Hydrology of the Rhine basin. Report no. II – 10

CHR/KHR (1996b): Feststoffbeobachtung im Rhein. Beschreibung der Messgeräte und Messmethoden. Internationale Kommission für die Hydrologie des Rheingebietes (KHR). International Commission for the Hydrology of the Rhine basin. Report no. I – 16

CHR/KHR (2000): Feststoffmessungen zum Vergleich von Messgeräten und Messmethoden im Rhein, 10. – 12. März 1998. Internationale Kommission für die Hydrologie des Rheingebietes (KHR). International Commission for the Hydrology of the Rhine basin. Report no. I – 18

COMMISSION INTERNATIONALE DE L`HYDROLOGIE DU BASSIN DU RHIN (CHR) (1977) Le bassin du Rhin. Monographie hydrologique. CHR/KHR, Den Haag, The Netherlands

DE CESARE, G. (1998): Alluvionnement des retenues par courants de turbidité, PhD Thesis, Communication 7, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne EPFL, Lausanne, Switzerland

DE CESARE, G., B. MONGIARDINO, F. BINDER AND R. ZUGLIAN (2008a): Sedimentevakuation aus dem Speicher Gübsensee über die Triebwasserleitung, Symposium 08 - VAW ETHZ, Neue Anforderungen an den Wasserbau

DE CESARE, G. ET AL (2008b): Reservoir Sedimentation. Overview on the problematic of sedimentation and sediment management in Alpine reservoirs, Rapport No 2. Lausanne

DRÖGE, B., H. ENGEL AND E. GÖLZ (1992): Channel erosion and erosion monitoring along the Rhine River. IAHS Publ. no 210, 493-503

DRÖGE, B. (1992): Change of river morphology by controlled erosion and deposition. Proc. 5th International Symposium on River Sedimentation, Karlsruhe, S. 85-94

DRÖGE, B. (1994): Measurements of bed load in the River Rhine. International Jounal of Sediment Research, Vol. 9, S. 256-263

DVWK (1986): Schwebstoffmessungen. DVWK-Regeln zur Wasserwirtschaft 125/1986, Hamburg (Parey), 46pp

EHRENBERGER, R. (1931): Direkte Geschiebemessungen an der Donau. Die Wasserwirtschaft, 34

EIDG. POST- UND EISENBAHNDEPARTEMENT (1921): Das Rheindelta im Bodensee; Wiederholung der Aufnahme von 1911. Mitt. Nr. 15 des Amtes für Wasserwirtschaft

EIDG. POST- UND EISENBAHNDEPARTEMENT (1926): Il delta della Maggia nel Lago Maggiore. Mitt. Nr. 21 des Amtes für Wasserwirtschaft

EIDG. POST- UND EISENBAHNDEPARTEMENT (1932): Wasserführung, Sinkstoffführung und Schlammalagerung des Alten Rheins. Régime des débits, charriage et dépot des alluvions de Vieux Rhin. Mitt. Nr. 31 des Amtes für Wasserwirtschaft

EIDG. POST- UND EISENBAHNDEPARTEMENT (1939): Untersuchungen in der Natur über Bettbildung, Geschiebe- und Schwebstofführung. Mitt. Nr. 33 des Amtes für Wasserwirtschaft

EIDG. POST- UND EISENBAHNDEPARTEMENT (1939): Deltaaufnahmen des Eidgenössischen Amtes für Wasserwirtschaft. Mitt. Nr. 34 des Amtes für Wasserwirtschaft

FÄH, A., B. CAVELTI, B. ZARN AND H. MÜLLER-LEMANS (2002): The Flood Estimation Puzzle, Proceedings, International Conference on Flood Estimation, March 6-8, 2002 Berne, Switzerland, pp. 469-478

FAN, J. (1985): Methods of preserving reservoir capacity, Methods of Computing Sedimentation in Lakes and Reservoirs: A contribution to the International Hydrological Programme, IHP-II Project A. 2.6.1 Panel, S. Bruk, ed., Unesco, Paris, pp. 65-164

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

FEHR, R. (1987): Geschiebeanalysen in Gebirgsflüssen. Umrechnung und Vergleich von verschiedenen Analyseverfahren. Mitt- Nr. 92 der VAW-ETH- Zürich

FRAUENFELDER-KÄÄB, R. (2005): Gletscherschwund 1850-2000 im Einzugsgebiet der Abflussmessstation Ilanz. Unveröff. Bericht im Auftrag des Bundesamtes für Wasser und Geologie (CH), Zürich

FRINGS, R.M. AND M.G. KLEINHANS (2006): A porosity-based method to distinguish between wash load and bed-material load in the river Rhine. Report ICG 06/02 Centre for Geo-ecological Research, University of Utrecht

GEES, A. (1996): Analyse historischer und seltener Hochwasser in der Schweiz: Bedeutung für das Bemessungshochwasser. Geographisches Institut. Bern

GHO, ARBEITSGRUPPE FÜR OPERATIONELLE HYDROLOGIE (1983): Verzeichnis von in der Schweiz durchgeführten Feststoffbeobachtungen, Delta-, Seegrund- und Querprofilaufnahmen. Bern

GHO, ARBEITSGRUPPE FÜR OPERATIONELLE HYDROLOGIE (1984): Feststoffbeobachtung in Schweizerischen Fliessgewässern. Schlussbericht der Arbeitsgruppe für Feststoffbeobachtung. Bern, Landeshydrologie

GHO, ARBEITSGRUPPE FÜR OPERATIONELLE HYDROLOGIE (1996): Empfehlung zur Abschätzung von Feststofffrachten in Wildbächen. Grundlagen und Anleitung. Mitt. der Arbeitsgruppe für operationelle Hydrologie (GHO) Nr. 4, Landeshydrologie und -geologie, Bern

GHO, ARBEITSGRUPPE FÜR OPERATIONELLE HYDROLOGIE (1999): Feststoffverlagerung in steilen Fliessgewässern. Erhebung und Dokumentation nach Unwetterereignissen. Mitt. der Arbeitsgruppe für operationelle Hydrologie (GHO) Nr. 5, Landeshydrologie und -geologie, Bern

GIGER, W. (2007): Der Rhein rot, die Fische tot: Brandkatastrophe in Schweizerhalle 1986 – Rückblick und Bilanz. UWSF – Z Umweltchem Ökotox 19, Sonderausgabe 1:11-23

GÖLZ, E. (1986): Das rezente Rheingeschiebe; Herkunft, Transport und Ablagerung. Zt. dt. geol. Ges. 137, 587-611

GÖLZ, E. (1990): Suspended sediment and bed load problems of the Upper Rhine. Catena, 17, 127-140

GÖLZ, E. (1994): Bed degradation – nature, causes, counter measures. Wat. Sci. Tech., 29/3, 325-333

GÖLZ, E. (2002): Iffezheim field test – three years experience with a petrographic tracer. In: The structure, function and management implication of fluvial sedimentary systems (Proc. IAHS Symp. Alice Springs, September 2002), 417-425. IAHS Publ. no. 276

GÖLZ, E., M. SCHRÖTER AND M. MIKOS (1995): Fluvial abrasion of broken quarzite used as a substitute for natural bedload. In: Management of sediment – phylosophy, aims and techniques (ed. by C.V.J. Varma and A.R.G. Rao), 387-395. Oxford&IBH New Delhi

GÖLZ, E. (1999): Dynamic bed stabilisation of navigable rivers. In: River, Coastal, and Estuarine Morphodynamics (Proc. IAHR Symp.Genova), 101 – 110

GRASSO, D.A., A. JAKOB AND M. SPREAFICO (2006): Abschätzung der Schwebstofffrachten mittels zweier Methoden (Beispiel Hochwasser August 2005), «Wasser Energie Luft» – 99. Jahrgang, 2007, Heft 3, CH-5401 Baden, pp. 273-280

HEISE, S, U. FÖRSTNER, B. WESTRICH, T. JANCKE, J. KARNAHL AND W. SALOMONS (2004): Inventory of Historical Contaminated Sediment in Rhine Basin and its Tributaries. On behalf of the Port of Rotterdam. Hamburg, October 2004

HERRMANN, K. (2001): Massenverlust und Rundung von Granitschotter beim fluvialen Transport – ein sedimentologischer Beitrag zur Geschiebebewirtschaftung des Rheins. Diploma thesis, University of Stuttgart

HINRICH, H. (1972): Geschiebetrieb und Geschiebefracht des Rheins. DGM 16, S 29-71

HUNZIKER, R.P. (1995): Fraktionsweiser Geschiebetransport; Mitteilung Nr. 138 der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 209 Seiten

HUNZIKER, ZARN & PARTNER AG (2001): Morphologie und Geschiebehaushalt Alpen-rhein; Internationale Regierungskommission Alpenrhein, Projektgruppe Flussbau (Hrsg.)

Hydrologischer Atlas der Schweiz (1998)

ICPR (2007a): Living and linking Rhine – common challenge of a watershed. Conference of Rhine Ministers. Ministerkommunique MIN07-02e, Bonn, 18 October 2007.

ICPR (2007b): Report No. 159 http://www.iksr.de/index.php?id=30

ICPR (2009) Report In press: Sediment Management Plan.

IHP/OHP (1996): Deutsches IHP/OHP-Nationalkomitee, Sonderheft 9

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

IRMER, H. (1996): Rhine water quality and its development. Deutsches IHP/OHP-Nationalkomitee, Sonderheft 9, 39-46

INGE HYDROLOGIE ALPENRHEIN BESTEHEND AUS INGENIEURBÜRO HEIERLI AG, HUNZIKER, ZARN & PARTNER AG, TERGESO AG (2003): Hydrologie Alpenrhein - Zusammenfassender Bericht; Internationale Regierungskommission Alpenrhein, Projektgruppe Flussbau (Hrsg.)

JACOBS, F., WINKLER, K., HUNKELER, F., VOLKART, P. (2001): Betonabrasion im Wasserbau, VAW Mitteilung 168, ETH Zürich, Switzerland

JACOBSEN, T. (1998): New Sediment removal techniques and their applications, Hydropower & Dams, Aix-en-Provence, France, pp. 135-146

DE JONG, J., J.M. BRILS, A.J. HENDRIKS AND W.C. MA (1999): Ecological and ecotoxicological surveys of moderately contaminated floodplain ecosystems in The Netherlands. Aquatic Ecosystem Health and Management. 2(1):9-18.

JULIEN, P.Y., G.J. KLAASSEN, W.B.M. TEN BRINKE AND A.W.E. WILBERS (2002): Case study: bed resistance of Rhine River during 1998 flood. Journal of Hydraulic Engineering 128: 1042-1050

KEMPE, S. AND P. KRAHE (2005): Water and biochemical fluxes in the River Rhine catchment. Erdkunde, Bd. 59, 216-250

KLEINHANS, M.G. (2002): Sorting out sand and gravel: sediment transport and deposition in sand-gravel bed rivers. PhD-thesis Utrecht University

KLEINHANS, M.G. AND W.B.M. TEN BRINKE (2001): Accuracy of cross-channel sampled sediment transport in large sand-gravel-bed rivers. Journal of Hydraulic Engineering 127, 258-269

KÖTHE, H., S. VOLLMER, V. BREITUNG, T. BERGFELD, F. SCHÖLL, F. KREBS AND C. VON LANDWÜST (2004): Environmental aspects of the sediment transfer across the Iffezheim barrage. River Rhine, Germany. Proc. 17th World Dredging Conference WODCON XVII, September 27-October 01, 2004, Hamburg, Germany

KUHL, D. (1992): 14 years artificial grainfeeding in the Rhine downstream the barrage Iffezheim. In: Sediment Management (Proc. 5th Int. Symp. River Sedimentation, Karlsruhe 1992) VOL II, 1121-1129

LAMBERT, A. (1989): Das Rheindelta im See. Vermessung – Photogrammetrie – Kulturtechnik 87/1, 29 – 32

LANDESHYDROLOGIE (2005): Sediment data bank of the swiss national hydrological survey. Bern.

LEHMANN, C. (1993): Zur Abschätzung der Feststofffracht in Wildbächen. Grundlagen und Anleitung. Geographica Bernensia G42. Bern

LEHMANN, C. (2001): Geschiebestudie hinteres Lauterbrunnental. Unveröffentlicht. Bericht, TBA-OIK-II. Thun

MEYER-PETER, E. AND C. LICHTENHAHN (1963): Altes und Neues über den Flussbau; Eidg. Departement des Innern, Veröffentlichung des Eidg. Amtes für Strassen- und Flussbau, Eidg. Drucksachen und Materialzentrale, Bern, 59 Seiten

MEYER-PETER, E. AND R. MÜLLER (1948): Formulas for Bed-Load Transport; IAHSR, Stockholm 7.-9. 6. 1948, 1-26

MORRIS, G.L. AND J. FAN (1997): Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoir and Watersheds for Sustainable Use, McGraw-Hill, New York, xxiv+805 pp

MORRIS, G. L. AND J. FAN, J. (1998): Reservoir Sedimentation Handbook. Design and Management of Dams, Reservoirs, and Watersheds for sustainable Use. New York

MÜLLER, P. (2007): Sedimentation problems in the reservoirs of the Kraftwerke Sarganserland, Travail de diplôme postgrade EPFL-LCH, Lausanne, Switzerland

OEHY, CH. (2003): Effects of obstacles and jets on reservoir sedimentation due to turbidity currents, PhD Thesis N° 2684 and Communication du Laboratoire de constructions hydrauliques - LCH N° 15, Lausanne, EPFL, Switzerland

OEHY, CH. AND A. SCHLEISS (2001): Numerical modelling of a turbidity current passing over an obstacle – Practical application in the Lake Grimsel, Switzerland, Proc. Of the 2001 Int. Symposium on Env. Hydraulics, Tempe AZ, USA

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

OFFICE FEDERAL DE L'ENVIRONNEMENT, DES FORETS ET DU PAYSAGE (OFEFP) (1994): Conséquences écologiques des curages de bassins de retenue, Cahier de l'environnement 219

OWENS, P. N., S. APITZ, R. BATALLA, A. COLLINS, M. EISMA, H. GLINDEMANN, S. HOORNSTRA, H. KÖTHE, J. QUINTON, K. TAYLOR, B. WESTRICH, S. WHITE AND H. WILKINSON (2004): Sediment Management at the River Basin Scale. Synthesis of the SedNet Work Package 2 Outcomes. Soils & Sediments 4, 219 – 222. Landsberg

PGEKG (2005): Gesamtkonzept zur Durchführung einer Erfolgskontrolle des Geschiebemanagements am Rheinstrom. Bericht Projektgruppe „Erfolgskontrolle Geschiebemanagement am Rheinstrom", December 2005

POLSCHINSKI, M. (2007): Informationen über die deutsch-französische Arbeitsgruppe "Sediment- und Baggergutmanagement entlang des Oberrheins". Wasserwirtschaft 4/2007, 18-21

PORT OF ROTTERDAM (2001): Rhine Research Project II – POR II: towards cleaner dredged material, Port of Rotterdam

RIZA, BFG (2001): Bed level changes and sediment budget of the Rhine near the German-Dutch border

SALOMONS, W. AND J. BRILS (eds) (2004): Contaminated Sediments in European River Basins. Final version, December 29th, 2004. European Sediment Research Network (SedNet). EC contract no.: EVK1-CT-2001-20002. Publication available through: www.SedNet.org

SAMI, T. (2004): Reservoir Sedimentation Management with Bypass Tunnels in Japan. Proceedings of the Ninth International Symposium of River Sedimentation, October 18-21, 2004, p. 1036-1043. Yinchang, China

SCHÄDLER, B. (1985): The Water balance of Switzerland. Communication of the Swiss Hydrological Survey No 6a

SCHÄDLER, B. AND BIGLER, R. (1992): Water balance of river basins, Plate 6.1, In: R. Weingartner and M. Spreafico, eds. Hydrological Atlas of Switzerland (HADES), Bern, Swiss Federal Office for Water and Geology

SCHITTLY, J. - ELECTRICITÉ DE FRANCE (EDF) (2005): personal communication

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

SCHLEISS, A. AND C. OEHY (2002): Verlandung von Staussen und Nachhaltigkeit. Wasser, energie, luft-Eau, Energie, Air 7/8

SCHMID, K., S. BADER AND T. SCHLEGEL (2005): Starkniederschläge 19. bis 23. August 2005. MeteoSchweiz, Bundesamt für Meteorologie und Klimatologie. Mitteilung vom 24. 8.2005

SEDNET (2006): Sediment Management – an essential element of River Basin Management Plans. Report on the SedNet Round Table Discussion, Venice, 22-23 November 2006. Publication available through: www.SedNet.org

SPREAFICO, M., C. LEHMANN, A. JAKOB AND A. GRASSO (2005): Feststoffbeobachtungen in der Schweiz aus der Sicht der Landeshydrologie. Bern

SPREAFICO, M. AND C. LEHMANN (1994): Sediment transport observations in Switzerland. Variability in Stream Erosion and Sediment Transport (Proceedings of the Canberra Symposium, December 1994). IAHS Publ. 224, 259 - 268

STRICKLER, A. (1923): Beiträge zur Frage der Geschwindigkeitsformel und der Rauhigkeitszahlen für Ströme, Kanäle und geschlossene Leitungen; Mitteilung Nr. 16 des Amtes für Wasserwirtschaft; Eidg. Departement des Innern, Bern

STUMPF, W. (1916): Methode der Deltavermessungen der Abteilung Wasserwirtschaft. Annalen der Schweizer Landeshydrographie, Bd. 2. Bern

STURM, M. AND A. MATTER (1972): Sedimente und Sedimentationsvorgänge im Thunersee. Eclogae Geologicae Helvetiae 65/3, 563 - 589

SUTER, P. (1998): Verlandung und Spülung des Rempenbeckens der AG Kraftwerk Wägital, wasser, energie, luft 5/6, 127-131

VAN MAZIJK, A. (1996): One-dimensional approach of transport phenomena of dissolved matter in rivers. PhD Thesis, TU Delft, Delft, The Netherlands

VAW/GIUB (1987): Emme 2050 - Studie über die Entwicklung des Klimas, der Bodenbedeckung, der Besiedlung, der Wasserwirtschaft und des Geschiebeaufkommens im Emmental, sowie über die Sohlenentwicklung und den Geschiebehaushalt in der Emme und mögliche zukünftige Verbauungskonzepte. Bericht im Auftrag des Oberingenieurkreises IV, Tiefbauamt des Kt. Bern und des Kt. Solothurn; Versuchsanst. für Wasserbau, Hydrologie und Glaziologie der ETH Zürich/Geogr. Inst. der Univ. Bern, 4 Bände, (unveröff. Auftragsstudie)

VISCHER, D.L., W.H. HAGER, C. CASANOVA, B. JOOS, P. LIER AND O. MARTINI (1997): Bypass tunnels to prevent reservoir sedimentation. 19 Congress ICOLD, Florence Q74 (R.37): 605-624

VOLLMER, S. AND E. GÖLZ (2006): Sediment monitoring and sediment management in the Rhine River. In: Sediment Dynamics and the Hydromorphology of Fluvial Systems (Proceedings of a symposium held in Dundee, UK, July 2006). IAHS Publ. 306, 2006

WFD (2000): Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy (Water Framework Directive). Official Journal of the EC, L327

WILBERS, A.W.E. (2004): The development and hydraulic roughness of subaqueous dunes. PhD Thesis Utrecht University

WILBERS, A.W.E. AND W.B.M. TEN BRINKE (2003): The response of subaqueous dunes to floods in sand and gravel bed reaches of the Dutch Rhine. Sedimentology 50, 1013-1034

WILDENHAHN, E. AND U. KLAHOLZ (1996): Große Speicherseen im Einzugsgebiet des Rheins. KHR II-10

WISCHMEIER, W.H. AND D.D. SMITH (1978): Predicting rainfall erosion losses: A guide to conservation planning. Agriculture Handbook No 537, U.S. Department of Agriculture 1978, pp. 58

WITT, O. (2004): Erosionsstabilität von Gewässersedimenten mit Auswirkung auf den Stofftransport bei Hochwasser am Beispiel ausgewählter Stauhaltung des Oberrheins. *Mitteilungsheft* Nr. 127, (Promotionsschrift) Institut für Wasserbau, Universität Stuttgart, 2/2004. ISBN: 3-933761-30-1

WITT, O., M. KELLER, D. TEN HULSCHER, M. LEHMANN AND B. WESTRICH (2003): Resuspension risk of polluted sediments in the river Rhine. Vom Wasser 101, 189-204

ZARN, B. (1997): Einfluss der Flussbettbreite auf die Wechselwirkung zwischen Abfluss, Morphologie und Geschiebetransportkapazität; Mitteilung Nr. 154 der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, 240 Seiten

ZARN, B. (1999): Der Alpenrhein - ein Kieslieferant? Wasser - Energie - Luft 91. Jahrgang, Heft 7/8, 157-164

ZARN, B. (2003): Alpenrhein - Modellierung von kiesführenden Flüssen mit Bänken - die Mastrilser Rheinauen am Alpenrhein in: Feststofftransportmodelle für Fliessgewässer, ATV-DVWK Arbeitsbericht, Seite 195 – 212

ZARN, B. (2005): Geschiebehaushalt Alpenrhein, Domat/Ems, Entwurf 29.12.2005

ZOTTL, H. (1999): Sohlsicherung der Donau im Abschnitt Wien bis zur österreichisch-slowakischen Grenze. Unpublished paper, presented at the 2. Deggendorf Donau-Symposium, Deggendorf

General Information about the International Commission for the Hydrology of the Rhine basin (CHR)

The CHR is an organisation in which the scientific institutes of the Rhine riparian states develop joint hydrological measures for sustainable development of the Rhine basin.

CHR's mission and tasks:
Extension of knowledge of the hydrology of the Rhine basin through:
- joint research
- exchange of data, methods and information
- development of standardised procedures
- publications in the CHR series

Making a contribution to the solution of cross-border problems through the formulation, management and provision of:
- information systems (CHR Rhine GIS)
- modellen, e.g. models for water management and the Rhine Alarm Model

Co-operation countries:
Switzerland, Austria, Germany, France, Luxembourg and The Netherlands.

Relationship with UNESCO and WMO:
The CHR was founded in 1970 following advice by UNESCO to promote closer co-operation between international river basins. Since 1975 the work has been continued within the framework of the International Hydrological Programme (IHP) of UNESCO and the Hydrological Water Resources Programme (HWRP) of WMO.

For more information on the CHR, please visit our website at: www.chr-khr.org

Publications of CHR

CHR/KHR (1978): Das Rheingebiet, Hydrologische Monographie. Staatsuitgeverij, Den Haag / Le bassin du Rhin. Monographie Hydrologique. Staatsuitgeverij, La Haye. ISBN 90-12017-75-0 (out of print)

CHR Reports

I-1 GREBNER, D. (1982): Objektive quantitative Niederschlagsvorhersagen im Rheingebiet. Stand 1982 / Prévisions objectives et quantitatives des précipitations dans le bassin du Rhin. Etat de la question en 1982 (out of print)

I-2 GERHARD, H., J.W. VAN DER MADE, J. REIFF, L.P.M. DE VREES (1983): Die Trocken- und Niedrigwasserperiode 1976. (2. Auflage 1985) / La sécheresse et les basses eaux de 1976 (2ème édition, 1985). ISBN 90 70980 01 0 (out of print)

I-3 HOFIUS, K. (1985): Hydrologische Untersuchungsgebiete im Rheingebiet / Bassins de recherches hydrologiques dans le bassin du Rhin. ISBN 90 70980 02 9 (out of print)

I-4 BUCK, W., R. KIPGEN; J.W. VAN DER MADE, F. DE MONTMOLLIN, H. ZETTL, J.F. ZUMSTEIN (1986): Berechnung von Hoch- und Niedrigwasserwahrscheinlichkeit im Rheingebiet / Estimation des probabilités de crues et d'étiages dans le bassin du Rhin. ISBN 90 70980 03 7 (out of print)

I-5 TEUBER, W., A.J. VERAART (1986): Abflußermittlung am Rhein im deutsch-niederländischen Grenzbereich / La détermination des débits du Rhin dans la région frontalière germano hollandaise. ISBN 90 70980 04 5 (out of print)

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I-8 ENGEL, H., H. SCHREIBER, M. SPREAFICO, W. TEUBER, J.F. ZUMSTEIN (1990): Abflußermittlung im Rheingebiet im Bereich der Landesgrenzen / Détermination des débits dans les régions frontalières du bassin du Rhin. ISBN 90 70980 10 x (out of print)

I-9 CHR/KHR (1990): Das Hochwasser 1988 im Rheingebiet / La crue de 1988 dans le bassin du Rhin. ISBN 90 70980 11 8 (out of print)

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I-12 SPREAFICO, M., A. VAN MAZIJK (Red.) (1993): Alarmmodell Rhein. Ein Modell für die operationelle Vorhersage des Transportes von Schadstoffen im Rhein. ISBN 90 70980 18 5

I-13 SPREAFICO, M., A. VAN MAZIJK (réd) (1997): Modèle d'alerte pour le Rhin. Un modèle pour la prévision opérationnelle de la propagation de produits nocifs dans le Rhin. ISBN 90¬70980 23

I-14 EMMENEGGER, CH. ET AL. (1997): 25 Jahre KHR. Kolloquium aus Anlaß des 25jährigen Bestehens der KHR / 25 ans de la CHR. Colloque à l'occasion du 25e anniversaire de la CHR. 1SBN 90 70980 24 x

I-15 ENGEL, H. (1997): Fortschreibung der Monographie des Rheingebietes für die Zeit 1971 1990 / Actualisation de la Monographie du Bassin du Rhin pour la période 1971 1990. ISBN 90 70980 25 8

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I-19 BARBEN, M. ET AL. (2001): Übersicht über Verfahren zur Abschätzung von Hochwasserabflüssen – Erfahrungen aus den Rheinanliegerstaaten. ISBN 90-36954-11-8

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Katalog/Catalogue 1 SPROKKEREEF, E. (1989): Verzeichnis der für internationale Organisationen wichtigen Meßstellen im Rheingebiet / Tableau de stations de mesure importantes pour les organismes internationaux dans le bassin du Rhin. ISBN 90 70980 08 8

Reports sponsored by CHR

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