BERLINER GEOGRAPHISCHE ABHANDLUNGEN

Heft 65

Jens Bölscher, Peter-Jürgen Ergenzinger, Peter Obenauf
(Editors)

Hydraulic, Sedimentological and Ecological Problems of Multifunctional Riparian Forest Management - RIPFOR -

The Scientific Report

2005

Im Selbstverlag des Instituts für Geographische Wissenschaften der Freien Universität Berlin

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Berliner Geographische Abhandlungen, Heft 65: 1-145, Berlin 2005

Satz und Layout: Jens Bölscher & Ingo Schnauder

BERLINER GEOGRAPHISCHE ABHANDLUNGEN

Herausgegeben von Margot Böse, Brigitta Schütt und Achim Schulte

Schriftleitung: Dieter Jäkel

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145 Seiten, 101 Figuren, 15 Tabellen

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ISBN 3-88009-066-1

Scientific Report

Hydraulic,Sedimentological and Ecological Problems of Multifunctional Riparian Forest Management

Freie Universität Berlin

University of Natural Resources and Applied Life Sciences - Vienna

Universität Karlsruhe

Universita degli Studi di Trento

University of Bucharest

Federal Ministry of Agriculture and Forestry - Austria

Agenzia Provinciale per Protezione dell´Ambiente - Trento

Fifth framework programme of the European Community for research, technological development and demonstration activities (1998 – 2002)

Quality of Life and Management
of Living Resources Programme

Key Action N° 5:
Sustainable Agriculture, Fisheries and Forestry, and Integrated Development of Rural Areas, Including Mountain Areas

Period 01/03/2000 - 28/02/2003 - Contract number QLRT-1999-1229

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PREFACE

The problem of prevention with regard to floodplains is related to two extremes: Prevention of floods and prevention of droughts, both urgent socioeconomic issues during the last years.

„Retard the flow of water in the stream corridor" is the message to cope with both kind of problems. An amphibian landscape will help to maintain water supply during periods of droughs and by its retention area to reduce peaks of high floods.

Flood retention areas will function sustainably only if there is an intact ecological system and equilibrium between erosion and accumulation of sediments which in turn both depend from the evolution of the hydraulic conditions and from the succession of the riparian forest.

The RipFor – project laid emphasis on the hydraulic processes and their erosion / accumulation effects in retention areas with the aim to get insight into the interaction between riparian vegetation, sediment transport, hydraulics and ecology. Interdisciplinary and intereuropean work was carried out in the field, the laboratory and by modelling.

Results of the RipFor – project as presented in this report and the attached „guidelines" in this way are a contribution to the international discussion on river restoration and to the implementation of the European Water Framework Directives.

The scientific report was compiled by Ingo Schnauder and Jens Bölscher (Karlsruhe and Berlin) from contributions of all partners, whereas the bulk of work on the „Guidelines" was done by Ingo Schnauder (Karlsruhe), Jens Bölscher (Berlin) and Harald Meixner (Vienna), who also cared for the layout. Reporting of the Romanian NAS partner was directed by Virgil Iordache.

Assistance of subcontractors and endusers is highly appreciated, especially by Otmar Huppmann (Gewässerdirektion Oberrhein).

Funding within „Quality of Live and Management of Living Resources" in the RP5 framework of the European Union was essential for this project and is highly acknowledged.

Prof. Dr. Peter-Jürgen Ergenzinger

THE FIFTH FRAMEWORK PROGRAMME OF THE EUROPEAN COMMUNITY FOR RESEARCH, TECHNOLOGICAL DEVELOPMENT AND DEMONSTRATION ACTIVITIES (1998-2002)

The Fifth Framework Programme (FP5) sets out the priorities for the European Union's research, technological development and demonstration (RTD) activities for the period 1998-2002. These priorities have been selected on the basis of a set of common criteria reflecting the major concerns of increasing industrial competitiveness and the quality of life for European citizens. The Fifth Framework Programme has two distinct parts: the European Community (EC) framework programme covering research, technological development and demonstration activities; and the Euratom framework programme covering research and training activities in the nuclear sector. FP5 differs considerably from its predecessors. It has been conceived to help solve problems and to respond to the major socio-economic challenges facing Europe. To maximise its impact, it focuses on a limited number of research areas combining technological, industrial, economic, social and cultural aspects. Management procedures have also been streamlined with an emphasis on simplifying procedures and systematically involving key players in research. A major innovation of the Fifth Framework Programme is the concept of "Key actions". Implemented within the specific programmes, these flexible instruments are targeted at achieving solutions to topics of great concern in Europe. "Key actions" will mobilise the wide range of scientific and technological disciplines - both fundamental and applied - required to address a specific problem so as to overcome the barriers that exist, not only between disciplines but also between the programmes and the organisations concerned. The aim of the Key Action N°5 (Sustainable Agriculture, Fisheries and Forestry, and Integrated Development of Rural Areas including Mountain Areas) is to develop the knowledge and technologies needed for the production and exploitation of living resources, including forests, covering the whole production chain, adapted to recent adjustments in the common agricultural and fisheries policies, while also providing the scientific basis for Community regulations and standards. Similarly, the aim is to promote the multipurpose role of forests and the sustainable management and utilisation of forest resources as an integral factor of rural development. Priority areas include:

- new and sustainable systems of production, including breeding methods, and exploitation in agriculture, forestry, fishing and aquaculture, taking into account profitability, the sustainable management of resources, product quality and employment as well as animal health and welfare,
- the integrated production and exploitation of biological materials (non-food uses),
- sustainable and multipurpose utilisation of forest resources; the integrated forestry-wood chain,
- development of methods of control, surveillance and protection, including protection of land and prevention of soil erosion,
- prelegislative research designed to provide a scientific basis for Community legislation,
- the production of new tools and models for the integrated and sustainable development of rural and other relevant areas based on optimisation of the specific potential of each area, including at regional level, diversification of activities and land use, and involvement of the people concerned.

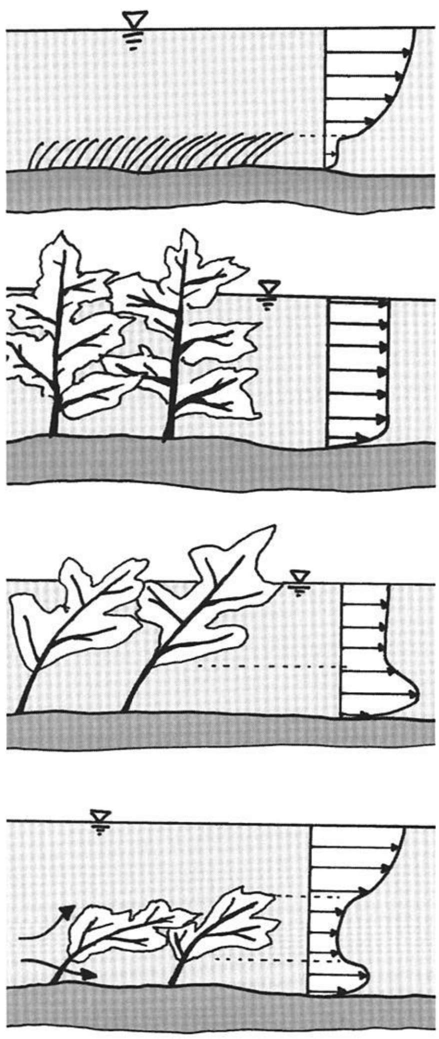
The Editors

SUMMARY

Floodplain Stability

The results from field and laboratory measurements prove the importance of vegetation properties for the bank and floodplain stability. In this case, stability means a balance between sedimentation and erosion of sediments where the initial cross sectional profiles are maintained.

First it could be shown, that a static equilibrium with no sedimentation or erosion does largely not occur at natural or restored rivers and riparian systems. Instead, continuous morphological changes take place that depend mainly on the properties of the flow interacting with the properties of the vegetation. Hereby, the most important classification was found to be the flow condition arising from the vegetation height, flexibility and the present hydraulic conditions such as water depth and velocity. The results of the experiments showed that the flow conditions can be classified in four categories (see also **Figs.1a-d**):



Figs. 1 a-d
Flow conditions for vegetation

a) *Submerged conditions*, in which the plants are tall compared with the water depth and/or have flexible properties that allow biological drag reduction by bending in flow direction. The resulting flow field can be separated into the flow inside the vegetation close to the bed and the flow above the vegetation that shows the classical logarithmic mean velocity distribution (**Fig.1 a**).

b) *Non-submerged (or emerged) conditions*, in which the plants are taller than the water depth and/or rigid enough to withstand the flow. In this case the flow is almost constant over the water depth and can be characterized by classical friction laws (Darcy-Weisbach or Gauckler-Manning-Strickler formula) (**Fig.1 b**).

c) *Emerged conditions with canopy and bottom flow*. In this case the plants are too rigid to bend completely so that their canopies still protrude the water surface. The flow can be separated into decelerated canopy flow through the foliage and accelerated bottom flow underneath the canopies (**Fig.1 c**).

d) *Submerged conditions with canopy and bottom flow*. Contrary to the emerged case, the water depth is higher than the bent plant height. The vertical velocity profile resembles condition c) up to the canopy flow but has an additional logarithmic distribution above the canopy layer (**Fig.1 d**).

These categories are closely related to the sedimentation/erosion effects within floodplains and river banks. Hereby, local effects have to be differentiated from large-area processes. Fully *submerged conditions* lead to a decrease in velocities near the bottom and within the vegetation (see Fig.1 a). In such way, they protect and stabilize the floodplain bed as observed for the fully submerged and bend willows at the river Wien and grasses at the Upper Rhine. If the vegetation grows homogenously in density and height, large areas can be affected by sedimentation. E*merged flow conditions* occur with older vegetation such as trees that have highly rigid plant properties (e.g. woody stems, see Fig.1 b) and low vegetation densities due to the shading effects of their canopies. These rigid structures generate wake flows and tend towards local scouring around the plants. When *bottom flow* occurs, the flow is contracted underneath the vegetation canopy and causes increased velocities close to the bed and consequently increased local erosion around the plants. This effect was observed for young willow trees at the Upper Rhine (*emerged conditions* with canopy flow as shown in Fig.1 c) and for spherical bushes in the flume experiments at Trento (*submerged conditions* with canopy flow as shown in Fig.1 d). The canopy in both cases was compact and dense with a rigid stem-structure at the bottom that anticipated a full bending of the plants. Considering in general the large-area effects on the floodplain stability, the vegetation increases the hydraulic roughness significantly and reduces the flow and the velocities. Consequently, less sediment can be transported by the flow and sedimentation predominates on the floodplains. Experiments at Trento showed that the total shear forces have to be increased up to 200 percent in presence of dense vegetation to get equal transport rates as for non-vegetated floodplains. This mechanism is important for long-term floodplain elevation and transition between softwood riparian forest that grows on the lower levels of the floodplain with higher and longer periods of inundation and hardwood riparian forest. Besides the vegetation-induced flow conditions, the strength of the flood waves characterized by their peak discharge has an influence on sedimentation/erosion. The rates of sedimentation within the submerged grasses at the Upper Rhine increased with higher-discharge flood events and with declining water depths and flow velocities in the run-off phase of the flood wave. Simultaneously, the local erosion within the willows with bottom flow increased with higher discharges. Furthermore the accumulation of woody and floating debris influenced the sedimentation/erosion strongly. The trapping of floating debris by the vegetation close to the water surface enforced the occurrence of bottom flow conditions and consequently local scouring. Whereas the accumulation of woody debris on the floodplain caused local protection of the bed and sedimentation to a large extent.

River Bed and Bank Stability

In general, the bed stability of rivers can be characterized by the grain size distribution and the effective hydraulic stresses acting on the river bed sediments. In the case of rivers with riparian floodplains, the hydraulic stresses are a result of interactions between the flow and the vegetation. Therefore, laboratory studies investigated the influence of floodplain vegetation on the flow field, sediment transport and sedimentation/erosion processes. The results of the physical models show, that strong interactions between the floodplain flow and the flow in the unvegetated river channel (or main channel) occur. The interactions are characterized by a strong turbulent exchange and secondary currents. These effects are generated at the edge or banks of the floodplain and expand far into the open main channel. As a result, the turbulent shear stresses and erosive forces acting on the river bed are increased.

In the experiments on riparian morphology, the sediment transport rates in the main channel were increased up to more than 100 percent in the case of a narrow main channel with dense vegetation on both banks compared to a scenario without vegetation. The strength of the exchange processes is related to the plant properties as shown by the experiments at Karlsruhe. Waving motions of emerged flexible vegetation caused an increase of the strength of secondary currents, whereas the compression and waving of foliage had a damping effect. Besides, local morphological changes such as sand ridge ("Rehne") formation on the banks are generated by the flow interacting with the vegetation. In nature, sand ridge formation has been observed as an important initial state of riparian succession. Willows find excellent growth conditions on the ridges and stabilize the sediments by their roots. Therefore, additional experiments investigated the influence of dense vegetation strips on the banks. It was found that significant damping of momentum exchange and sediment transfer between main channel and floodplain occurred. In such way, the sand ridge formation is a self-stabilizing reaction of the bed and floodplain morphology towards an equilibrium stage.

Roughness and Flood Protection

According to the classification in Figs.1a-d, the roughness of single plants is dependent of the plant properties interacting with the flow. Hereby, the flexibility of stem, branches and foliage plays an determining role because it enables the plants to streamline and reduce their frontal area and consequently the exerted hydraulic forces biologically. This phenomenon was investigated at large-scale flume experiments with natural willows at Trento, at the River Wien and at the field measurements at the upper Rhine. The willow is a typical and frequent representative of softwood riparian forest and highly adapted to the flow and sediment dynamics of its habitat and was therefore chosen as the ideal test plant. In general, all measurements could prove that vegetation causes an increase of roughness and consequently decreased mean velocities and the discharge capacities. The maximum reduction of flow velocities at the river Wien (*submerged conditions*) and at the Upper Rhine (*emerged conditions with bottom flow*) was found to be 30-45 percent compared to un-vegetated conditions. Even if the flow conditions were different, the flow was decelerated significantly for both cases and in the same order magnitude. This deceleration can also be expressed as a Strickler resistance coefficient that covered a range between 19 and 32 $m^{1/3}/s$ in the Trento flume experiments. The spread of the values proves that the resistance is not constant but a function of the relative submergence and plant density. Higher values of relative submergence and lower plant densities caused lower hydraulic resistance. In the experiments, bending started at flow velocities of about 0.15 m/s until the plants reached their maximum submerged compression at about 0.6 m/s. This streamlining effect lead to a reduction in total drag forces of about 80 percent for a single plant. Furthermore, it could be shown that a removal of leaves reduced the drag forces up to 25 percent for maximum compression and 75 percent for low velocities before bending occurs. This implies the significant contribution of foliage to the overall plant resistance and its seasonal dependency. Besides, the vegetation vitality and properties were observed to change in short-term during flood events. Submerged grasses at the Upper Rhine decreased their flexibility and roughness due to longer inundation and showed stronger bending at the run-off phase of the flood wave. Furthermore, the trapping of driftwood and floating woody debris by the vegetation were found to influence the streamlining. Accumulation of floating debris increased the frontal area and drag of willows and caused bending at earlier stages of the flood. In the case of rigid emerged plants where no bending occurred, the accumulation lead to a significant increase of roughness and induced in some cases bottom flow conditions below the debris that was deposited in the height of the water level. Models to predict the streamlining effects of various types of vegetation and the reduction of frontal area and drag forces have not been established yet. Hereby, the biggest difficulty is a physically-based description and quantification of the complex vegetation properties and structures. Therefore, flood prediction focused on large-scale models and roughness estimations that integrated the above mentioned local effects. For this purpose, a 1D unsteady numerical model was developed and tested at a 28 km long reach of the Upper Rhine. In the model, the calculated from vegetation density and stem diameters as well as the width of the vegetated floodplain were varied. The results could show that denser floodplain vegetation has no significant influence on the flood hydrograph and peak discharges and causes only a small retardation of the flood wave. The reason for this is that floodplains with riparian forests that are adjacent and directly connected to the river are already inundated when the flood peak arrives and thus do not contribute as storage reservoirs. Consequently, the value of riparian forests as flood protection measures is strongly dependant of their lateral and longitudinal extensions and the resulting inundation dynamics.

Floodplain Ecology and Riparian Succession

The ecological importance of riparian forests and floodplains as buffer strips for wildlife habitats, groundwater protection and prevention of pollution is well known from literature. Therefore, one part of the ecological work within the project was directed towards the determination of the ecological functionality as a key aspect of riparian forest. The analysis of leaf-pack processing, short-term retention of organic matter and benthos sampling introduced quantitative and practicable methods to fulfill these objectives. Additionally, the fluvial functioniong index (FFI) was introduced to include descriptive qualitative analysis of larger river systems. These methods provide a broad insight in riparian ecology, its actual state and deficits and were applied succesfully for the rivers Fersina and Enz. The second ecological workpackage was the characterisation of stages of succession of riparian forests and its prediciton exemplarily at the Upper Rhine. In such way, the hydraulic and morphological field investigations were complemented with botanical studies of the vegetation. These studies showed that the succession of riparian floodplains with limited lateral extensions (below 150 m) is strongly influenced by the flow and sediment dynamics in exchange with the river. Hereby, different factors were identified: primary the flow velocity and water depth, secondary the formation of virgin soils by sedimentation, settlement and germination conditions. Only flow-adapted species were able to withstand the direct hydraulic stresses and drag forces. The most frequent one was the white willow. These species is able to streamline and to decrease the exerted stresses biologically. Nevertheless, damages and fractures occurred after exceeding critical stresses but due to the secondary mechanism of re-lignification the willow mortality was low. But it shows that the succession at the Upper Rhine gets hardly beyond the stage of softwood riparian forest even if the flood duration would allow formation of hardwood forest. Additionally, the formation of dense reed layers on the virgin soils where erosion/sedimentation occurred was found to prevent the succession of trees. Reeds establish at many sites and were even able to form permanent communities supported by the sedimentation and decrease of bed shear as already mentioned above for submerged flow conditions.

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1. INTRODUCTION

The present final scientific report is a summary of the research activities within the workpackages of the project partners covering the whole three year period of the project. It presents the objectives, work and results archieved during its lifetime and reflects the collective efforts made by all partners.

1.1 Objectives and Achievements of RipFor

The RipFor - Project was concerned with the optimisation of Riparian Forest Management, with special regard to hydraulic and sedimentary problems occurring in floodplains. The influence of riparian forest vegetation on the overall flow field and sediment erosion/deposition were studied. Guidelines were worked out for the implementation of new floodplain forests and the management of existing ones: Retention of high floods, protection of river banks, improvement of water quality, habitats for plants and animals, recreational areas for the local population are important aspects which were included in a multifunctional riparian forest management.

Field work was directed to describe the hydraulic conditions inside riparian forests, roughness, erosion and sedimentation. This was achieved by flow field measurements, surveys of channels and sediments and sediment sampling. Results included analysis of data sets of hydraulic and sedimentary processes from laboratory experiments, physical and numerical modelling and flood protection planning.

An important measure was the reduction of flow velocity forced by vegetation. Investigation took place not only in the Upper Rhine but also during phases of artificial floodings in the vegetated channel of the Wien river. The analysed data sets can be used for planning of river reaches in open landscapes and urbanised areas.

Laboratory work investigated the effective resistance of individual plants, the resistance of flow through riparian forests and resistance coefficients of the interface between the flow in the main channel and the riparian forests; work was carried out by use of a flume adapted for measurements with clear and sediment-laden water. The results were analysed by numerical modelling and validated by comparison with data measured under natural conditions.

Physical modelling was directed to measure the resistance of single plants, the interaction of vegetation and sediment transport and work with a simplified model of the Wien river. Data sets included flume experiments using different types of artificial vegetation on river beds and banks. Data sets of the Wien river model were used for analysis, for numerical modelling and for planning of renaturalisation of rivers.

Numerical modelling was directed to the simulation of the flow field in riparian forests by a 3D model. The model was used for analysis of project results and impacts of riparian forest management. Furthermore, the simulation of flood wave propagation along a river with riparian forests was achieved by a 1D model. Model results can be used for the optimisation of riparian forests retention measures.

Ecological field studies were arried out for organic material retention and processing, macroinvertebrate habitat studies and mapping of the ecological functionality of streams. This work was concentrated on the Fersina torrent. Data sets were used for water quality monitoring and for riparian management studies.

Riparian forest management focused on interactions between fluvial processes and riparian forests, which were investigated by studies of forests at different field sites and types of vegetation, their distribution and hydraulic resistance parameters. These results form an essential part of the guidelines in view of sound ecological constructions of flood control works and maintenance of rivers and riparian forests.
The guidelines form a separate and stand-alone document and contain an elaboration of project results for the optimisation of riparian forest management, with a special focus on hydraulic and sedimentological problems. The guidelines were developed on the basis of essential project results. They are directed to authorities, agencies involved in flood protection, landscape planning and forestry.

1.2 Structure of the Final Scientific Report

Chapters and Subchapters
The present report includes the chapters:

1. INTRODUCTION
2. MATERIAL AND METHODS
3. RESULTS AND DISCUSSION
4. CONCLUSION
5. EXPLOITATION AND DISSEMINATION OF RESULTS
6. POLICY RELATED BENEFITS
7. LITERATURE CITED
8. PUBLICATIONS AND ABSTRACTS

At the end of Chapter 4 ("CONCLUSION"), a summary and synthesis of all achieved results was made. The synthesis reflects the following RipFor key aspects:

- Floodplain Stability
- River Bed and Bank Stability
- Roughness and Flood Protection
- Floodplain Ecology and Riparian Succession

Subchapters, Workpackages and Responsibilities
To get a clear structure of the linked work, the initial workpackages have been re-combined into the following subchapters:

Subchapters in the final report;
Initial workpackage (WP):

1. Field Work at the Upper Rhine (FS1): WP1.1 and 1.2
2. Field Work at the Wien River (FS3) WP1.1, 1.2 and 1.3
3. Field Work at the Fersina (FS4) and Enz River (FS2) WP4
4. Flume Experiments on Riparian Flow Field WP2.1
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9. 1D Numerical Modelling of Flood Wave Propagation WP2.3
10. Riparian Succession at the Upper Rhine (FS1) WP1.1

The responsible partners for the workpackages were:

WP1.1	FUB – Freie Universität Berlin, Institute of Geographic Sciences
WP1.2	FUB – Freie Universität Berlin, Institute of Geographic Sciences
WP1.3	BOKU – University of Natural Resources and Applied Life Sciences, Vienna - Department of Soil Bioengineering and Landscape Construction
WP2.1	UNIKARL – Universität Karlsruhe, Institut für Wasserwirtschaft und Kulturtechnik
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WP4	APPA – Agenzia Provinciale per la Protezione Dell'Ambiente, Trento

WP5 ("RIPARIAN FOREST MANAGEMENT") and WP6 ("GUIDELINES") are not included here, because they form a separate, stand-alone document that was created parallel to this final scientific report.

2. MATERIAL AND METHODS

The development of *guidelines for riparian forest management* as a main objective of the project implemented the use of material and methods that had to be comparable and transferable to a wide range of practical applications. RipFor met these concerns by researching on various scales and geographic regions and employing multi-disciplinary approaches and scientific methods. Within RipFor, *field* and *laboratory work* as well as *numerical modelling* were linked to provide a profound insight into riparian forest related processes. The following field sites were chosen to cover various categories of land-use and function at different scales:

- a reach of the Rhine river south of Breisach (Germany, macro-scale)(FS 1)
- a reach of the Enz river (Germany, meso-scale, rural environment) (FS 2)
- the Wien river (Austria, meso-scale, urban environment) (FS 3)
- the Fersina torrent (Italy, micro-scale, mountainous environment) (FS 4)

The *field work* was directed to describe the hydraulic conditions inside riparian forests, particularly with regard to flood protection, river morphology, bank and floodplain stability. Hereby, the methods applied form the partners ranged from flow field measurements, mapping of vegetation to surveys of channel geometry and sediment sampling. Important tasks were the characterization of flow velocity reduction forced by different types of riparian vegetation. Field measurements took place at a large-scale test site at the Upper Rhine (FS 1), and in smaller scale at the vegetated experimental flume at the Wien river (FS 3). Complementary studies of the succession and growth of riparian vegetation and plant communities were drawn up at both sites.

Furthermore, ecological field studies were carried out to determine organic material retention and processing, macroinvertebrate communities and the ecological functionality of streams. This work was concentrated on the Fersina torrent (FS 4), with additional studies on the Enz river (FS 2).

Laboratory work focused riparian forest relevant processes in more detail, such as the effective resistance of individual plants, the flow field within riparian forests and the exchange processes between the flow in the main channel and in the riparian floodplains; the work was carried out at the partner's facilities and by use of physical models adapted for measurements with and without sediment feeding. The physical models employed different types and stages of succession of riparian vegetation representing scenarios at the Upper Rhine (FS 1) and the Wien river (FS 3).

Numerical modelling was applied to simulate the flow field in riparian forests by a 3D model and the propagation of flood waves by a 1D unsteady model. Validations were carried out using laboratory data of flume experiments for the 3D model and field data of the Upper Rhine (FS 1) for the 1D unsteady model.

2.1 Field Work at the Upper Rhine (FS1)

Flow Field Measurements

Intensive study of past flood events and consultation with competent authorities revealed several problems for field-work during the planning stage. This was primarily due to the fact that this specific type of measurement has rarely been attempted. The particular characteristics of the Rhine and the ensuing provisions relating to activities allowed by the competent authorities during flood periods also posed a lot of problems. The assessment of the situation was based on historical data and contacts both with the competent authorities and people living in the immediate vicinity of the test site. This analysis showed the unpredictability of flood events, the danger of severe and extensive damage to the instrumentation by driftwood, the rapid increase in water levels and the extent of changes in water level. As a consequence the design of the instrumentation has been adapted to these specific requirements. It was necessary to develop and design instrumentation able to resist high current velocities and huge amounts of driftwood. As the flood plain is a high-risk area during flood events, a device is needed to control instruments remotely for safety reasons.
To investigate the influence of young flexible trees on the flow field and the interaction between the floodplain and the open channel one ADCP was mounted inside a willow grove close to the main river. The second ADCP was installed in the floodplain more close to the embankment at a spot covered by grass only, namely Phalaris arundinaceae. The design of experiment allows comparative studies of flow fields under the influence of different types of riparian vegetation at these two locations inside the floodplain.
The measurement is based on the principle of the Acoustic Doppler Profiling. The ADCPs measure at two different locations in the floodplain the water velocity in three dimensions over all the flood period. To carry out measurements the minimum height of the water column must be almost 100 cm. The water column over the ADCP will be subdivided into cells of a single height of 10cm. The first depth cell is at 70cm. At each cell the direction and speed of water and the magnitude of velocity and direction is recorded over an interval of 15 minutes. During this period 2000 single measurements (so called pings) are carried out. For each interval an average value are calculated. Intervals, cell size, pings and range of the beams can be changed according to the flood phase.
Due to the installed technique accurate information are obtained both about vertical changes of velocity and direction in the water column -caused by different types and properties of vegetation- and as well about very low water velocities at the end of flood events. This will lead to an improved understanding of boundary conditions for discharge and sedimentation respectively erosion processes in riparian forest at different stages of floods and enabled us to study the resistance of discharge flowing through riparian forest under non-stationary conditions, for longer periods and with respect to differences in the flow field caused by willows and grass
After completion of the installation several investigations of the flow fields were carried out during the flood period in spring and summer 2001. The first measuring period could be completed in summer 2001. A second one could be realized for the flood period in 2002.
The WSA Freiburg provided the project with data sets of the gauging stations Rhein-weiler (2000, 2001, 2002), which is located about 20 km upstream of the test site. Therefore a comparison could be made

between the upstream and the local water level records to check the quality of flow field data sets.

Monitoring of vegetation and flow field is realized by a digital video camera mounted on the embankment at a height of 4 meter. Every second one monochrome picture of the floodplain was recorded. The picture shows the area where the ADCPs are located. The pictures are saved as jpg-files and are compared with velocity data to examine at which velocity, discharge and water level the willows submerge and when the flexible branches of the trees will be compressed by water. The pictures are used for an on-line monitoring of water level and changes in vegetation during and after flood periods.

Sedimentation and Erosion

After each flood period geodetic measurements of riparian forest topography, geomorphologic mapping and roughness measurements were carried out. Sediment samples were taken and analysed in the laboratory.

Special attention was given to sedimentation during floods by applying sediment traps and sediment samplers at different locations in the riparian forest (FS1). The amount of sediment traps was depending on the homogeneity of the test site. According to conditions 30 sediment traps were installed and sampled and 3 sets of roughness measurements in terms of geodetic surveys were obtained at FS 1 for all remarkable flood events. The experiences of the first field campaign lead to redesign of the traps and scour chains. As a result 120 new sediment traps (30 locations, each with 4 traps), 30 scour so called "Leopold chains" and 90 measurement points in 10 transects (30 locations, each with 3 fixed pools) for total erosion and sedimentation were installed in spring time at test site FS1. The sediment traps were of 5.5cm height, 9.5cm width, and 19.5cm length and had a surface of 185.25cm^2.

Sediment Traps

At the beginning of the field campaign samples were taken at the site and grain size distribution was examined with a view to establish the micro-level roughness of the sediments on the test field FS1 in summer 2000. The sediment traps, Leopold chains, and the fixed pools were investigated after the flood in summer 2001, 2002 and winter 2002 /2003. At all locations the height of sedimentation and erosion was measured, statistically analysed and compared with the results of the geodetic surveys. In the lab wet and dry weight, grain size distribution and water content of samples from 120 locations (sediment traps) of the floodplain were analysed.

Geodetic Survey

As a first step and before the flood events in 2001 several geodetic surveys were carried out between summer 2000 and spring 2001 to describe the actual situation of topography and morphology. A topographical map has been designed based on these first data.

In late autumn 2001, in summer 2002 and in winter 2002 /2003 – always after the bigger flood events- these surveys were carried out again to examine changes in topography in between the years 2000 and 2002. Data sets were checked and analysed. Based on the comparison of all data sets differences in height before and after the flood periods in 2001 / 2002 could be calculated.

These data and maps were merged to generate maps of erosion and sedimentation in comparison with the situation in 2001. The data of the geodetic surveys were used to detect changes in volume, the total gain and loss of material under influence of flow field and vegetation and for the calculation of sedimentation rates for the last 2 years along cross sections and for the complete test site. These data were compared with the data sets of the sediment traps. Based on this information both the micro scale and meso scale dynamic of erosion and sedimentation under the influence of topography and vegetation could be described and analysed.

2.2 Field Work at the Wien River (FS3)

Introduction

The Wien is a river of not more than 34 km in length, partly flowing through an urban area, and it has the discharge regime of a torrent. A soil-bioengineering test flume was constructed in 1996 to assess the stability under load for the different soil-bioengineering structures and the hydraulic action of the vegetation (Gerstgraser, 2000). Artificial flooding allows observing the distribution of the flow velocity. Velocity profiles show the difference between the open channel and the vegetated bank. Long-term monitoring of the growth of local riparian vegetation allows an assessment of its influence on the discharge capacity. The soil bioengineering test channel is located directly in the Wien river bed at the outskirts of the City of Vienna.

Construction

The construction of the test flume began in 1996 with the construction of a run of sheet piling that divides the test channel into two

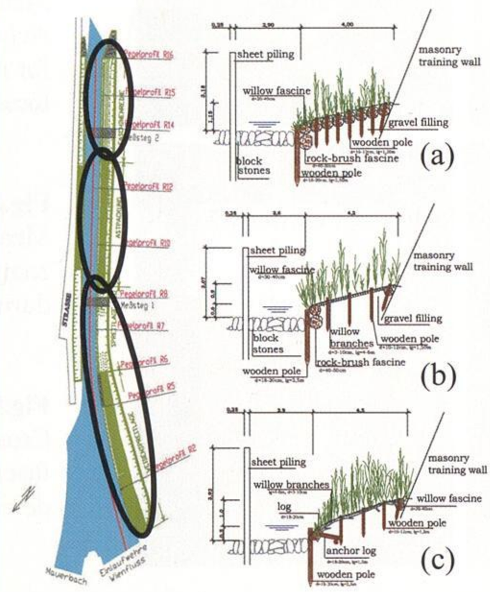


Fig.2 (top left): Construction phase of the test flume

Fig.3 (top right): schematic view of the test flume and the soil-bioengineering measures:
(a) Fascine layer
(b) Branch layer and
(c) Brush mattress with willows

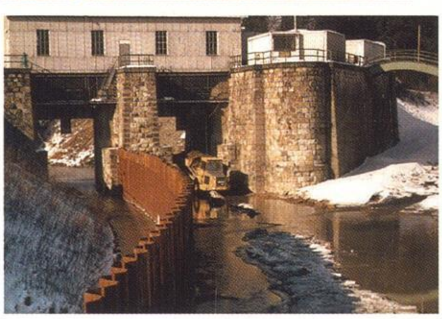


Fig.4 (left): Construction of the test flume: upstream view towards wicket dam and sheet piling

Fig.5 (right): The test flume after completion: downstream view parts which can be flooded separately. It was completed in 1998 with the construction of three soil bioengineering structures done jointly with students of the Vienna University of Agricultural Sciences (Figs.2-5).

Artificial Flooding

Artificial floods are obtained by opening a weir which is located just upstream of the test flume and which serves as a wicket dam of a 350.000 m³ retention reservoir. During flooding, a discharge of 20 to 35m³/s can be achieved for 40 to 60 minutes. This enables researchers to observe the distribution of the flow velocity in both the vegetated and the bare part of the cross-section. To this end, acoustic Doppler velocimeters and acoustic Doppler profilers are used and controlled from a measurement bridge (Figs.6-9).

The discharge Q is a function of the water level in the retention reservoir and the opening height of the weir. The discharge coefficients to apply an analytical formula for discharge calculation were known from a physical model, representing the orifice geometry and the overflow situation. In addition, the water level in the test flume is observed during the floods at five cross-sections.

Fig.6 (top left):
Measuring devices: acoustic Doppler profiler used top-down for vertical velocity profiles

Fig.7 (top right):
Measuring devices:
Acoustic Doppler velocimeters used for point-measurements at different locations in the cross-section

Fig.8 (left):
Measuring bridge with signal analyser equipment at profile 15 during a flooding campaign

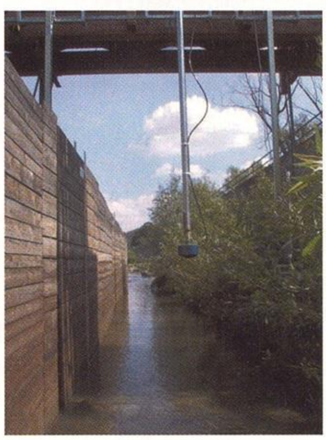


Fig.9 (right):
Cross section at profile 15 (within fascine layer) with the measuring devices

Monitoring of the Riparian Vegetation

In order to describe the interaction between vegetation and hydraulic parameters it is necessary to characterise the vegetation, to measure relevant parameters and to observe its development over several years.

Relevant parameters that are collected once a year are given below:

- the botanic species,
- the location (geodetic survey),
- the shape of the crown and its maximum extent,
- the tilt or inclination in degrees,

- the basal diameter and the diameter at a height of one metre,
- the height at the beginning of the crown,
- the length (top height of the trees),
- the number of shoots per plant and per m^2 or density (with a scale form 1 to 5),
- the flexibility (with a scale from 1 to 5),
- the vitality (with a scale from 1 to 5).

Comparing these annual data provides an overview of the development of the bank vegetation. Typical types of damage to the vegetation are valuable clues to the plants' loading capacity and therefore documented precisely. Typical growth forms indicate the plants' strategy to cope with the load applied by the drag force of the water.

2.3 Field Work at the Fersina (FS4) and Enz River (FS2)

Objectives

The structure and composition of lotic macroinvertebrate communities are known to depend on both biotic and abiotic characteristics of stream habitats (Resh & Rosenberg, 1984). The River Continuum Concept (Cummins, 1974) of the stream ecosystem describe the role of allochtonous organic and nutrient input and autochtohonous production to maintain the quality of running water life, and also describe the increase of structural and ecological complexity from the upper to the lower reaches. Litter is one energy source for streams providing various food source, and habitat for aquatic invertebrates (Lopez, 1997), and the presence of vegetated river banks is very important to guarantee an high functional level of stream ecosystem. Litter production, decomposition and transport are the main processes in river corridor (Malanson, 1993), and the composition and richness of riparian forestry are related to litter distribution in the river. The main objectives of this part of the project are to evaluate the relationship between vegetated riparian zone and ecological functionality of the running water. This research was planed considering different approaches of study, which are able to describe:

- the importance of litter fall as food source of macroinvertebrate community using leafpack method,
- the capability of river to impound the litters under large stones, cobbles, pebbles, and so to evaluate the organic matter retention ability
- the functional capability of river ecosystem using FFI method
- the composition of macroinvertebrate community

The results should provide useful information to river managers and end-users for a better and integrated approach to plan interventions on river banks considering the hydraulic and ecological requirements.

Evaluation of Stream Ecological Aspects using Short Term Retention Measurements

The process of retention is based on the immediate trapping of coarse organic matter, e.g. leaves fallen in the river, and their successive storage of the material for a long term. Retention can be measured as the quantity of material transported in a range of stream compared to the initial quantity of the material released in the stream. For this study we use leaves of *Ginko Biloba*, because it's an exotic plant and its leaves have a particular shape and maintain the yellow colour for a long time, for this reason these exotic leaves cannot be confused with autochthonous leaves. The leaves were soaked before being used because dry leaves float on the surface of the running water and cannot be trapped by the streambed under cobbles, boulder and bedrock. We release one thousand leaves at the top of a stretch of river of 100 meter, and we count the leaves that arrive at the transverse end line of the stretch, after 1, 2, 3, 4, 7, 10, 15, 20, 40 and 60 minutes after the release. In this way is possible to compare the retention of each site and to elaborate some hypothesis on retention feature.

"Leafpack" Methodology

For the formation of the leafpack (called LP) alder (*Alnus glutinosa*) leaves are used because it is a riparian plant and the leaves are rapidly demolished. The leaves, after complete dehydration in oven at 40°C, are made into packs weighing 5 ± 0.1 grams. The LPs prepared like this are taken to the site of the investigation and softened with stream water. Subsequently some LPs (around 7) are fixed with plastic staples onto nylon chords. In each site 5 chords with the LPs are anchored onto the bed. In total 35 LPs per site are positioned whereas 5 LPs are inserted into plastic sacks with stream water to determine leaching after 48 hours in the laboratory. At weekly intervals 5LPs are removed, one for each chord, collecting everything with a small-meshed net (200-300µ). The washed leaves are then dehydrated in oven at 40°C. The weight of each dried LP is measured with a precision of ±0.1 grams. As temperature influences the processes of bacterial demolition, at the moment of sampling the temperature of the water is ascertained and then transformed into degree/day, multiplying the average daily temperature for the time between two samples. The LP weight data is worked out as indicated in literature (Peterson and Cummins, 1974), using the following calculation:

$$Wt = Wo*e^{-kt}$$

Wo = initial weight (grams)
T = time (days)
K = leaf demolition constant

From the previous relation one obtains:

$$K = -t - In\ (Wt/Wo)$$

And the value of the daily % loss:

$$Loss\% = (1-e^{-k})*100$$

These LPs simulate the importing of leaves which may enter the river ecosystem, offering an aggression site by fungi and cellulosolitic fungi and bacteria capable of softening the foliar tissues. The leaves thus softened are colonised by the macrobenthos which recycle the organic material.

Benthos Quantitative Sampling

With this methodology abundance of macrobenthonic community can be correlated with a fixed area of the riverbed. Quantitative sampling allows population dynamics and productivity estimates. Reliability of mean density estimates depends on a great number of variables, such as number and size of samples, substratum typology or macrobenthos distribution on the substratum. Choice of sampling sites is made in areas where substratum is homogeneous.

For quantitative sampling on compact substrata Surber is the most used sampler. Macroinvertebrate quantitative collection consists of jabbing the Surber sampler in the riverbed. Surber is thrust into the target habitat and cobbles present into surber are swept and cleaned for a fixed period (5 minutes). Collected organisms were preserved in 70° Ethanol. For each sample individuals were sorted, classified using taxonomic keys and counted.

Morphological and Ecological Features (FFI - Fluvial Functioning Index)

The FFI is a development of the RCE-2, the first draft of which was drawn up by Siligardi and Maiolini (Siligardi & Maiolini, 1993) which in its turn derives from the Riparian Channel and Environmental Inventory (RCE-I) drawn up by Peterson from the Institute of Limnology of Lund University (Peterson, 1990). RCE-I was initially created as a proposal for the drawing up of an inventory for the state of the sides and banks of rivers. Only later, after many applications, was the importance that this method could have as a model for the determination of environmental quality recognised.

The FFI record was further refined and foresees 14 questions, with 4 predetermined answers to each question, concerning almost all the ecological characteristics of a watercourse. The answers have a numerical expression by classes of numbers with a minimum of 1 and a maximum of 30, capable of expressing the qualitative differences between individual replies. From the mathematical point of view there is no justification of the attribution of the numeric weight of the answers, but only statistical-ecological motivations which are based on the mutual relations existing between the concepts contained in the answers, making the method substantially more stochastic and less deterministic.

The FFI record is thus made up of a series of questions which embrace several subjects concerning the natural state of the watercourse and linked between each other in such a way as to make the record balanced.

The compilation of the record terminates with the calculation of the sum of the different weight given to the answers identified (one is compulsory for each question) and hence with the definition of the SCORE which may go from a minimum of 14 to a maximum of 300 and which has been translated into 5 quality classes, giving each a rating and a colour according to the points band, with the scope both of illustrating a map and of making interpretation easier also for those not in the field.

Monitoring and Guidelines at the Enz River (FS2)

The Enz River contributed as an excellent example for river and floodplain restoration and maintenance. Situated in an urban area of the city of Pforzheim, a reach with former double-trapezoidal cross section of about 1500 m was renaturalised in 1990. Periodical monitoring of vegetation growth and maintenance (photographs), morphological changes (geodetic surveys and photographs) and hydrology (data from multiple pressure gauges and a fixed gauging station) was undertaken. In such way, the experiences from the renaturalisation were analysed and presented as a case study within the RipFor-Guidelines.

Morphological and Ecological Features at the Enz River (FS2)

Additionally, the FFI (Fluvial Functioning Index, see previous chapter) method was applied for the first time at the river Enz. In spring 2002 the whole urban reach as well as the upstream tributaries (Grosse Enz and Nagold) were analysed in longitudinal steps of 300-1500 m.

2.4 Flume Experiments on Riparian Flow Field

Introduction

The present study (RipFor WP2.1) focuses on the interactions between flow and vegetation, covering two basic aspects. First, how floodplain vegetation influences the integral flow field and secondly, how the hydrodynamic feed-back changes shape and structure of vegetation. Therefore, a physical model of a river-floodplain system with half-trapezoidal compound channel cross section was constructed at the Theodor-Rehbock laboratory at the University of Karlsruhe. The geometry, longitudinal slope and discharges were transferred from field data in order to keep the comparability to a simplified scenario at the Upper Rhine near Breisach, Germany. Special regard was given to the occurrence of high water levels that differ significantly from lowland river characteristics. The aim of the experiments was the characterization of the turbulent exchange processes and its impact on the flow velocities in the transition from the open main channel towards the flow through riparian forest. Hereby, different stages of succession were modelled using simple approaches that take into account changing flexibility and spacing of individual plants. The results provide a better insight for the Upper Rhine but are also relevant for similar geometries, vegetation and flood dynamics.

Interaction Phenomena

Compound channels are characterized by a change of roughness and water depth across the channel resulting in strong gradients of the mean flow velocity. The low velocity floodplain flows are dominated by the large roughness generated by the vegetation and lower water depths than in the open main channel. Between these two sections a region with strong momentum exchange and production of coherent turbulent structures occurs, where the velocities are decelerated in the main channel and accelerated on the floodplain. This region is known from literature as interaction zone or apparent shear layer. Many researchers have investigated the interaction phenomena. First, Zheleznyakov (1965) and Sellin (1964) visualized horizontal vortices with vertical axes along the shear layer as the basic mechanism of transfer of momentum (see Fig.10). The dimensionless relative water depth h/H [-], where h [cm] is the water depth on the floodplain and H [cm] in the main channel, was found as the primary parameter for the momentum exchange and strength of the vortices. In the majority of experiments, only small relative water depths and smooth floodplains with homogenous bed roughness and no vegetation were considered. Recent studies of Nezu et al. (1999) could show for a similar geometry without vegetation on the floodplains, that for higher water depths (h/H>0.625) the influence of the horizontal vortices decreases and secondary currents and a strong 3D-

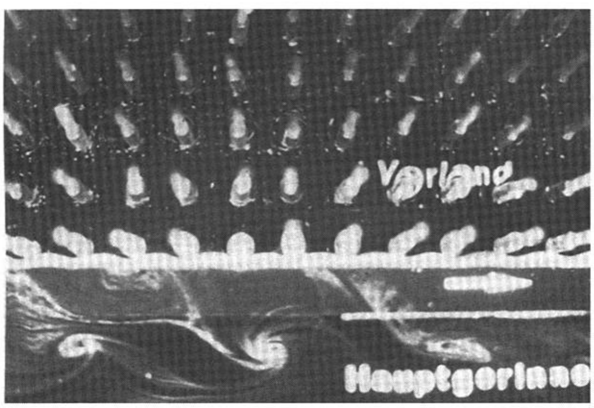


Fig.10 Photograph of interaction phenomena: horizontal vortices with vertical axes for vegetated floodplain and small relative water depths (Pasche, 1985)

vorticity dominate the exchange of momentum (Fig.11). Most of the experiments referring to these effects were carried out using rigid cylinders for small floodplain water depths and did not count for high relative water depths and flexible vegetation properties that are relevant at the Upper Rhine.

Floodplain Vegetation and its Properties
Vegetation along the floodplains of rivers has an important influence on morphology and hydraulics. Basically, vegetation under a hydraulic point of view can be classified as two different categories: flow above relatively short and highly flexible vegetation that is submerged and flow through tall non-submerged vegetation dominant (Kouwen, 2000). For flow through homogenous, woody riparian forest the non-submerged vegetation is assumed to be more relevant because the pressure drag forces exerted by the trees are much higher than the surface friction.

Up to now, the major problem with flexible vegetation is that no reliable methods are known to describe their physical behaviour properly due to hydraulic stresses. This lack of information is caused by the complexity of the vegetative macro-structures such as patchiness, density and succession as well as the micro-scale structure of leaves, branches, stems and the difficulty to put it into physical parameters.
Therefore, simplifications were made such as

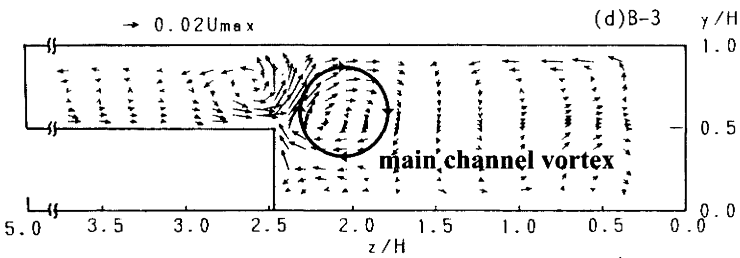


Fig.11 Measurements of secondary currents and typical main channel vortex modified after Tominaga et al. (1989)

where the mechanical plant properties are stiff enough to keep the plants erect. The transition between the two categories is dependant from hydrodynamic properties of the flow (e.g. water depth and mean flow velocity) and bio-mechanical properties of the plants (e.g. stiffness, compressibility of branches and foliage). Flexible bio-mechanical properties allow the plants to streamline and to a biological drag force reduction (White, 1999). On the other hand, in the non-submerged case the pressure drag related to the frontal area of the plants is modelling the vegetation as rigid cylinders that are defined by a certain stem diameter and a longitudinal and lateral spacing between individual plants. Compared to natural conditions, this approach is only valid for homogenous groups of fully-grown trees that are only stem-submerged below the canopy level. The important effects of bending, waving and compression of stem and foliage that occur in nature were neglected. The present study takes into account these properties and introduces measurable physical parameters to define it.

Experimental Equipment: Flume and LDV

A 1:100 scale physical model of a half-trapezoidal compound channel was constructed at the laboratory facility. The rectangular flume employed for the experiments was 1m wide, 20m long and set at a fixed bed slope of 0.001. The compound cross section (Fig.12 refers) was constructed in the rear 9m of the flume with wooden panels. The main channel and floodplain were B=52cm and b=48cm wide, the floodplain elevation was Δz=2.3 cm. The main channel bank slope was set at 1:1. Water was conveyed through a pipe into the headbox passing an electromagnetic currency meter (ECM) for discharge control. The flow was straightened by honeycombs. Uniform flow conditions were adjusted by six separated outfall flaps located at the exit of the flume. The main channel as well as the floodplain were roughened and calibrated equally with PVC granules of 3mm diameter (with an equivalent sand roughness of k_S = 3.6mm).

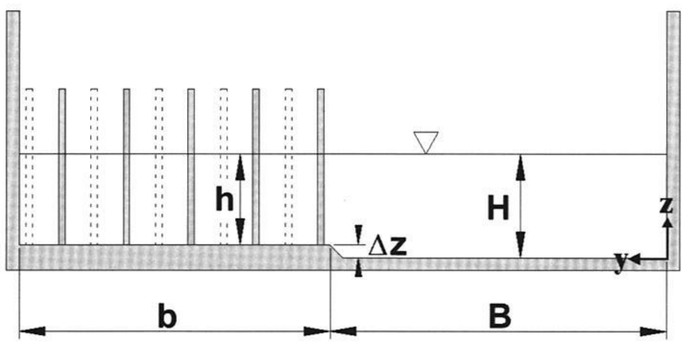


Fig.12 Schematic view of the flume cross section

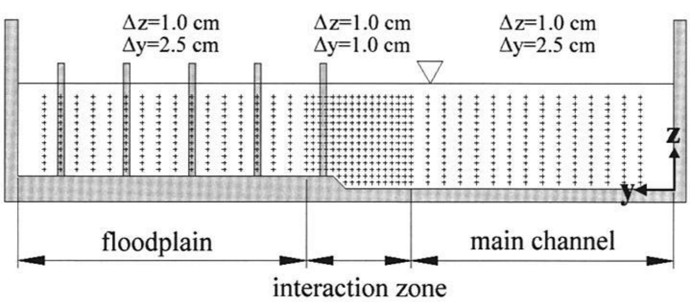


Fig.13 Schematic view of the data collection grid for the different sections

The LDV was an Aerometrics 300mW Argon-Ion fibre-optical LASER system operating in backward scattering mode. The system had two components (4-beam), used down-looking for the longitudinal and lateral velocity components in x- and y- direction. Feeding particles (TiO_2) were added to the flow to obtain valid sample rates within time steps of 60 seconds at each location. The probe head was mounted on a computer controlled rail carriage equipped with a two-axis traversing system to allow precise control in three directions. The LDV measurements were carried out in a way that separated the cross sections into three regions: main channel, interaction zone and floodplain. The grid of data collection points was densest in the interaction zone (0.4m<y<0.56m) with lateral and vertical distances of Δy=Δz=1cm (see Fig.13). In the main channel (0<y<0.4m) and floodplain (0.56m<y<1.0m) a lower density of Δy=2.5cm and Δz=1cm was chosen. Furthermore, several cross sections in flow direction (2 in main channel and floodplain, 4-6 in the interaction zone) were measured to allow spatial averaging of the data and independency from local conditions.

Experimental Equipment: Vegetation Prototypes and Properties

For the experiments, three different types of artificial vegetation (see Fig.14 and Tab.1) were used in two different densities. The first setup (S1) were rigid PVC cylinders of d_S=10mm stem diameter in a staggered pattern, in which each cylinder covered a projected area of 100 cm². This floodplain scenario was chosen as a potential stage of succession at the Upper Rhine. For the second setup (S2), the rigid cylinders were replaced by flexible ones fabricated of foam rubber with sealed, air-filled pores that kept the cylinders non-submerged for all tests. The same rigid and flexible cylinders were used in setup (S3) and (S4) but for a higher density in which each element covered a

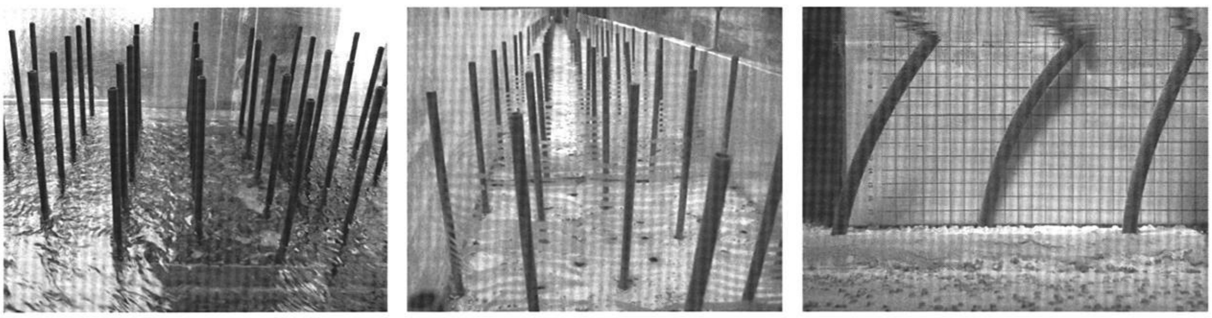


Fig.14 Pictures of the tested vegetation elements (from left to right): rigid cylinders (side view), leafy cylinders (seen in flow direction) and flexible cylinders (side view with cm-grid)

Run	Vegetation	Density	Discharge	H	h/H	Re main channel	Re floodplain	u_{veg}	$\langle u \rangle_{max}$
		[cm²]	[l/s]	[cm]	[-]	10^6 [-]	10^6 [-]	[m/s]	[m/s]
s1q10	rigid	10 * 10	10	7,5	0,77	184	52	0,101	0,245
s1q20			20	11,3	0,83	305	86	0,090	0,270
s1q30			30	16,0	0,87	523	163	0,064	0,327
s2q10	flexible		10	7,1	0,76	172	43	0,054	0,242
s2q20			20	12,3	0,84	365	97	0,096	0,297
s2q30			30	15,5	0,87	491	139	0,097	0,317
s3q10	rigid	5 * 10	10	8,3	0,78	204	39	0,056	0,245
s3q20			20	13,5	0,85	388	94	0,084	0,288
S3q30			30	17,3	0,88	560	137	0,119	0,324
s4q10	flexible		10	8,3	0,78	188	33	0,105	0,226
s4q20			20	13,5	0,85	390	63	0,072	0,289
s4q30			30	17,3	0,88	581	108	0,092	0,335
s5q10	leafy	20 * 20	10	7,2	0,76	180	62	0,127	0,250
s5q20			20	11,4	0,83	334	105	0,116	0,253
s5q30			30	15,7	0,87	513	171	0,127	0,327
s6q10		10 * 20	10	8,2	0,78	212	22	0,038	0,258
s6q20			20	13,4	0,85	407	71	0,064	0,304
s6q30			30	17,3	0,88	585	112	0,074	0,338

Tab.1 Overview of the setups and typical characteristics

projected area of 50cm². Afterwards, the third type of vegetation was developed based on the idea to have a rigid stem structure together with a highly flexible body of foliage. Therefore, stripes of 120µm thick polypropylene foil of 0.5cm width and 11.0cm lengths were glued horizontally on the rigid cylinders. The vertical distance between each stripe was fixed at 0.5cm. Consequently, the frontal area seen from the stream increased considerably for an individual plant. This was counterbalanced by a decrease of the plant density from 100 cm² for the rigid/flexible cylinders (S1, S2) to 400cm² for the leafy ones (S5), respectively from 50cm² to 200cm² (S6) for the setup with higher plant density. In such way, the blockage ratio of the floodplain vegetation defined as frontal area divided by plant density was kept constant in both cases and allowed the comparability of the results.

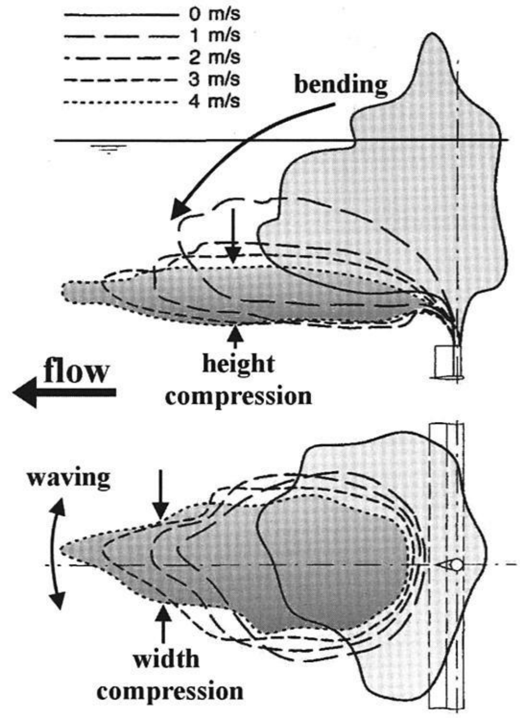


Fig.15 Waving, bending and compression of a young willow for different mean flow velocities modified after Oplatka (1998)

Two techniques were applied to collect data of the floodplain vegetation: head-loss tests to determine the integral floodplain resistance and measurements of parameters to characterize the flexibility of the plants. The head-loss tests included non-uniform flow conditions for various discharges (2.5-15l/s with steps of 2.5l/s) and water depths (5-15cm with steps of 2.5cm). For the tests, the floodplain was separated by a skimming wall from the main channel flow. Head-losses and flow depths were measured by pointer gauges in the centre of the cross sections and at three locations along the flume (x=2, 4 and 6m) and averaged afterwards. The discharge was measured by an ECM (Electromagnetic Currency Meter) installed at the inflow pipe of the flume. The analysis of the data applied the momentum/energy equations and the frontal area of the plants to calculate the drag forces.

The flexibility of the plants was characterized by measuring the feedback impacts caused by the flow. Basically, three different effects occurred similar to natural vegetation: bending, waving and compression (see Fig.15). Parameters that were useful to describe these effects are

Type of vegetation	Setup	Bending / Parameter		Waving / Parameter		Compression / Parameter	
Rigid cylinders	(S1) (S3)	-	horizontal deflection d_h [mm]	-	amplitude A_w [mm] and frequency f_w [Hz]	-	compressed width b_w [mm]
Flexible cylinders	(S2) (S4)	in flow direction (stem)		laterally to the flow (stem)		-	
Leafy cylinders	(S5) (S6)	in flow direction (foliage)		laterally to the flow (foliage)		width compression (foliage)	

Tab.2 Summary of the observed properties and parameters for their determination

given in Tab.2. Hereby, the horizontal deflection d_h [mm] characterized the bending of the stem (flexible cylinders) respectively the deflection of the foliage (leafy cylinders) in flow direction. The value was measured directly at the water surface level with a calliper gauge. The amplitude of waving A_w [mm] represented one parameter for the oscillatory waving motion that occurred for flexible and leafy cylinders. In the first case the maximum amplitudes of the stem laterally to the flow were measured at the water surface level, in the latter the maximum amplitudes of the foil stripes. The compressed width b_w [mm] defined the lateral distance between the tips of the compressed and deflected foliage stripes of an individual plant. The frequency of waving f_w [Hz] was determined by measuring the length of time for a certain amount of swings (about 10-30) by the foil tips and calculating the value of swings divided by the unit time. Data of 10-20 plants located in the centre of the flume were taken and averaged afterwards.

2.5 Flume Experiments on Riparian Morphology

Strong interactions between flow, sediment and vegetation occur in this area and determine the function of the whole riparian system. Thus, laboratory experiments were carried out and existing data from Specht (2002) were summarized and prepared to determine the influence of emerged rigid vegetation of the flow and sedimentation processes in compact and compound channels.

Herein, the interactive zone between the vegetated banks and flood plains and the main channel is of great importance. It is characterized by an intensive exchange of momentum and mass. The vortices (macro turbulence) caused at this zone are as well in a close interaction with the processes on the river bed.

The following hydraulic/sedimentological processes are observed (see Fig.16):

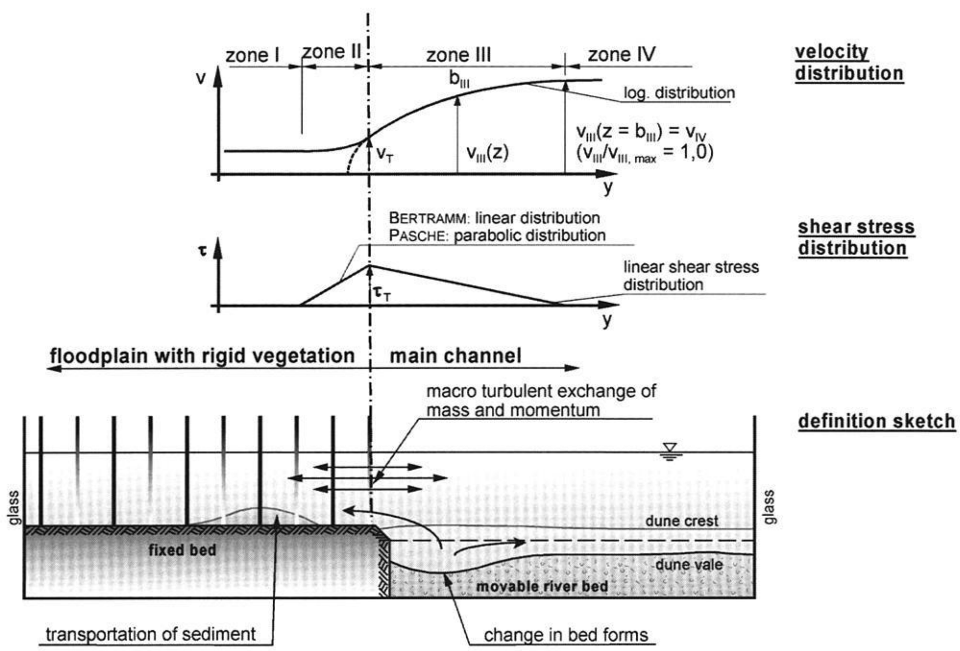


Fig.16
Definition sketch of the influence of flood plain vegetation on the hydraulic/sedimentologic processes

- high shear stresses at the interface between the vegetated flood plain and the main channel
- increased flow velocities and turbulences in zone II of the flood plain
- reduced flow velocities in zone III as a consequence of the macro turbulence caused by the vegetation
- increase in bed load transport due to the increase in macro turbulence
- change in bed resistance due to change in bed forms
- vegetation dependent sediment transport on the flood plain resulting in the formation of "Rehnen" at the boundary to the main channel

The aim of the study consisted in the following aspects:

- to summarize the results of the experimental work of Specht (2002) concerning the influence of emerged rigid vegetation on bed load transport and bed forms in trapezoidal channels of different width
- to carry out laboratory experiments for the investigation of flood plain vegetation on the transportation/sedimentation processes at the boundary to the main channel ("Rehnen"-formation).

2.6 Flume Experiments on Floodplain Vegetation and Sediment

Introduction: Resistance of Vegetation

In the last decades there has been increasing use of live materials in rivers, such as living bushes, in order to reduce the environmental impact of banks stabilisation. One of the problems due to plants presence is the high resistance to flow that they induce; concerning this aspect, the way to face the problem is quite different depending on the characteristics of the plants. Very short and flexible plants, having height markedly lower than the flow depth, like in grassed channel, can be treated as a wall roughness and the well-known formulas for homogenous roughness, like Gauckler-Strickler-Manning formula or Chézy-Tadini formula, can be used. For forms of vegetation represented by single, or groups of single plants or bushes -both partially and fully submerged- the plants height, h_p, is of the same order of magnitude of the flow depth, h, and, in this case, the combined effect of the hydrodynamic drag of the single plants has to be taken into account for the schematisation and evaluation of the equivalent resistance.

The last schematisation has been suggested firstly by Petryk & Bosmajian (1975); according to them, in case of rigid plants, partially submerged and uniformly distributed along the bed channel, the resistance produced by the single plant is equivalent to:

$$F_i = C_d A_{pi} \rho \frac{V^2}{2} \qquad (1)$$

where F_i = drag force absorbed by the *i-th* plant; C_d = drag coefficient; A_{pi} = area of the *i-th* plant projected in streamwise direction; ρ = mass density of water; V = mean channel flow velocity.

One of the problems of this approach is represented by the definition of the drag coefficient, C_d, and of the reference velocity, V. Often, in order to overcome the problem, the plants are simply regarded as a series of cylinders invested by the flow. However in case of groups of plants the "cylinders" cannot be treated as isolated, and the reference velocity is not the undisturbed one. It is therefore obvious to assume as reference velocity the cross-averaged velocity that, in this case, is in turn affected by plants presence.

Simplified models have been introduced by many researchers, accounting both for fully and partially submerged plants

(Tsujimoto et al., 1992). Among others, is to be mentioned the problem of spatial non-uniformity of the plants and the necessity to properly introduce the dispersive stresses due to the space averaging of the balance equations. (Nikora et al., 2001; Righetti & Armanini, 2002).
Moreover most of the models are usually calibrated on laboratory measurements and their application to real cases is quite difficult. Actually the behavior of real plants is far more complicated to be schematized: the vegetative state of the plant, and hence its height, its flexibility and the foliage diffusion, are fundamental parameters influencing the drag resistance and, till now, have been investigate only marginally.
In this study, to develop a rational method to estimate a drag coefficient in relation with the shape, the dimension and the vegetative state of the plants, a series of measurements of the hydrodynamic strength acting on a real willow, fixed at the bottom of a laboratory channel have been performed. The plants have been studied in submerged and non-submerged conditions, isolated and at different vegetation densities. For the experiments on fully submerged isolated willows, the tests have been repeated with the same plants without leaves in order to appreciate the influence of the foliage, and therefore of the vegetative state, on the total drag. The willows used in the experiments were of the species *Salix Alba*, one of the most used plants in restoration works along rivers and also into the Wienfluss.
The measurements in real (or almost real) scale give also useful information's in order for the choice of the most important parameters to take into account for the physical modelling of vegetation at laboratory scale. Moreover the force measurements allow to separate between the flow resistance due to the plants and the bed shear.

Introduction: Vegetation and Sediment Transport
The influence of vegetation presence on sediment transport is an important aspect that is still not completely debated. Relatively recent studies (Ming Li & Shen, 1973; Haber, 1982; Tsujimoto, 1992; Okabe et al., 1995; Lopez & Garcia, 1998; Elliot, 2000) pointed out the reduction in sediment transport capacity for vegetated bed. In general this reduction can be ascribed to various aspects, such as:
The reduction of the net surface where the sediments exchange between the bed and the flow take place;
The plants drag partially counteracts the streamwise momentum of the flow, so the net shear stress at the bed is reduced.
One possible rational approach on the quantification of the solid discharge in vegetated bed is to modify the classical solid discharge formulae (e.g. the Meyer-Peter-Müller formula for the bed load) introducing suitable coefficients that can take into account the plants presence. Following this procedure, the M-P-M formula can be considered:

$$\Phi = 8\left(\vartheta' - \vartheta_{crit}\right)^{3/2} \qquad (2)$$

where: $\Phi = \dfrac{q_s}{d\sqrt{g\Delta d}}$; q_s is the solid discharge per unit of width; $\vartheta = \dfrac{(u_*)^2}{g\Delta d_s} = \dfrac{h\, i_f}{g\Delta d_s}$ is the mobility parameter of the flow, h is the flow depth, i_f is the bed slope; g is the gravity acceleration, d_s is the grains diameter, Δ is the relative density of the grains; $\vartheta' = \dfrac{(u_*')^2}{g\Delta d_s}$ is the net mobility parameter, that refers only to the grain resistance (see e.g. Yalin., 1977), usually it is experimentally evaluated and can be expressed as a function of ϑ (Engelund, 1966) and can be generalized as follows to the vegetated beds:

$$\Phi = 8(1 - C_v)\,(\xi_v \vartheta - \vartheta_{crit})^{3/2}$$
(3)

where: C_v is the ratio of bed surface occupied by the plants; ξ_v is a suitable correction factor that has to be experimentally evaluated.

The dimensional analysis rule (see e.g. Yalin, 1977; Lopez & Garcia, 1998) suggest that, for vegetated bed, this factor could depends to various dimensionless parameters, among them the *vegetation density* $\lambda_{VEG} = A_{Pi} / a_X \, a_Y$ (where a_X , a_Y are the streamwise and transversal distances between adjacent plants respectively), and/or the *density of plants*, $\lambda = d_P^2/a_x a_y$ (that is surface occupied by the single plant per unit bed surface) play a crucial role. Nevertheless also other dimensionless parameters have to be taken into account (see e.g. Lopez & Garcia, 1998), that can take into account also other characteristics of the plants and of the sediment. A series of experiments has been performed in order to quantify the correction factor and its dependence on the various dimensionless parameters.

Hydrodynamic Resistance of Isolated and Group of Real Plants

Experiments were conducted at the Experimental Centre for Hydraulic Models of "Consorzio Venezia Nuova", in Voltabarozzo (Padova-Italy). The laboratory flume used in the tests is 150 m long, 2 m wide, 2 m deep and the bed and the walls are of concrete, except for a length of 12 m where one of the two banks is made of glass. The final section of the flume ends with a rectangular adjustable weir. The water flows through a closed circuit by means of a group of four electro-pumps, up to a maximum discharge of 1.5m^3/s. The discharge is measured by means of an electromagnetic flow meter.

The forces acting on a single real willow both totally and partially submerged were measured. A force transducer that could work completely submerged was therefore designed, assembled and calibrated. The transducer could be fixed at the bottom of the laboratory channel, while the plant had to be blocked on the cylinder placed on the superior plate of the sensor. In this way, if the plant was perfectly integral to the cylinder, the strength that acted on the tree was totally transferred to the superior plate and then to the four aluminium foils, causing their deformation and therefore, throughout a Weatston bridge, to measure the force. The force transducer was fixed at the bottom of the laboratory channel and it was carefully surrounded with sand, gravel and concrete in order to avoid any discontinuity in the bed channel and consequently in the flow field.

The experiments were carried out using willows of the species Salix Alba, since these plants are widespread along watercourses, both because of their natural diffusion and of their increasing use in the bioengineering management of the rivers. Two series of measurements were performed, the first series on isolated willows, and the second series on willows uniformly distributed along the bed, at two different vegetation densities: $\lambda_{VEG} \cong 0.0006$, and $\lambda_{VEG} \cong 0.0014$ respectively.

Concerning the force measurements on isolated plants, they were performed on several plants, which could be divided in two groups according to their height, h_p. The plants of the first group, later on called "tall Salix", were all slender willows high more than 2.5 m. The average diameter of the main trunk was between 15 and 20 mm. The willows belonging to the second group were obtained by cutting the top of other plants, for an approximate length of 1 m, in order to achieve smaller plants, with weaker, and therefore more flexible, branches and thicker foliage. The geometrical characteristics of all the plants were carefully measured, registering height and diameter of the main trunk and dimensions and position of the principal and of the 2nd order branches, related to the base.

Effect of Vegetation Presence on Sediment Transport

The experiments are performed in a close circuit, sediment feed flume, 12m long, 0.31 m wide, the bushes are simulated by means of spherical steel wools, having diameter of 4 cm. Three different vegetation densities are simulated: *sparse* (a_x=30 cm, a_y=10 cm); *intermediate* (a_x=15 cm, a_y=10 cm) and *dense* (a_x=10 cm, a_y=10 cm) configurations; two different classes of sand are used as feeding granular material: one having mean diameter d_s=0.5 mm (*fine* sand) and the other having d_s=1.3 mm (*coarse* sand). More than 40 runs are performed, for each of them the equilibrium state is reached and so the uniform flow conditions, at different liquid and solid discharges.

2.7 Physical Model of the Wien River (FS3)

Flow Resistance of Vegetated Banks and the Wienfluss Physical Model

The field site of Wienfluss (managed by the group of BOKU University of Wien) has been a useful and powerful opportunity to have a deeper insight about the hydrodynamic behavior of real plants and vegetated banks in torrents. The field site plan is reported in Fig.17: the reach presents a curve in the upstream part; the water flows from a reservoir; the discharge is regulated by a control gate. Various types of banks remediation works are presents along the stream; they are characterized by different types of plants and different vegetation densities, that also varies along the three years of experimentation as the plants grows. Attention is focused on the simulation at a laboratory scale of the geometric and hydraulic conditions as measured at section 14; as far as it concerns vegetation densities and flexibility, the conditions measured on July 2000 ($\lambda \cong 0.125$; h_P ranging between 1.5 and 2 m) has been taken as reference. So the physical model is a straight flume, where the geometry measured at Section 14 and the relative characteristics of the plants are reproduced at geometrical scale $1:r_G = 1:12$; the physical model is in Froude similitude.

The elastic plants are simulated with Teflon cylinders, 18 cm long and 3 mm in diameter, due to dimensional analysis considerations, the ratio between the elasticity module of the real plants, as measured in the field, and that of the Teflon is equal to r_G. Also flow measurements with rigid cylinders has been

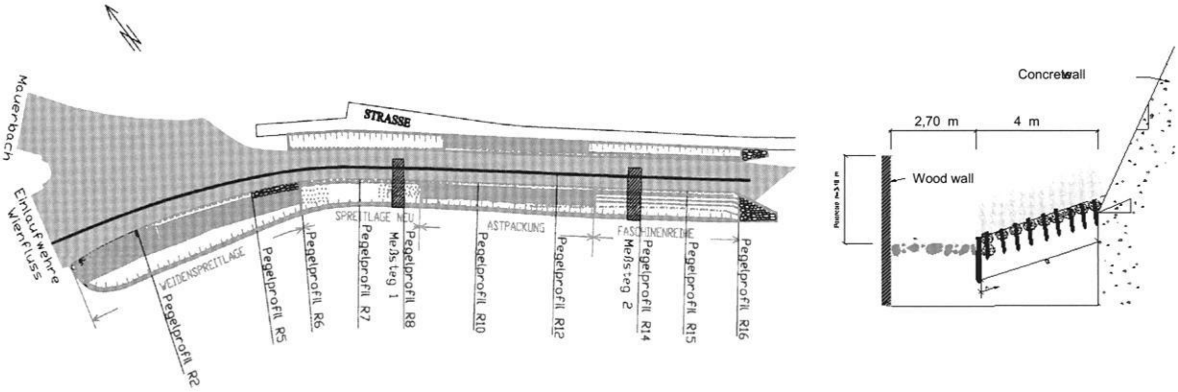


Fig.17 Plan view of Wienfluss and characteristics of Section 14.

performed in the model; both the rigid and flexible cylinders has been tested at various discharges, for three densities of plants ($\lambda = 0.47*10^{-1}$; $1.17*10^{-1}$; $1.67*10^{-1}$ respectively, called in the following: *sparse*, *intermediate* and *dense* density of plants respectively);

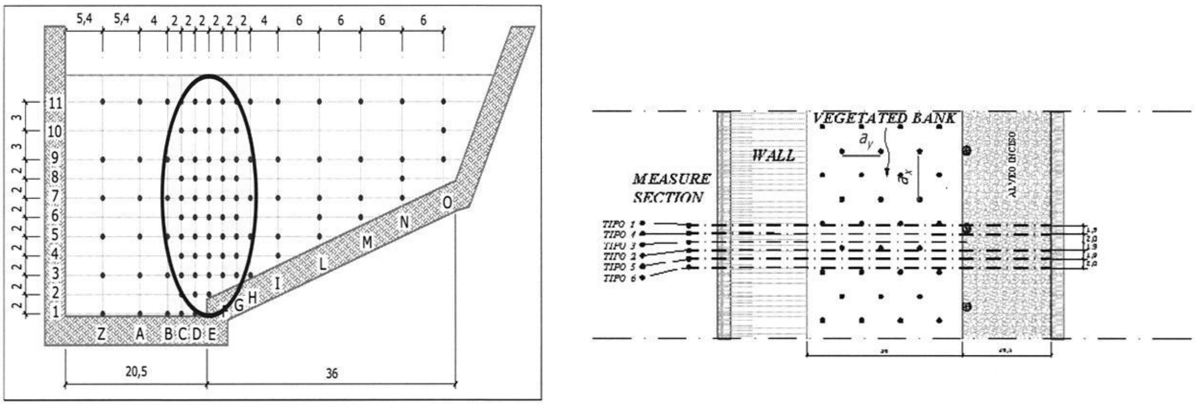


Fig.18 Measurement points into the generic cross section and different cross sections

this allows to compare the hydrodynamic behavior of flexible and rigid plants at the banks at different densities. The cinematic characteristics (mean velocities and turbulent shear stresses) of the flow field are measured using a ultrasonic probe (2D-Sontek MicroADV) at different locations in the generic cross section; the double averaging technique (temporal and spatial) among homologous point at different cross sections (Fig.18) is applied (Righetti & Armanini, 2002), in order to evaluate also the dispersive component of the turbulent stresses.

2.8 3D Numerical Modelling of Riparian Flow Field

Many rivers are more or less vegetated and it is essential for the practical engineer to determine velocity distributions and thus discharge capacity for floodplain management, river training works or water resources activities that account for such processes. Therefore, the aim of the numerical simulation in this project is to analyse the flow of partly vegetated compound channels in order to predict the flow velocities at different discharges and consequently the flow depths in the main channel and on the floodplains. The results of the three dimensional numerical were then tested against the laboratory experiment.

3D Numerical Model

The numerical model solves the Reynolds-averaged Navier-Stokes equations in three dimensions to compute the water flow using the finite volume approach as discretization method. The k-ε turbulence closure scheme (Rodi 1980) computed the stress term and the *SIMPLE* method (Patankar 1980) the pressure term. To model the additional flow resistance of vegetation the drag force of a rigid obstacle has been introduced as a sink term into the Navier-Stokes equations. The advantage with this method compared with using large roughness on the river bed, is that effects of the vegetation over the whole water depth can be taken into account, instead of only affecting the velocity near the bed. Concerning the modelling of the flexible vegetation the drag force was reduced by a value being a function of the bended angle. This angle is resulting by solving the equilibrium of the internal forces due to material characteristics, and the external ones resulting of the water body where the obstacle is exposed on.

2.9 1D Numerical Modelling of Flood Wave Propagation

Flood prevention is of great importance in densely inhabited countries, and the utilisation of the riparian forests and vegetation for regulating the propagation of the flood waves is one of the highlights in the field of hydraulic engineering. It is the most fundamental research to evaluate the influence of the riparian forests and vegetation on the flow resistance, and researchers previously reported numerous results. In the Integrated Rhine Programme, an imaginary enlargement of the floodplain on the German side is planned up to utmost 90 m and natural succession of the potential natural vegetation is expected on it in the upper reach of the Rhine between Rheinweiler (186.156 km from Lake Constance) and Hartheim (214.244 km). First, a 1D steady-state flow simulation was carried out in order to identify the roughness parameters and analyse the parameter sensitivity with the previous flood records. Consequently, 1D unsteady-state flow simulations were carried out to investigate the propagation of the flood waves along the river course of the upper reach of the Rhine during the course of the flood events according to 24 scenarios with 4 types of different vegetation.

Description of the Data and the Study Site
The study site is the upper reach of the Rhine between the two gauging stations Rheinweiler (186.156 km from Lake Constance) and Hartheim (214.244 km) shown in Fig.19. The bed slope S and the relations between water depth h, cross-sectional area A, and hydraulic radius R were computed from surveys of the cross-sections almost every 100-200 m in the reach. The characteristic dimensions of the riparian forests and vegetation were obtained from field surveys (Hartmann et al., 1998) conducted at several typical sites along the

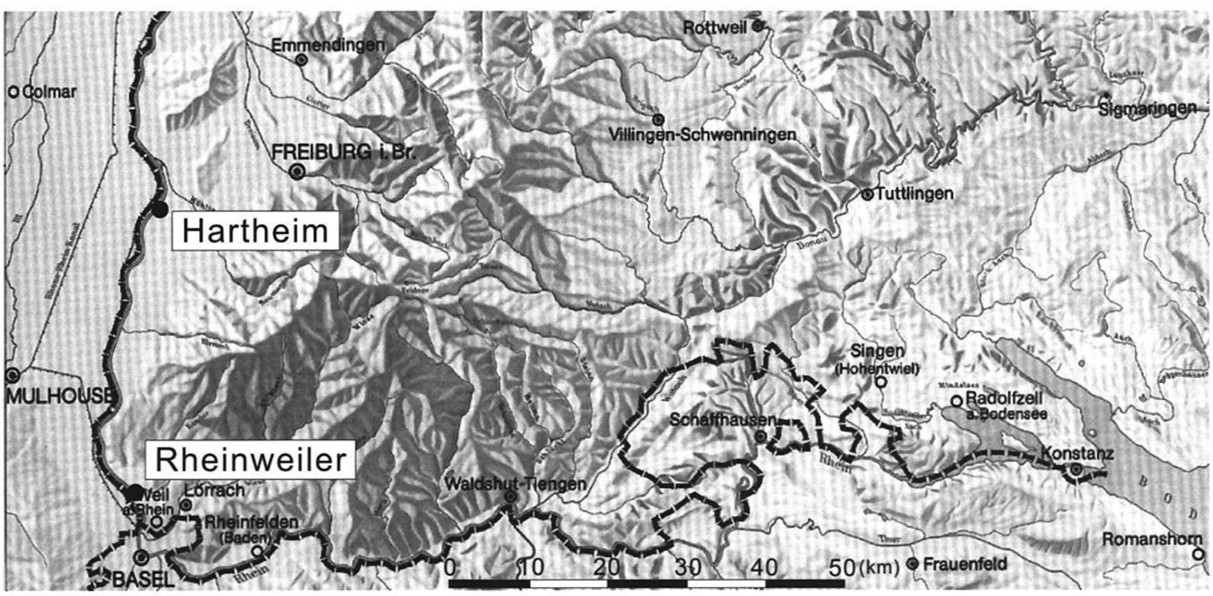


Fig.19 Study site Upper Rhine Hartheim / Rheinweiler

river course. The dimensions are as follows: 1) diameter of the trunk of the riparian trees, and 2) longitudinal and lateral spacing of the trees. Several sets of flood data were accumulated in the 90s.

Description of the Model

The governing equations of a 1D unsteady-state flow in compound open channels are the equation of continuity and the Saint-Venant equation as shown in Eqs. (1) and (2):

$$\frac{\partial A}{\partial t}+\frac{\partial (VA)}{\partial x}=0 \qquad (1)$$

$$\frac{1}{g}\frac{\partial V}{\partial t}+\frac{\partial}{\partial x}\left(\frac{V^2}{2g}+h\right)=S-S_f \qquad (2)$$

where A = cross-sectional area, V = depth-averaged flow velocity, g = the gravitational constant, h = water depth, S = bed slope, S_f = friction slope, and t and x = time and longitudinal co-ordinates, respectively.

$$\frac{1}{g}\frac{V_j^{n+1}-V_j^{n-1}}{2\Delta t}+\frac{\left(\frac{V^2}{2g}\right)_{j+1}^{n}-\left(\frac{V^2}{2g}\right)_{j-1}^{n}+h_{j+1}^{n}-h_{j-1}^{n}}{2\Delta x}=S_j-S_{f,j} \qquad (5)$$

where Δx and Δt denote the spatial and time increments, respectively, and the superscript n and the subscript j denote the time and spatial steps, respectively.

1D Flow Simulations

The steady-state flow simulations were carried out with the fundamental equations the unsteady terms of which are removed prior to the unsteady-state simulations. Three data sets of water tables and flow discharges along the river course were applied to the model, and roughness parameters, namely the Darcy-Weisbach friction factor f, were identified for each sub-cross-section. In order to set the initial water tables along the river course, the flow

Case	a_x (m)	a_y (m)	d_p (m)	c_{WM}	Comments
Type-1	5.66	10.34	1.00	1.20	Typical forests in the left side (French side, Ecological goal)
Type-2	1.23	3.01	0.23	1.20	Typical highly dense forests in the right side (German side)
Type-3	3.48	5.43	0.73	1.20	Typical dense forests in the right side (German side)
Type-4	10.00	10.00	1.00	1.20	Hypothesical future forests in the right side (German side)

Tab.3 Details of vegetation parameters

The influence of bed roughness, riparian forests and the interaction between the main channel and floodplains on the flow resistance was evaluated based on the idea proposed by Pasche and Rouvé (1985). The governing equations are discretised by the explicit finite difference method (the leap-frog scheme) as shown in Eqs. (4) and (5). The central difference schemes are employed in t - and x – terms, respectively:

$$\frac{A_j^{n+1}-A_j^{n-1}}{2\Delta t}+\frac{(VA)_{j+1}^{n}-(VA)_{j-1}^{n}}{2\Delta x}=0 \qquad (4)$$

simulations were carried out for the fixed flow discharge Q = 600 m^3/s, afterwards 24 scenarios of different hydraulic conditions were applied to the unsteady-state flow simulations as shown in Tables 3 and 4. The details of the dimensions of the vegetation parameters are illustrated in Fig.20.

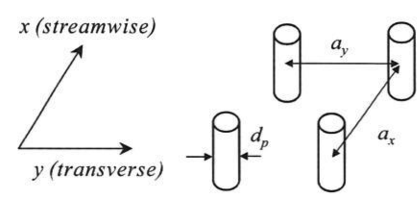


Fig.20 Details of vegetation parameters

Vegetation Type	Main channel	Left-floodplain (France)				Right-floodplain (Germany)				Enlarged area (Germany)				Coeff.
	k_{mc} (%)	k_L (m)	a_x (m)	a_y (m)	d_p (m)	k_R (m)	a_x (m)	a_y (m)	d_p (m)	k_{en} (m)	a_x (m)	a_y (m)	d_p (m)	c_{WM}
Case-0	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23					1.20
Case-1	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	10.00	10.00	1.00	1.20
Case-1+20	+20	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	10.00	10.00	1.00	1.20
Case-1-20	-20	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	10.00	10.00	1.00	1.20
Case-1S	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	2.00	10.00	10.00	1.00	1.20
Case-2	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	0.00	0.00	0.00	0.00
Case-3	original	2.00	3.48	5.43	0.73	2.00	3.48	5.43	0.73	0.15	10.00	10.00	1.00	1.20
Case-3+20	+20	2.00	3.48	5.43	0.73	2.00	3.48	5.43	0.73	0.15	10.00	10.00	1.00	1.20
Case-3-20	-20	2.00	3.48	5.43	0.73	2.00	3.48	5.43	0.73	0.15	10.00	10.00	1.00	1.20
Case-3S	original	2.00	3.48	5.43	0.73	2.00	3.48	5.43	0.73	2.00	10.00	10.00	1.00	1.20
Case-3S+20	+20	2.00	3.48	5.43	0.73	2.00	3.48	5.43	0.73	2.00	10.00	10.00	1.00	1.20
Case-3S-20	-20	2.00	3.48	5.43	0.73	2.00	3.48	5.43	0.73	2.00	10.00	10.00	1.00	1.20
Case-6	original	2.00	5.66	10.34	1.00	2.00	5.66	10.34	1.00	0.15	10.00	10.00	1.00	1.20
Case-6+20	+20	2.00	5.66	10.34	1.00	2.00	5.66	10.34	1.00	0.15	10.00	10.00	1.00	1.20
Case-6-20	-20	2.00	5.66	10.34	1.00	2.00	5.66	10.34	1.00	0.15	10.00	10.00	1.00	1.20
Case-6S	original	2.00	5.66	10.34	1.00	2.00	5.66	10.34	1.00	2.00	10.00	10.00	1.00	1.20
Case-6S+20	+20	2.00	5.66	10.34	1.00	2.00	5.66	10.34	1.00	2.00	10.00	10.00	1.00	1.20
Case-6S-20	-20	2.00	5.66	10.34	1.00	2.00	5.66	10.34	1.00	2.00	10.00	10.00	1.00	1.20
Case-11	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	5.66	10.34	1.00	1.20
Case-12	Original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	3.48	5.43	0.73	1.20
Case-13	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	0.15	1.23	3.01	0.23	1.20
Case-11S	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	2.00	5.66	10.34	1.00	1.20
Case-12S	Original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	2.00	3.48	5.43	0.73	1.20
Case-13S	original	2.00	5.66	10.34	1.00	2.00	1.23	3.01	0.23	2.00	1.23	3.01	0.23	1.20

Tab.4 Simulation cases

2.10 Riparian Succession at the Upper Rhine (FS1)

In the southern section of the Upper Rhine River situated between Basel and Breisach, the former river bed is planned to be more intensely used for flood retention purposes. In this Franco-German border section the river bed is strongly incised as a result of bed erosion and is merely provided with about 20-30 m^3 water per second (residual flow) over more than four fifth of the year. The main water volume (up to 1400 m^3/s) is discharged over the lateral canal of the Rhine for energy generation purposes. The former river bed is to be broadened for flood retention purposes by means of diggings above the mean water level. The succession of vegetation occurring on this newly created floodplain stretch with an average width of 90 m, will naturally have a great influence on flood retention on the one hand and on sedimentation on the other hand. In the present study we tried to estimate the development of vegetation.

For this purpose, comparative studies of the vegetation existing in the former groyne fields (i.e. the areas situated between the groynes) and its development were conducted on both the German and the French side. In doing so it had to be considered that along the German river bank interventions as for the ligneous plant stands had taken place repeatedly, this was not the case on the French side. To document the existing vegetation, the plant communities were described according to the Braun-Blanquet-method and were put in a systematic order. Plant lists were drawn and life-form as well as dispersal type of the identified species were established.

3. RESULTS AND DISCUSSION

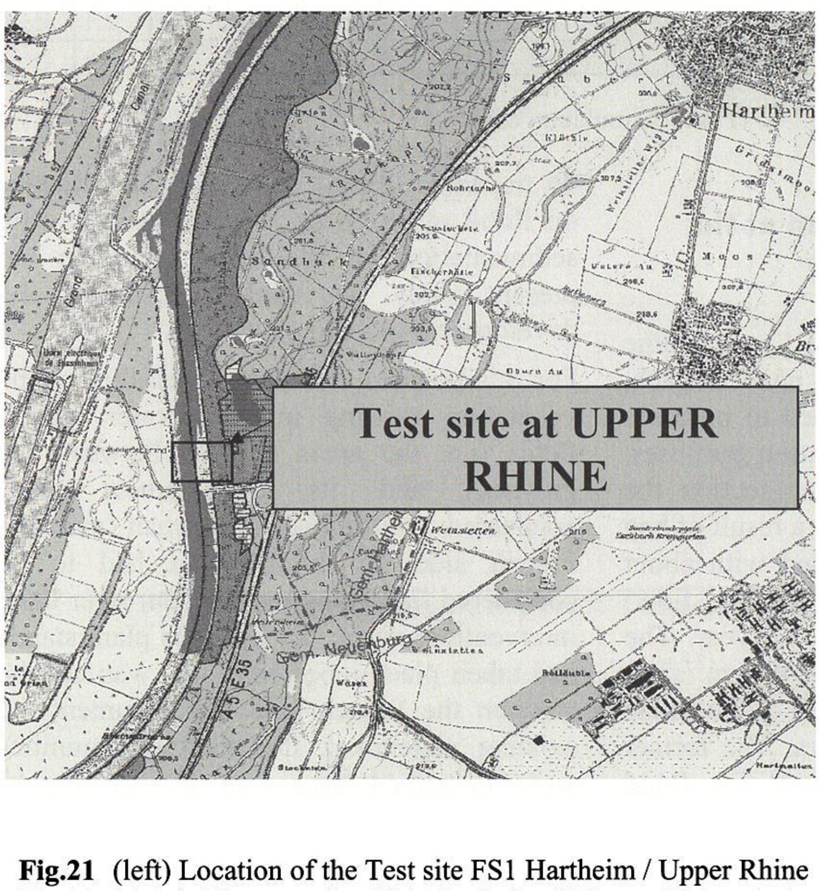
3.1 Field Work at the Upper Rhine (FS1)

Characterization of the Test Site

The investigated area is located inside a former groin field at the Upper Rhine in the south west of Germany close to the city of Freiburg. Fig.21 shows a detailed map of the site location with the original course of the river Rhine at the centre and the current situation of the Grand Canal d´ Alsace on the left hand side.

The Rhine signs the border between Germany and France. The western part of the test site is lined by the river Rhine at a normal discharge of 30m³/s. The eastern part is marked by the bank so called “Lainpfad”. The sediments in the main river are dominated by pebbles and stones. The sediments at the floodplain are characterized by a variation between clay, silt and sand.

Originally the Rhine was a braided system. The former river bed –before the regulation and correction of the Rhine was approximately at an elevation of 205m a.s.l. As a consequence of the human impact on the river system – rectification, construction of groins, regulation, canalisation- the Rhine incised his river bed. Today the elevation of the river bed is at about 193m a.s.l. The total difference in height between the river bed and the top of the embankment is about 12 meter. The total width of the river and floodplain is about 160m (Fig.23).



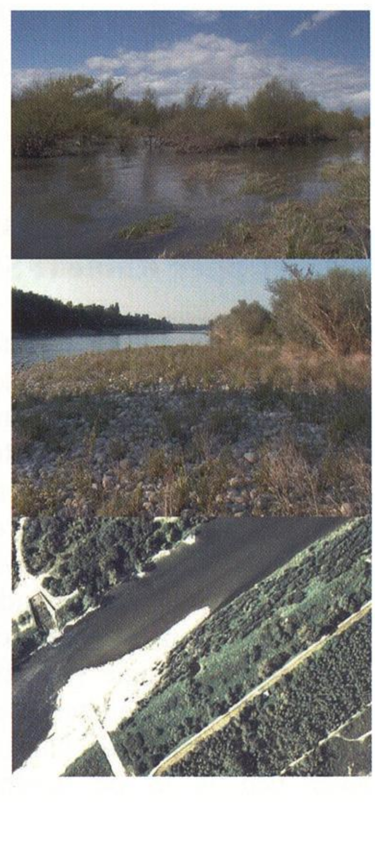


Fig.21 (left) Location of the Test site FS1 Hartheim / Upper Rhine

Fig.22 (right) The test site FS1 Hartheim / Upper Rhine during a smaller flood event (top) (Q=900m³/s), at normal water level and as aerial photograph (bottom)

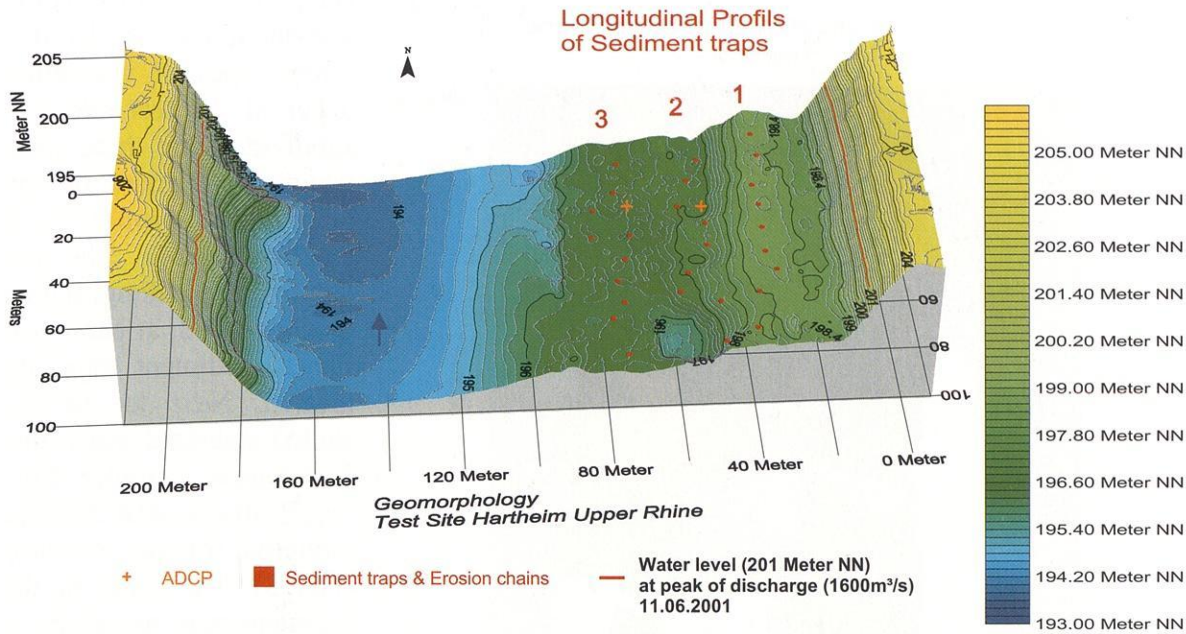


Fig.23 Geomorphology of the test site Hartheim / Upper Rhine; location of equipment

HHQ (May 1999) = 4550 m^3/s	Rheinfelden
Approximated value for the test site = 3150 m^3/s	
HNQ (December 1962)= 315 m^3/s	Rheinfelden
Approximated value for the test site < 30 m^3/s	
HQ 10 = 3544 m^3/s	Rheinfelden
Approximated value for the test site = 2144 m^3/s	
HQ 50 = 4098 m^3/s	Rheinfelden
Approximated value for the test site = 2698 m^3/s	
HQ 100 = 4308 m^3/s	Rheinfelden
Approximated value for the test site = 2908 m^3/s	
MQ (1935-2001) = 1042 m^3/s	Rheinfelden
Approximated value for the test site < 30 m^3/s	

Tab.5 Hydrological date gauging station Rheinfelden

The test site has a length of 100meter and a width of 80 meter, it does not include the river itself. The morphology of the groin field is dominated by a ridge with a mean height 2.00 meters above the normal water level at Q=30m³/s, the lower areas are between 50-100cm above the water level. This divides the test site into areas with different inundation levels. The depth of the river is between 150-200cm (at Q=30m³/s). The blue area shows the water level at the normal discharge of 30m³/s (Fig. 23).

The discharge is regulated by a weir at the city of Maerkt almost 35km upstream the test site. At Maerkt the Upper Rhine is divided into the Grand Canal d´Alsac (1400m³/s) and the original course of the river (30m³/s) and regulates the capacity of the channel and the river (between Maerkt and Breisach). If the discharge upstream the weir rises above 1400m³/s the test site will be flooded and the discharge at the test site can increase from the normal of 30 to 1600 m³/s within 3 days, which means an increase of about 50 times in 72 hours.

The hydrological situation of the gauging station Rheinfelden upstream the segregation into the original course of the river and the Grand Canal d´Alsace can be described by the values in Tab.5. It has to remarked that only flood events of a discharge bigger than 1000m³/s (at gauging station Rheinfelden >2400m³/s) (water level >400cm) inundate the upper parts of the floodplain.

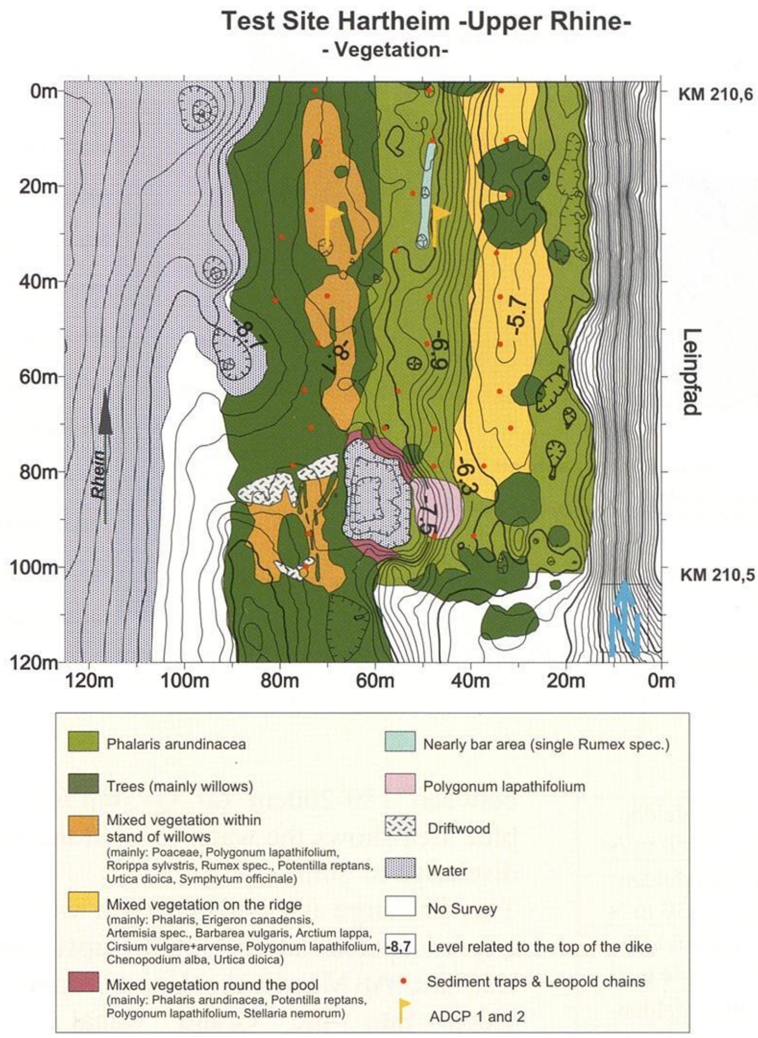


Fig.24 Test site Hartheim / UpperRhine; types and distribution of vegetation

Based on this information and due to the fact that different types of vegetation occur at the test site was subdivided into three areas which are marked by the longitudinal profile 1, 2 and 3 (Fig.23). The red dots mark the longitudinal profiles 1 2 3, at each profile 10 sediment traps are located. Next to the installed sediment traps also 2 Acoustic Doppler Current Profilers (ADCP) were mounted (orange crosses) (Fig.23). The order of the sediment traps are given in Tab.6.

The investigation of the interaction between vegetation, sediment transport and flow velocities made it necessary to characterize the spatial distribution of plant parameters. A geobotanic survey was carried out in summer 2000 to examine distribution of different types of vegetation. A vegetation map (species, distribution and area) has been designed (Fig.24). The lowest part of the

Profile 1 (lowest part of the floodplain; covered by willows) includes the sediment traps with the number 102, 202, 302, 382, 392, 402, 502, 602, 702, 802 (view from up-to downstream)
Profile 2 (lowest part of the floodplain; covered by grass) includes the sediment traps with the number 103, 203, 303, 383, 393, 403, 503, 603, 703, 803. (view from up-to downstream)
Profile 3 (highest part of the floodplain; covered by grass and herbs) includes the sediment traps with the number 104, 204, 304, 384, 394, 405, 505, 604, 704, 805. (view from up-to downstream)

Tab.6 Location and consecutive numbering of sediment traps

floodplain close to the river is dominated by young flexible willows (dark green colour). The ground cover is mainly a mixture of different types of grass and herbs. The lower area between the willow belt and the dike is mainly covered by grass (light green colour), the upper area by herbs and grass (yellow area). Single spots at the up- and downstream border of the test site are dominated by timber trees and bushes. A special survey examining the density, the height and distribution of trees in the floodplain was carried out by the colleagues from Vienna.

Description of the Hydrological Situation between 2000-2002

The hydrological situation of the years 2000-2002 is dominated by a large number of smaller flood events (<HQ 10) (Fig.25). In 2000 the main flood period was between June and August. The floodplain was inundated in total for 43 days (> 140m³/s). Only at two days the upper areas could be reached by the water (Q > 980m³/s). In 2001 the main flood period was between March and June. The maximum values were reached the first time in March with 1400m³/s and in June with 1600m³/s. Several smaller floods occurred. The lower floodplain was inundated in total for 142 days (> 140m³/s). Compared with the year 2000 the upper areas could be reached by the water in total for 18 days (Q > 980m³/s). In 2002 the floodplain was inundated in total for 91 days (> 140m³/s). Very similar to the last year situation the upper areas were inundated for 19 days. The flood period started in May and stopped at the end of the year. The maximum values were reached in August (1600m³/s), September (1700m³/s) and in November (1500m³/s). The longest inundation period could be observed in November. The main aspect of these data is that no bigger flood event occurred during the investigation period 2000-2002. The situation of the test site was dominated by a big number of smaller events without any extraordinary floods compared with e.g. the situation in 1999 (Q_{max} =3500m³/s at Rheinweiler).

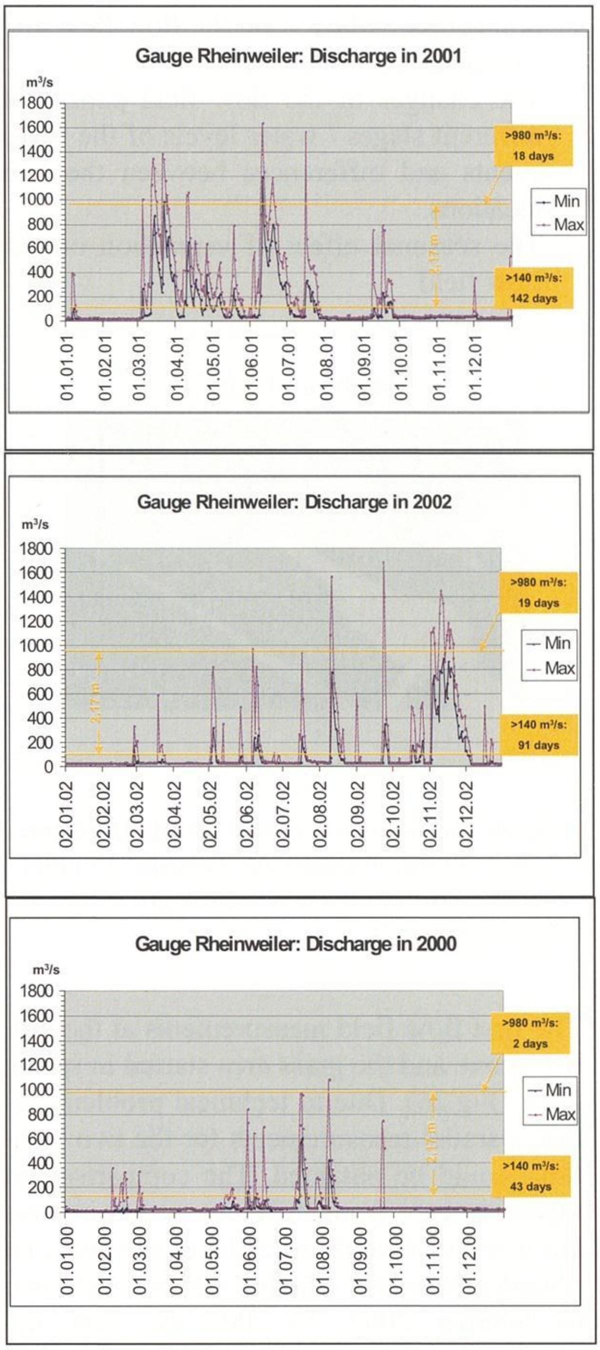


Fig.25 Gauging station Rheinweiler between 2000-2002 / Periods of inundation at the test site Hartheim

Flow Field Measurements

The investigation of the flow field inside a riparian forest at the Upper Rhine and the description and analysis of velocity data focus on three main aspects:

- The influence of different types of vegetation (grass, willows) on the flow field and a comparison of data sets
- The changes of the flow field pattern at different stages / water levels of the flood events and differences between the two locations
- The seasonal effect of vegetation on the flow field

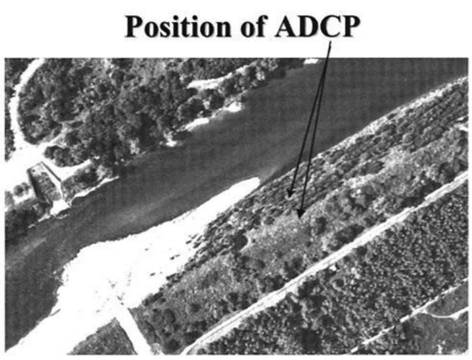


Fig.26 Bird-eye view of the test site Hartheim /Upper Rhine; location of Acoustic Doppler Current Profiler inside a willow grove and at a grass covered

The first flow field measurements at the willow grove and the grass area started in spring 2001 (Fig.26). Due to technical problems no time parallel measurements for the two locations could be obtained. The comparison of measurements from different points in time but always at same water level showed first remarkable results which could be confirmed in summer 2002. In 2002 the first and smaller flood events occurred during the late spring period between May and the end of July. The floodplain was partly inundated.

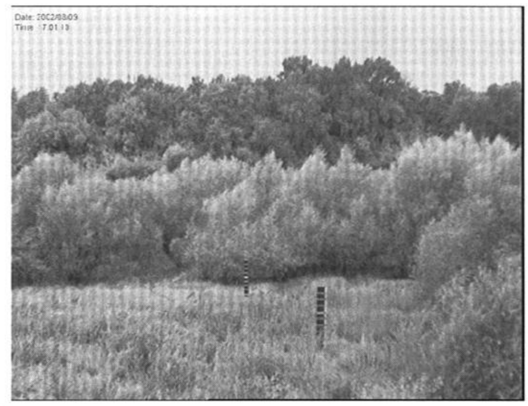


Fig.27 Situation before a flood event in August 2002

Heavy rainfalls in August lead to the first bigger flood event at the Upper Rhine. The water level reached the upper areas of the floodplain the first time that year. Fig.27 shows the situation before the inundation in August. The maximum water level was about 2.70 Meters at the test site (floodplain level) during the peak of discharge (1600m³/s) (Fig.28). This occurred again at the end of September (1700m³/s) and in the middle of November (1500m³/s).

Fig.28 Flood event in August 2002, maximum water level at the floodplain 2,75m, (Q= 1600m³/s)

During these events several flow field measurements were carried out with the ADCPs inside the stand of willows and at the grass covered areas (Fig.26). Data were recorded for the complete flood periods.

The graphs of Figs.29 and 30 illustrate the typical situation of a flood event at the Upper Rhine (FS1) and the evolution of the vertical velocity profiles at a grass and a willow covered area inside the floodplain before, during and after the peak of discharge. The maximum discharge is about 1600m³/s; the maximum water level at this location inside the floodplain is 2.40m (grass), 2.75m (willow).

The x-axis presents the flow velocity in mm/s. The y-axis shows the water depth and the range of the measured velocity profile. The colours show the velocity at different stages of the flood. Blue shows the velocities with rising water level, yellow shows the velocities with falling water level, e.g. the graphs R616 (Fig.29) and W44 (Fig.30) sign the initial stage of the flood event at a water level of about 80cm, the graphs R681 and W109 were recorded at the peak of discharge.

Flow Field Measurements Grass Area

In Fig. 29 the ground velocities vary between 100 and 300mm/s. They increase with rising water level. The highest velocities are always reached close to the water surface with a maximum of 1150mm/s at the peak of discharge, the minimum is reached at the beginning and the end of the flood event (100-150mm/s). With rising and falling water level both the ground and surface velocities increase, respectively decrease.

The span between ground and surface velocities is increasing with rising water level from almost zero (R616), 350mm/s (R638), 700mm/s (R658), up till 900 mm/s (R674). The comparison of situations at same water level before and after the peak shows that both ground and surface velocities have increased after the peak.

Flow Field Measurements Willow Area

In Fig. 30 the comparison of situations at same water level before and after the peak shows remarkable differences in the vertical distribution of the flow velocity. With rising and falling water level both the ground and surface velocities increase respectively decrease. The gradient between the ground velocities and velocities at a water depth between 90-120cm is positive. From a certain point on at the water column the

Velocities - Ground	**(at a height of 70cm)**	**Range between min. and max. velocities**
Before flood peak:	min 275mm/s max 925mm/s	650
After flood peak:	max 925mm/s min 550mm/s	375
Difference between min. before and min after the flood peak = 275mm/s		
Velocities	**(at a height between 80-120cm)**	
Before flood peak:	min 600mm/s max 1000mm/s	400
After flood peak:	max 1000mm/s min 700mm/s	300
Difference between min. before and min after the flood peak = 100mm/s		
Velocities - Surface	**(shifting height)**	
Before flood peak:	min 500mm/s max 650mm/s	300
After flood peak:	max 650mm/s min 500mm/s	300
Difference between min. before and min after the flood peak = 0mm/s		

Tab.7 Vertical distribution of velocities at different location and different stages of the flood event at the willow area

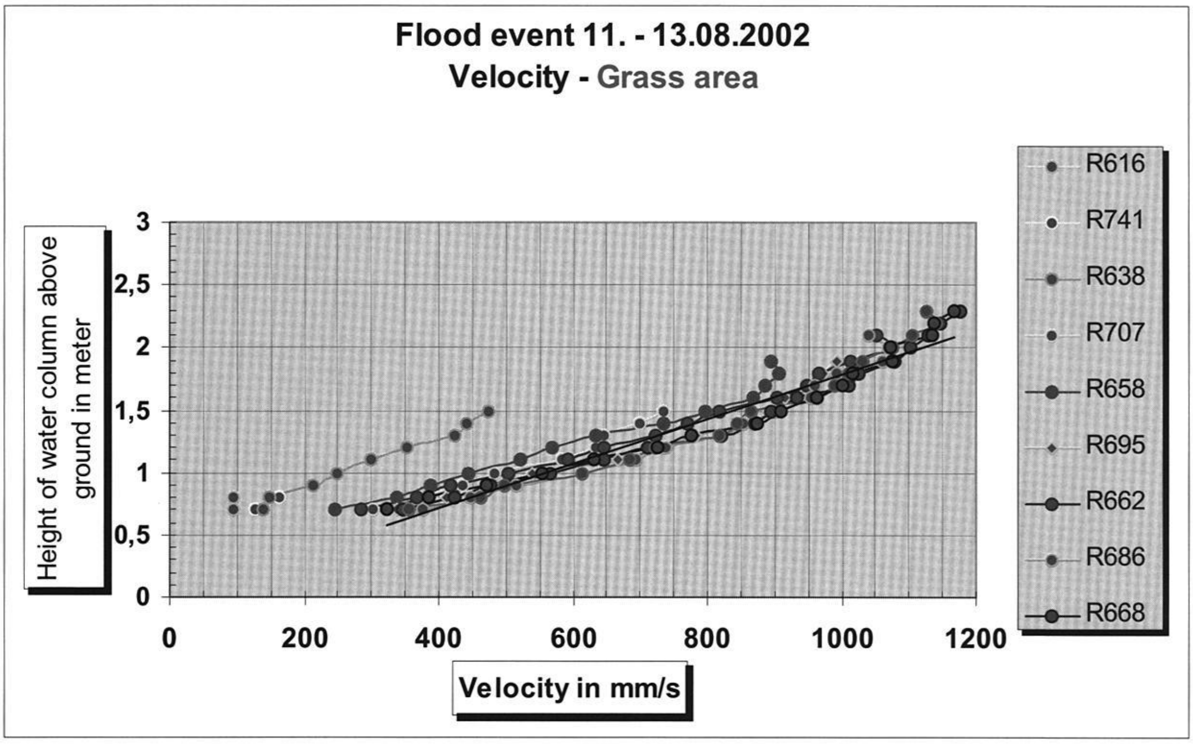


Fig.29 Flow velocities during a flood event at a grass covered floodplain area – test site Hartheim Upper Rhine

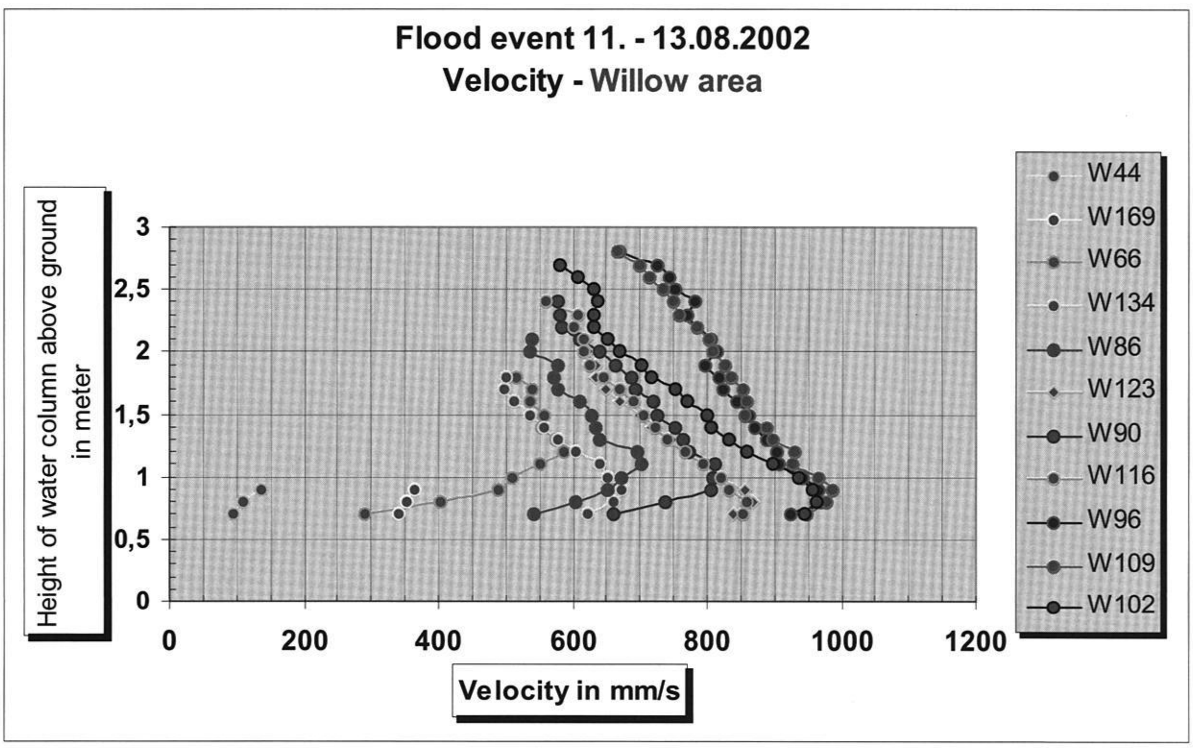


Fig.30 Flow velocities during a flood event at a willow grove at a floodplain area – test site Hartheim Upper Rhine

gradient of the velocity graphs becomes negative and after the peak of inundation it is getting lower. The ground velocities vary between 100 and 925mm/s. They increase with rising water level.
A detailed observation of the data sets (Tab.7) shows that the highest velocities are always reached at a height between 90-120cm above the ground with a maximum of 1000mm/s at the peak of discharge. At this height the minimum of 600mm/s is reached at the end of the flood event (with exception velocities are always lower than the ground velocities (Fig.30). The range between min. and max. values is constant for most parts of the profile before and after the peak of inundation, whereas close to the ground the range is decreasing (Tab.7). This is caused by an increase of the min. values before/after the flood peak from 275 up to 550mm/s. For all other parts the differences are almost constant. The min. max., the range and the shift of values can be described as following if W44 and W169 are excluded.

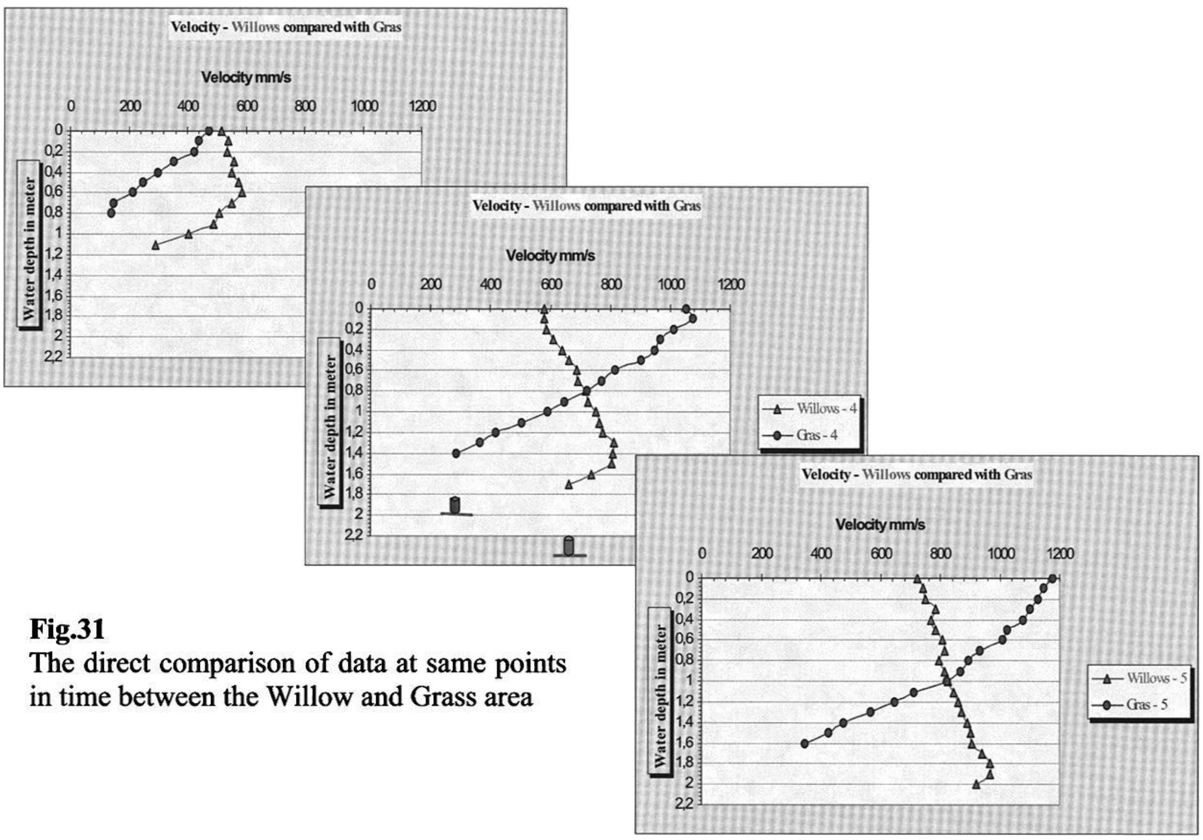


Fig.31
The direct comparison of data at same points in time between the Willow and Grass area

of W44 and W169; 150-350mm/s).
The surface velocities are always lower compared with the velocity at the lower third of the profile. They have a maximum of 650mm/s and with exception of W44 and W169 (150-350mm/s) a minimum of 500mm/s.
At a water level above 2.00m the vertical distribution of velocities always shows the minimum close to the water surface, these

The range between ground and surface velocities in Fig.30 is increasing up till a water level of 1.80m, the differences between ground and surface shift from 50mm/s (W44) up till 200mm/s (W66). At a water level of 2.20m the range is zero again. With ongoing rise of the water level the ground velocities become higher compared with the surface velocities and the range is increasing up till 275mm/s (W96). From the peak of

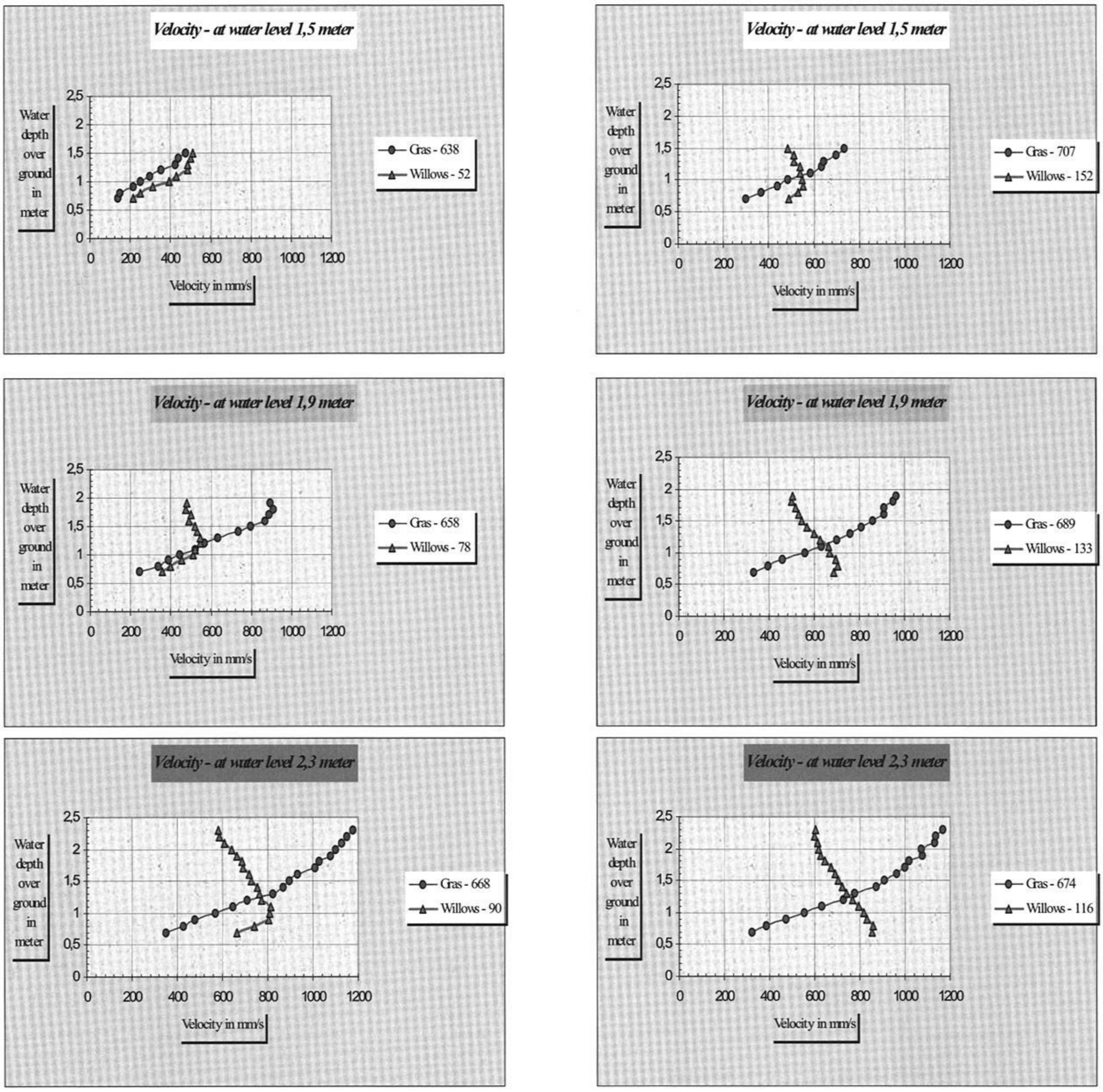


Fig.32 A comparison between two test sites at selected water levels before and after the peak of flood

discharge on and with falling water level the range is decreasing (325mm/s at W102; 300mm/s at W116; 250mm/s at W123 and 100mm/s at W134). At the end of the flood event both the ground and surface velocities -at about 350mm/s- are higher compared with the situation at same water level before the flood event (100-150mm/s).

The Graphs are plotted in Fig.31 starting at the water surface and ending 70cm over the ground. The impact of topography is not excluded, which means that the ADCP at the grass area is 40cm higher in elevation. During the first stage of inundation the surface and ground velocities at both locations are quit similar but they shift and spread with rising water level. From a certain point in time the graphs intersect due to increasing velocities from the ground to the top at the grass area and decreasing velocities at the willow grove. It exits a wide difference close to the ground with values at the grass area from 100 up till 300mm/s compared with the

willow grove 300 up till 900mm/s. The maximum velocities are reached at the grass area with values close to 1200mm/s near the water surface. Whereas at the willow grove the water body has the tendency to be decelerated. At the top a value of 900mm/s is reached.
The diagrams of Fig. 32 provide information about the interaction between different types of vegetation and the flow field standardized by same water levels to exclude the effect of topography. The x-axis presents the velocity in mm/s, the y-axis shows the water depth and the range of the measured velocity profile. The figures (Fig.32) show the velocity distribution at different stages of the flood at rising and falling water level. Secondly a comparison is made between the situation before and after the peak of discharge in order to estimate changes in the vertical velocity distribution.
The intersection of the graphs as discussed before can be proved again. This can be seen at a water level of 1.90m. At 1.50 m it is not obvious before the maximum but surprisingly after the peak. At water level 1.90 meter both at the grass and the willow area the velocities increase from the ground up till a level of 1.20m, they show very similar pattern. Whereas at the maximum of 2.30m and with falling water level the situation has changed. If one compare the situation of the ground velocities at water level 1.90 before and after it comes clear that at the willow area the velocity has increased from 350 to 700mm/s. At the grass area it is almost constant with a value between 225 and 300mm/s. At a water level of 2.30m the tendency is quit similar. At the willow area the velocity has increased from 650 to 850mm/s. At the grass area it is almost constant with a value between 300 and 350mm/s.

Local Discharge
The distinct differences in the vertical distribution are discussed with a focus on its im-

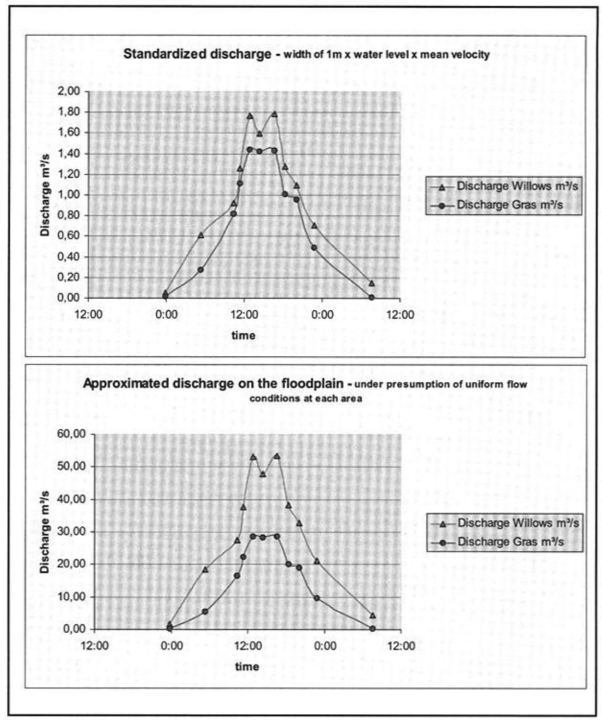


Fig.33
Local discharge under standardized conditions for grass and willow area

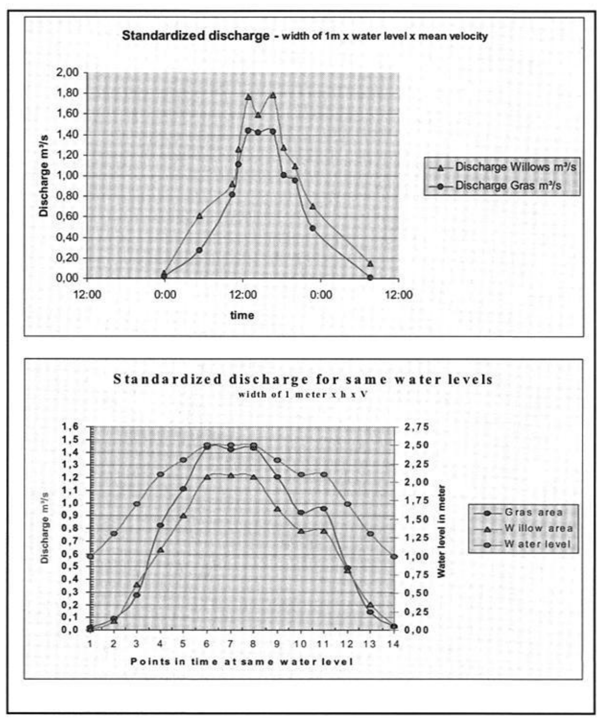


Fig.34
Approximated discharge for the test site

pact on discharge and the deceleration of water flow by vegetation.

The analysis of local impact of topography on discharge was carried out by a comparison of velocities values of both locations for same water level. Primarily the discharge was calculated for same points in time and secondly to exclude topographical effects for situations at same water level.

During a single flood event and without consideration of differences in topography the discharge is always higher at the willow covered area (Fig.33). If the topography is excluded the discharge is lower at these areas. Up to a water level of 1.00m the discharge values are quite similar for both locations (Fig.34). This implicates that an impact of the riparian forest at the test site on discharge can be considered only from a certain water level on.

Taking into account the whole area of the test site which is either covered by willows or by grass the total discharge is higher inside the willow grove. For the complete floodplain the approximated discharge is about 80m³/s (at a total discharge of 1600m³/s). That means less than 5% of the total discharge of the Upper Rhine can be allocated for the floodplain with 1.8% (grass area) and 3.4% (willow area). These data base on the assumption that the measured velocities are almost similar all over the test site.

Seasonal Effects on the Flow Field

The mean flow velocities at different flood events in 2002 vary between 840mm/s and 1080mm/s (grass) respectively between 710mm/s and 680mm/s (willows) (Fig.35/36). This means that the impact of the trees due to their roughness decelerate the velocity of the water body between 19 and 54% (Fig.36) whereby it has to take into account that during the flood event in November 2002 the mean velocities at the grass area were disproportional high compared with the situation in August and September 2002 (Fig.35).

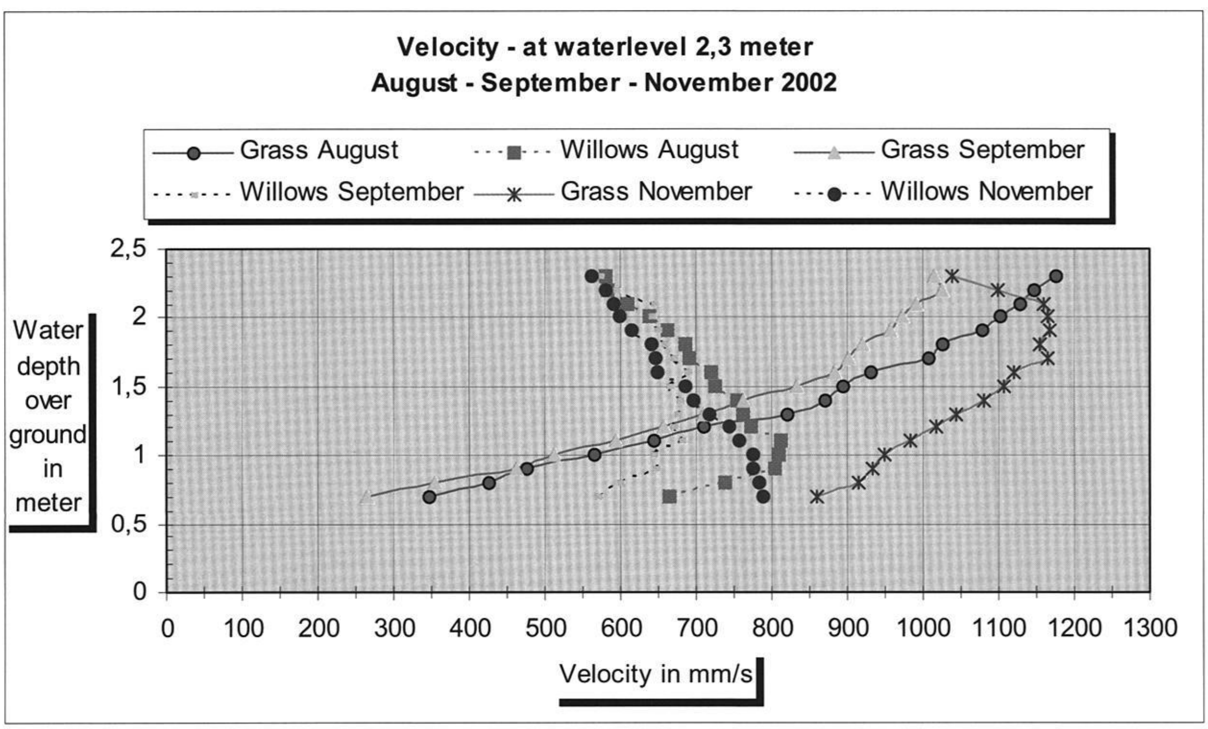
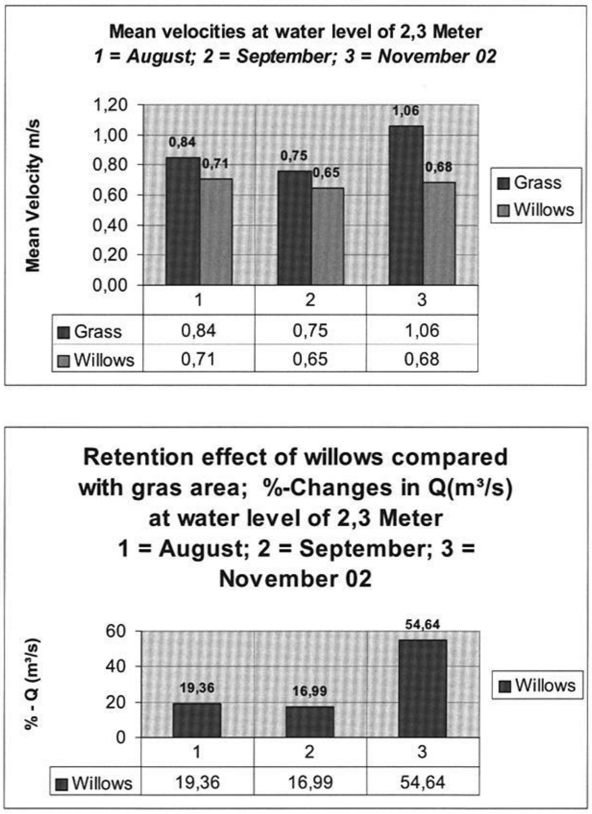


Fig.35 The impact of the seasons on the vertical distribution of the flow field

In co-operation with the WSA Freiburg three dimensional flow field measurements were carried out in the main river by boat (March 2001). The cross sections measured were located up- and downstream of the test site. The floodplain was not included. The data were analysed and discharge for the main river was calculated as discharge of almost 1100m³/s at a maximum of velocity of 3-5m/s.

The seasonal effect on the mean velocity and discharge due to decomposing, changes in the amount and density of leaves and branches is between 9 and 4 % at the willow area (Fig.37), whereas the grass area shows a decrease in September of 11% and an increase of more than 25% in November (Fig.37). The increase can be explained by the loss of ground roughness due to previous flood events and decomposing respectively dying off vegetation in autumn/winter time.



Figs. 36 Mean velocities and retention effect of willows compared with grass

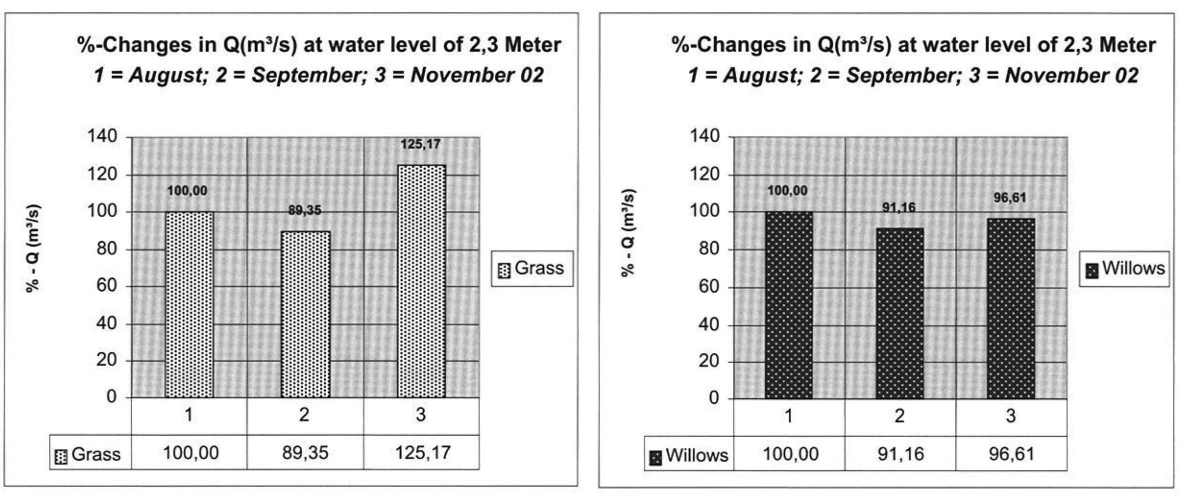


Fig. 37 The impacts of the seasons on mean velocities for August, September and Nov. 2002

Sedimentation and Erosion: Main Aspects

The description and analysis of sediment data has so far focused on four main aspects.

- The investigation of sedimentation / erosion due to changes in topography (meso scale roughness)
- The influence of different types of vegetation on sedimentation (meso scale roughness)
- The changes of the sedimentation pattern for different flood periods (meso scale roughness)
- The influence of different types of vegetation and flood periods on grains size distribution (micro scale roughness)

Sedimentation and Erosion: Analysis on the data base of the Geodetic Survey

As a first step and before the flood events in 2001 several geodetic surveys were carried out between summer 2000 and spring 2001 to describe the actual situation of topography and morphology. A topographical map has been designed based on these first data.

In late autumn 2001, in summer 2002 and in winter 2002 /2003 – always after the bigger flood events- these surveys were carried out again to examine changes in topography in between the years 2000 and 2002. Data sets were checked and analysed. Based on the comparison of all data sets differences in height before and after the flood periods in 2001 / 2002 could be calculated.

These data and maps were merged to generate maps of erosion and sedimentation in comparison with the situation in 2001 (Fig.38). The data of the geodetic surveys 2000, 2001 and 2002 were used to detect changes in volume and the total gain and loss of material under influence of flow field and vegetation and for the calculation of sedimentation rates for the last 2 years for the complete test site (Fig.39). As a result areas of sedimentation and erosion are characterized by different colour scales. Green means Erosion, respectively red sedimentation. The yellow areas mark areas of almost no change.

The upper levels of the test site are almost not affected by sedimentation respectively

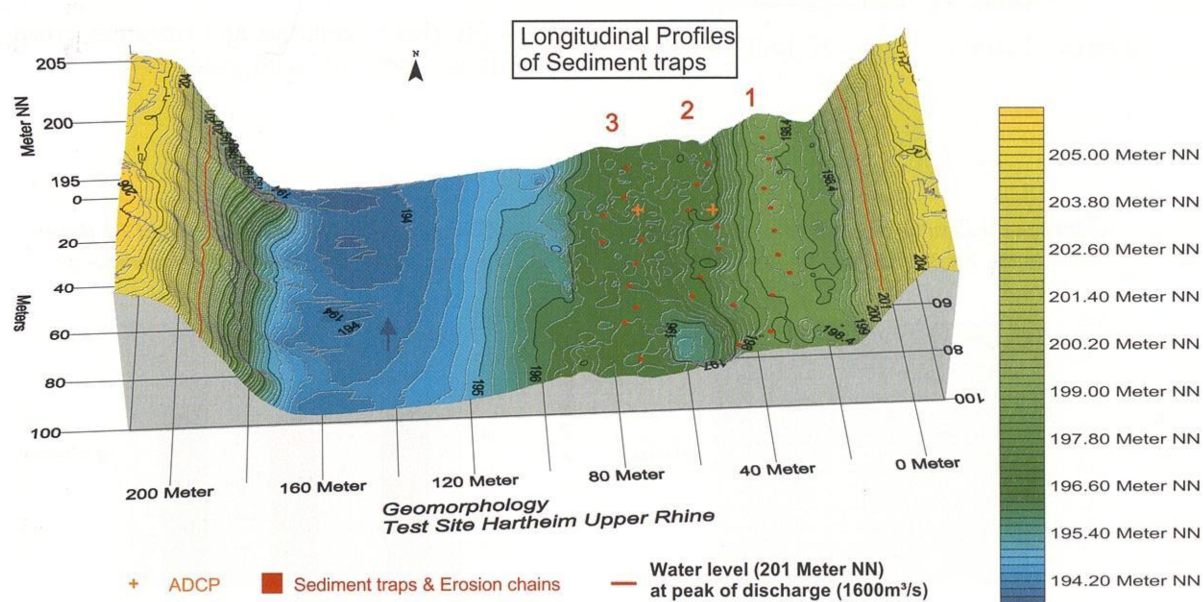


Fig.38 Digital elevation model -DEM- of the test site Hartheim / Upper Rhine in spring 2001

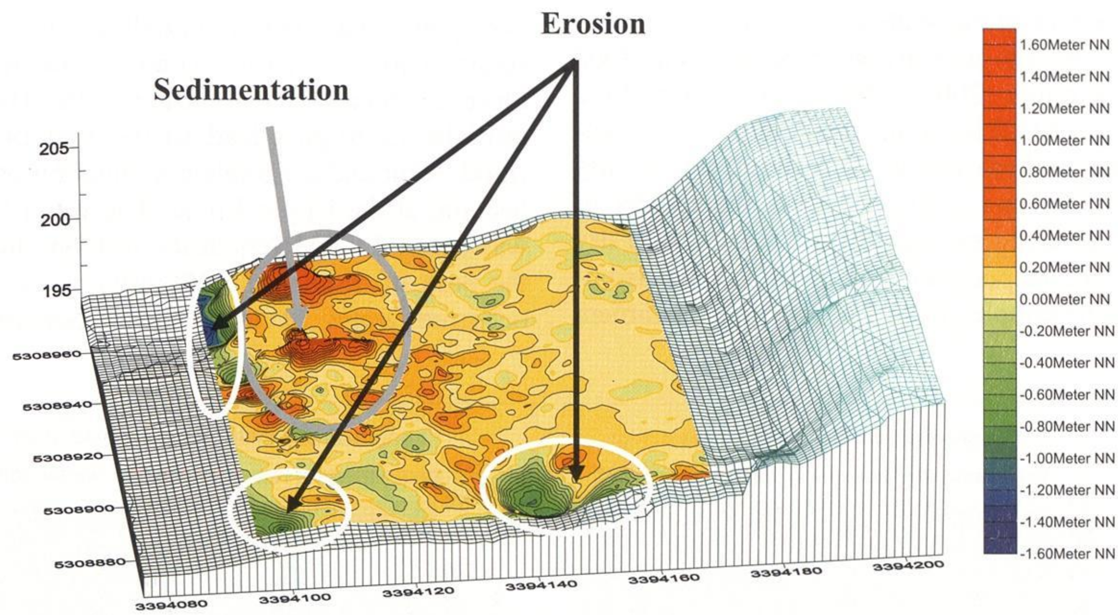


Fig.39 DEM; Sedimentation and erosion rates between spring 2001 and winter 2002 at the test site Hartheim / Upper Rhine

erosion. These areas were only inundated at a discharge bigger than 1000m³/s. This situation occurred at 18 days in 2001 and at 19 days in 2002. The lower levels of the floodplain show distinct proofs of sedimentation and erosion. These areas were inundated for 142 days in 2001 and 91 days in 2002. Erosion of material appeared at the upstream parts of the lower floodplain mainly at the willow covered sites and close to the borderline to the open channel. Sedimentation can be observed from the upstream end of the test site going along a diagonal in direction North West. Both willow and grass covered areas are affected. The high rates of sedimentation which can be observed at the North West area inside the willow grove are due to the accumulation of driftwood.

It can be stress out that almost no erosion has taken place with regard to total rates of sedimentation and erosion over a longer period and up till a maximum of discharge of 1600m³/ and flow velocities (70cm above the ground) which vary between 100 and 300mm/s (grass area) respectively 100 and 950mm/s (willows).

The calculated mean rate of sedimentation per year is about 5cm for the total area. The total loss of volume is about 367m³ per year at an area of 7500m². With regard to a pore volume of 40% of the accumulated material the loss of retention volume accounts 220m³. To confirm these results these data were compared with data sets of the sediment traps. Based on these information both the micro-scale and meso-scale dynamic of erosion and sedimentation under the influence of topography and vegetation could be described and analysed in a more detailed way.

Sedimentation and Erosion: Analysis on the Data Base of the Sediment Traps

The test site was investigated after the flood in summer 2001, 2002 and winter 2002 /2003. At all locations the height of sedimentation and erosion was measured, statistically analysed and compared with the results of the geodetic surveys. In the lab wet and dry weight respectively the grain size distribution of samples from 120 locations (sediment traps) of the floodplain were analysed.

The most important result of the first field campaign is that almost no erosion occurred during the flood events in 2001. The lower areas of the floodplain were affected mainly by sedimentation with an average height of 3 to 4 cm. In 2002 the first and smaller flood events occurred during the late spring period between May and the end of July. The floodplain was partly inundated thus no sedimentation / erosion could occur at the more elevated parts of the test site. Heavy rainfalls in August lead to the first bigger flood event and a complete inundation of the test site at the Upper Rhine. The water level was about 2.75 Meters at the test site during the peak of discharge (1600m³/s). This level occurred again at the end of September (1700m³/s) and in the middle of November (1500m³/s).

The second flood period between August, September and November 2002 led to a second field campaign to get a complete data set for the flood events in 2002. This work was carried out in January 2003. The sediment traps, scour chains and iron pools were in-

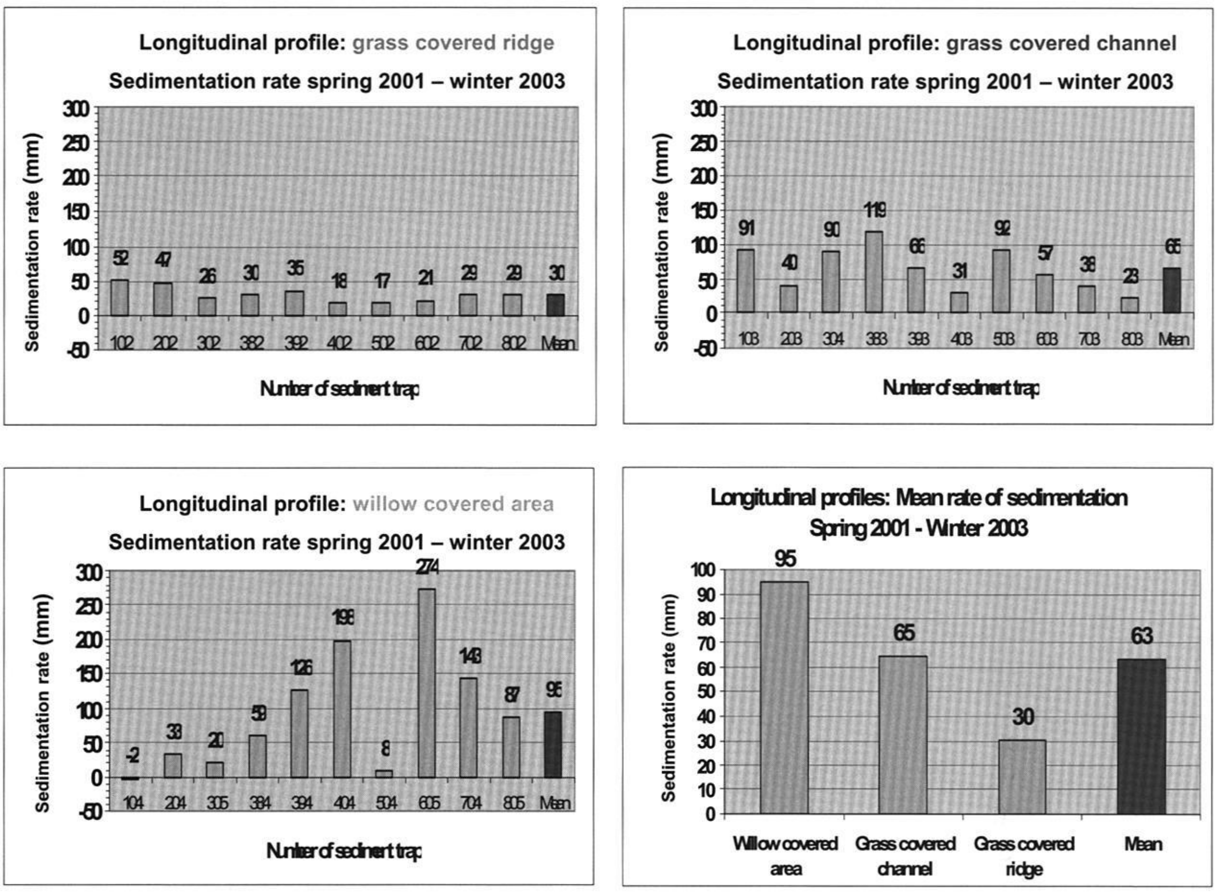


Fig. 40 Sedimentation rate along longitudinal profiles of different location within the test site Hartheim for the period 2001-2003

vestigated again and samples were taken into the lab for future analysis. At all locations the height of sedimentation and erosion was statistical analysed and compared with the results of the geodetic surveys. The data matched well.

The mean rate of sedimentation for the complete test site is about 3cm/ per year (5cm/year geodetic survey). The highest rates could be observed at the willow covered areas (Fig.40). These areas also show the highest max and min value, thus the range of data is more wide compared with the grass covered channel and ridge. The mean rate of sedimentation for the grass covered channel is about 3cm / year, the rate of the grass covered ridge accounts less than 1,5 cm. Erosion mainly occurred inside the stand of willows at the upstream part of the test site. The bigger flood events in summer and fall 2002 led to sedimentation rates with bigger max. / min. values and a higher amplitude of sedimentation rates. The smaller flood events in spring time caused lower sedimentation rates all over the area but also the amplitude was lower. A comparison between the willow and grass area showed that over the last 2 years the rate of sedimentation was remarkably higher inside the stand of willows.

The lower areas of the floodplain were affected mainly by yearly rates of sedimentation with an average height of 3 to 5 cm. This validates the results from 2001. The calculation of net loss / gain of retention volume is about 225m^3/year at an area of 7500m^2. With respect to a pore volume of 40% this means a net loss of retention volume 135m^3 /year (0.018m^3/year/m^2) at the test site.

Microscale Roughness – Grain Size Distribution with Regard of Temporal and Spatial Changes and the Impact of Vegetation

At the beginning of the field campaign samples were taken at the site and grain size distribution was examined with a view to establish the micro-level roughness of the sediments on the test field FS 1 in summer 2000. The lab analysis of samples between 2000 and 2002 are illustrated in Figs.41-43 as cumulative distribution of grain size for the longitudinal profiles L2, L3 and L4. All profiles are orientated from up-to downstream, parallel to the direction of the river and the embankment (e.g. 103 upstream, 803 downstream; L2: grass covered ridge, L3: grass covered channel of the lower floodplain level between the willow belt and the ridge, L4: willow belt along the borderline to the main river of the lower floodplain level). The repeated analysis of fresh sediments samples shows that the grain size distribution covers a range up to 2mm and is mostly dominated by fine sand, silt and clay with a d50 values of less than 2mm.

The initial situation in 2000 can be characterized by a range of the d50 value between 100-110μm for L2, with a d50 value between 10-110μm for L3 and a d50 value between 20-90μm for L4. The upper floodplain level is initially dominated by a sandy material, whereas the lower areas show a wide range between a very clayey and sandy material.

The situation in 2001 can be described by a wide range of the d50 value between 20-90μm for L2, with a d50 value between 30-80μm for L3 and a d50 value between 30-110μm for L4. In 2001 a distinct differentiation could be made between L3 and L4 due to a rate of fine sand between 60-80% at L4 and 30-60% at L3. L2 is quit similar to L3 with a range between 20-70%. The events in 2001 caused the accumulation of a more sandy, less cohesive material at the willow covered areas, whereas the grass covered areas show both a wide range in grain size distribution and a domination of a more fine silty material (20-40% <63μm at L4, 40-60% <63μm at L3). At all areas the amount of clay is remarkable high with a range between 2 and 20%. The lowest values for clay content could be observed at the willow area, the

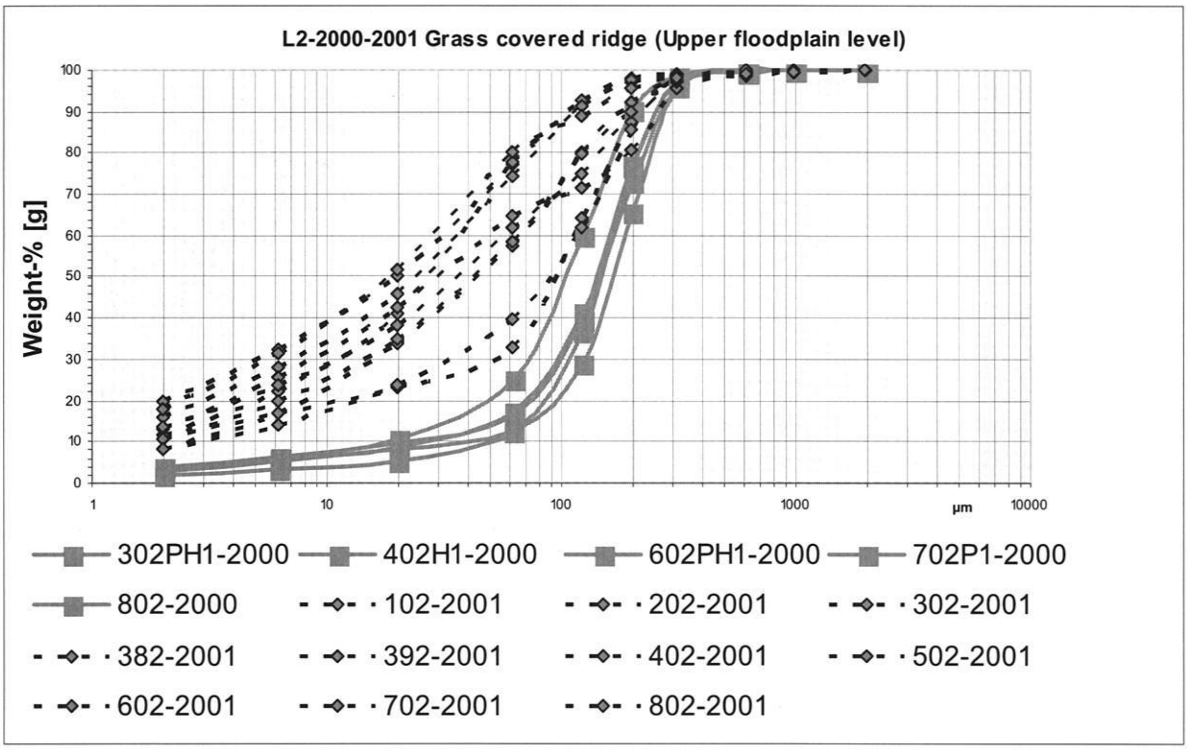


Fig.41 Grain size distribution for longitudinal profiles at the upper floodplain level

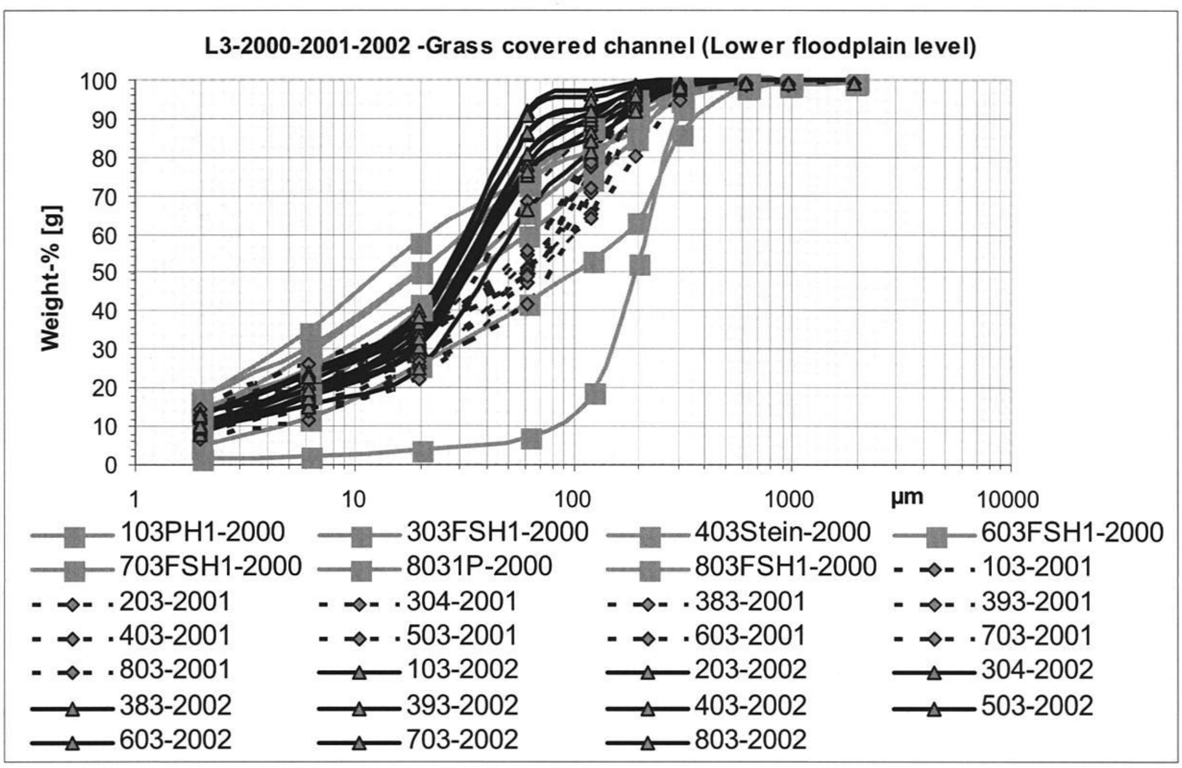


Fig.42 Grain size distribution for longitudinal profiles at the lower grass covered floodplain level

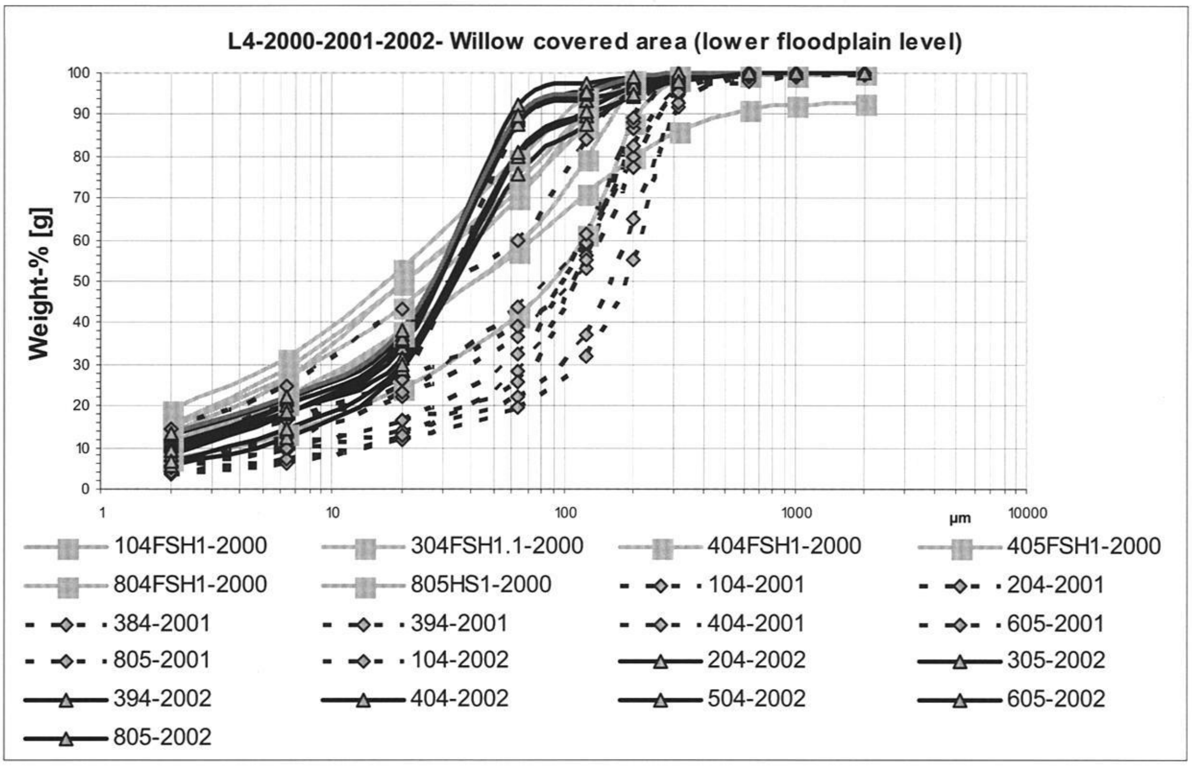


Fig.43 Grain size distribution for longitudinal profiles at the lower willow covered floodplain level

highest one at the ridge. The situation in summer 2002 can be described by a range of the d50 value between 20-30µm for L3 and a d50 value between 20-30µm for L4. For the profile L2 no data could be obtained due to the absence of inundation till summer 2002. The smaller floods in spring 2002 led to the sedimentation of a very fine material at both areas which is dominated by a very fine silty material, almost no sand occurred. Between 70-90 % of the grains are smaller than 63µm; 5-15% are smaller than 2µm. No distinct differentiation could be made between the grass and willow covered areas in 2002.

The comparison of data from 2001 and 2002 for L3 and L4 show a shift from a sandier in a more silty material. The analysis of flow velocities and grain size distribution with regard to Fig.44 shows that only inside the willow grove velocities occurred (950mm/s) which could possibly lead to a distinct erosion of consolidated material. This could also be observed by the data of the geodetic survey and the sediment traps.

Spatio-temporal Changes of Flow Field under Impact of Floodplain Vegetation

The existing results show a distinct difference at the two locations covered either with willows or grass as well with regard to maximum and minimum of current velocity as to its vertical distribution. The vertical distribution of flow velocities result in mean velocities at the test site which range between 0.84 (August 2003) and 1.06m/s (November 2003) for the grass area and 0,68and 0,71m/s for at a discharge of 1600m³/s and a water level of 2,3m (above floodplain level). The mean velocities at the willow area are between 15 and 35% lower compared with a grass covered area. These results were obtained both during the floods in 2001 and in 2002. The velocity close to the bottom is remarkable higher inside the willow grove than inside the grass covered area and decreases

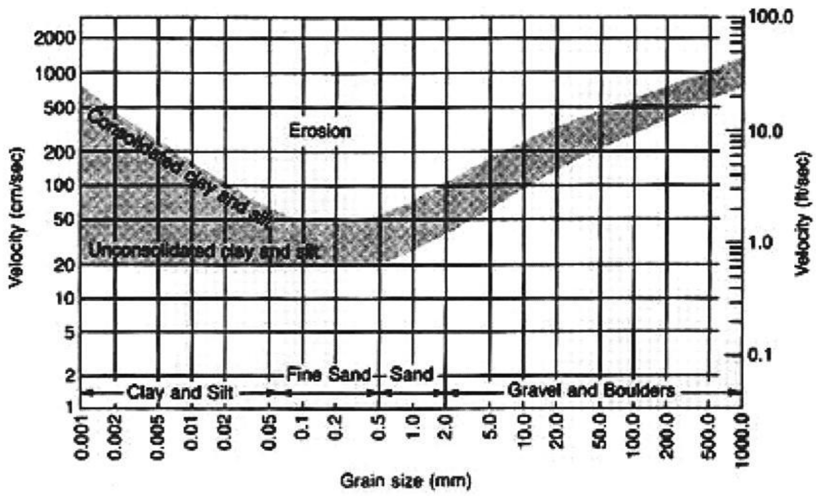


Fig.44
Hjulstroem diagram, modified after Sundborg (1965)

with height. At a certain point in the lower third of the water column the maximum is reached. From that point the velocity decreases. On the grass covered area the minimum is located at the bottom and the maximum close to the water surface. A comparison of data sets from both locations at same water levels shows an intersection of the velocity curves.
Thus it has to be discussed what are the main factors leading to the high velocities at the lower third of the profiles inside the willow grove. The direct comparison of both data sets leads to the assumption that the 18 years old willows decelerate the water body at the upper two third of the profile and accelerate it at the lower third. Since the high velocities do not occur at the grass covered site it can be assumed that the resistance of canopy against the flow field is the main factor for acceleration of ground near velocities and an almost linear decrease of velocity within the upper parts of the profiles. Copeland (Copeland, 2000) could observe that the foliage canopy of woody vegetation diverts flow beneath the canopy. Fischenich has described similar velocity plots for unsubmerged and submerged vegetation (Fischenich 2000). The correct estimation of roughness parameter for the willows at the test site demands a partition of roughness into four sections. The first one is dominated by ground roughness due to grass and herbs; the second one is under impact of the rigid part of the stem, the third one is located at a transition zone between rigid part of the stem and the starting of the canopy layer, the fourth one is dominated by flexible tree canopy.
Since the decelerating impact of stem flow and the accelerating impact of canopy subflow counterbalance each other, there is no net increase of discharge at the willow area compared with the grass area. This situation can change due to higher water levels and a change of flexible roughness of the tree canopy. Beneath a certain water level of about 1meter above floodplain level the willows do not have any impact on decrease of discharge.
Another observation was made due to submerged vegetation especially grass. During single subset flood events the ground velocities increased with ongoing time. At the end of one event the ground velocities were higher at the same water level compared with the same situation before the flood peak at the beginning of the event. This could also be estimated for all other sections in the vertical profile and for both locations. That points to the change of roughness of the grass and willows due to a change in shape and/or the impact of driftwood and drift

grass, whereas a distinct seasonal effect of vegetation on the flow field and discharge (density and amount of leaves, etc.) could not be observed both by the local measurements and with respect to the video monitoring images. An exception is the increase of ground velocities at both locations with regard of a comparison between September and November 2002.

Spatio-temporal Changes of Sedimentation and Erosion under Impact of Floodplain Vegetation

While at the grass covered areas the ground velocities are remarkable low, the high ground velocities at the willow covered area could lead to erosion of material. This could also be observed during the investigation period. Copeland describes that the foliage canopy diverts the flow beneath the canopy and the bottom flow with distinct high velocities. This could cause general scour and increased sediment transport respectively the bed velocities can be high enough to cause erosion (Copeland 2000).

The investigated floodplain test site is all over dominated by a fine to very fine material with range between clay and sand. The initial situation in 2000 of the upper floodplain level can be described by a grain size distribution which is dominated by a very sandy material whereas the lower areas both willow and grass sites are covered with a more silty material.

Since at both locations a high percentage of very fine material occurred the sedimentation seems to increase at the end of the flood events due to low flow velocities. Future investigations can give more detailed information about the critical water level and discharge.

The indication for instabilization of morphology due to high velocities at the ground and over a longer period can be stressed out by the results of the sediment traps since at the willow covered areas both the amplitude was quite high and erosion occurred especially during the bigger flood events. The grass covered areas show a distinct pattern of sedimentation which lead to the assumption that grass areas due to low ground velocities enforce sedimentation of material. These areas also show in general a lower D50 value. Furthermore during smaller flood events the amplitude at all locations was low and only sedimentation occurred. This indicates that smaller flood events enforce the siltation of the floodplain. No erosion occurred up to a water level of 2.7m and a discharge of 1600m³/s with its maximum velocities. The system is stable under normal flood conditions. Whereas the willow areas showed a slight tendency to erosion the grass cover protect the floodplain bed against erosion. Up to that point flexible young trees have a positive effect on net sedimentation. Copeland could observe that due to high velocities at the bottom higher rates of transported sediment occur but that also from a certain point erosion can take place. It can be concluded for the test site that smaller flood events up to a discharge of 1600m³/s lead to sedimentation, whereby the willow areas are always affected by higher rates of sedimentation compared with the grass area. At low discharge floodings –which have a high recurrence interval- the floodplain of the test site Hartheim has a tendency to pronounced sedimentation. Bigger flood events lead to higher amplitudes in rates of sedimentation, whereby local erosion could be observed at the willow sites. Therefore it can be assumed that due to the higher ground near velocities the floodplain inside the willow area becomes unstable. The critical water level for instabilization of the system is > 2.3 m (floodplain level) respectively >1600m³/s for total discharge at the Upper Rhine.

3.2 Field Work at the Wien River (FS3)

Four years of continuous observation have now provided the data to show the development of the vegetation for the different soil bioengineering structures and to present first results regarding the flow field distribution inside and outside of the vegetated flow area.

Bank Protection by Means of Vegetation

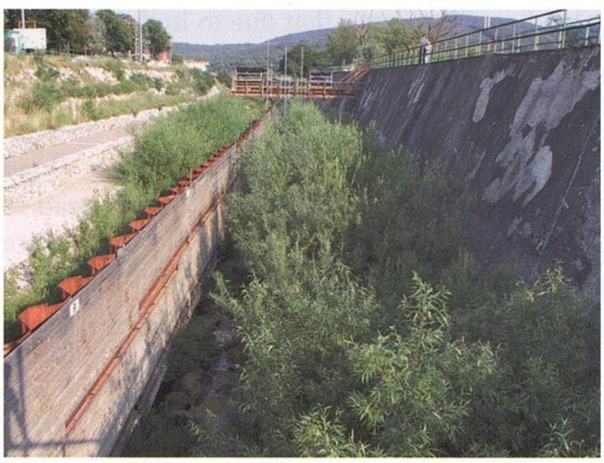
Figs.45-47 demonstrate the capability of willows to bend when flown over by a body of water, to cover the embankment and to protect it from erosion. Even plants with basal diameters of more than 6 cm are highly deformed and completely submerged. Within the vegetated part of the cross-section, flow velocity is reduced to less than 0.5 m/s at a depth of 20 cm above ground.

Flow Velocity Distribution

The distribution of the flow velocity (Fig.48) in the downstream direction shows that the velocity in the vegetated part of the cross-section (profiles "adp270stat" and "adp320stat") amounts to 1.8 to 2 m/s whereas velocities up to 4.2 m/s were observed in the open channel (profiles "adp70stat" to "adp220stat").

Relationship between Discharge and Water Level

Fig.49 shows the relationship between observed water levels – exemplary for cross-section 15 – and the discharge at the same moment: Comparing two floodings in 1999 and 2001 respectively shows that the same discharge volume caused higher water levels in 2001 than in 1999. In other words: the growth of the bank vegetation has a damming-up effect and thus causes the observed water levels to rise significantly.



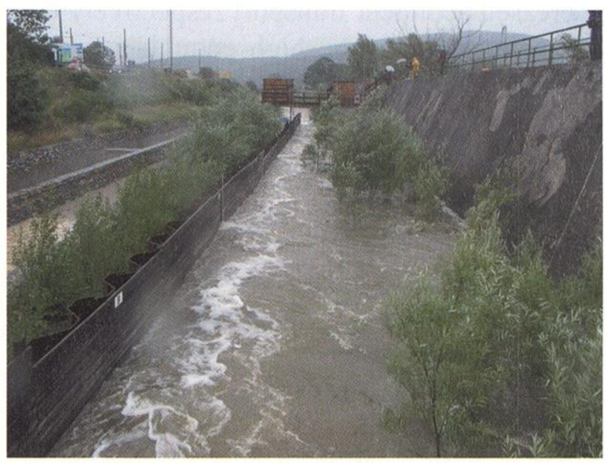


Fig.45 (top left):
Succession of willows after 3 years in 2001

Fig.46 (top right):
Artificial flooding July 2002: some plants still resist the drag forces exerted by the flow

Fig.47 (left):
Natural flood event August 2002: Situation of total submergence

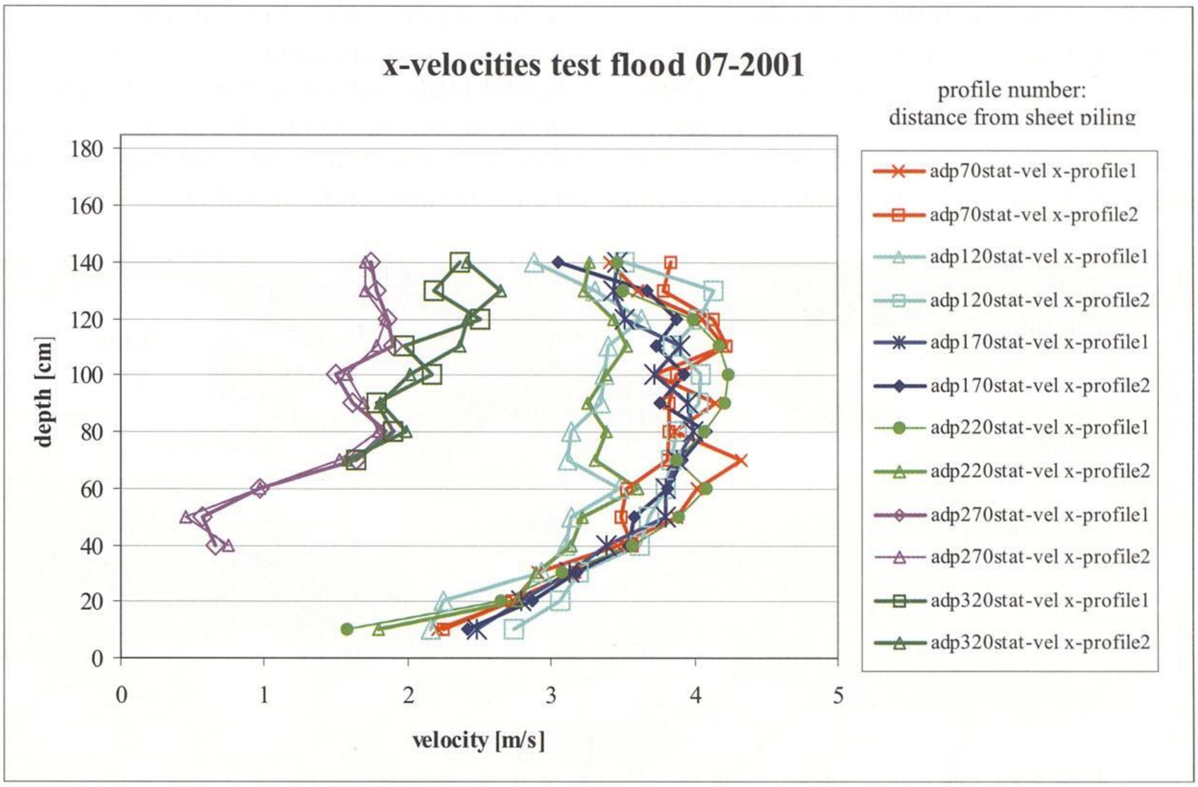


Fig. 48 Flow velocity profiles: open channel (profiles "adp70stat" to "adp220stat") vegetated bank (profiles "adp270stat" and "adp320stat")

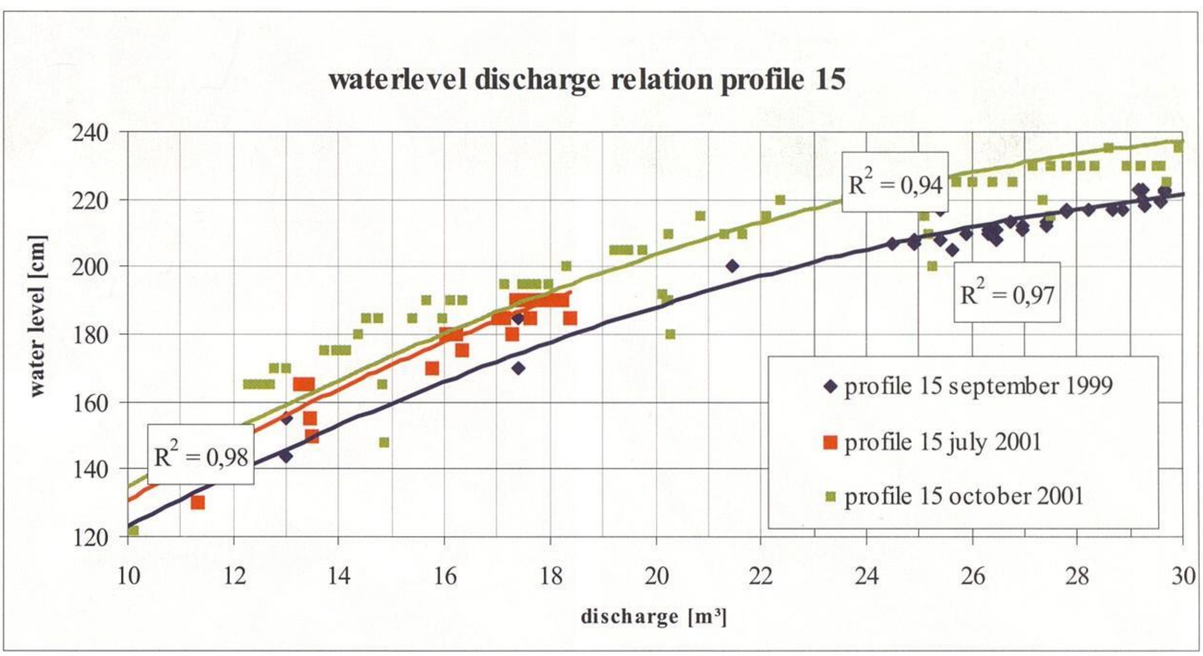


Fig. 49 Relationship between water level and discharge observed during floodings in 1999 and 2001

Damage to the Plants due to Floods

The plant species used (i.e. *Salix alba, S. caprea, S. purpurea., S. fragilis, S. x rubens*) are highly flexible and thus astonishingly resistant to bending stress. Nevertheless damage does occur, especially when the direction of the water's drag force differs from the anatomic load direction, i.e. the direction of natural loads applied to the plant by gravity, snow, wind, etc. (Figs.50-52). Yet, damage done to individual plants does not threaten the entire population of willows.

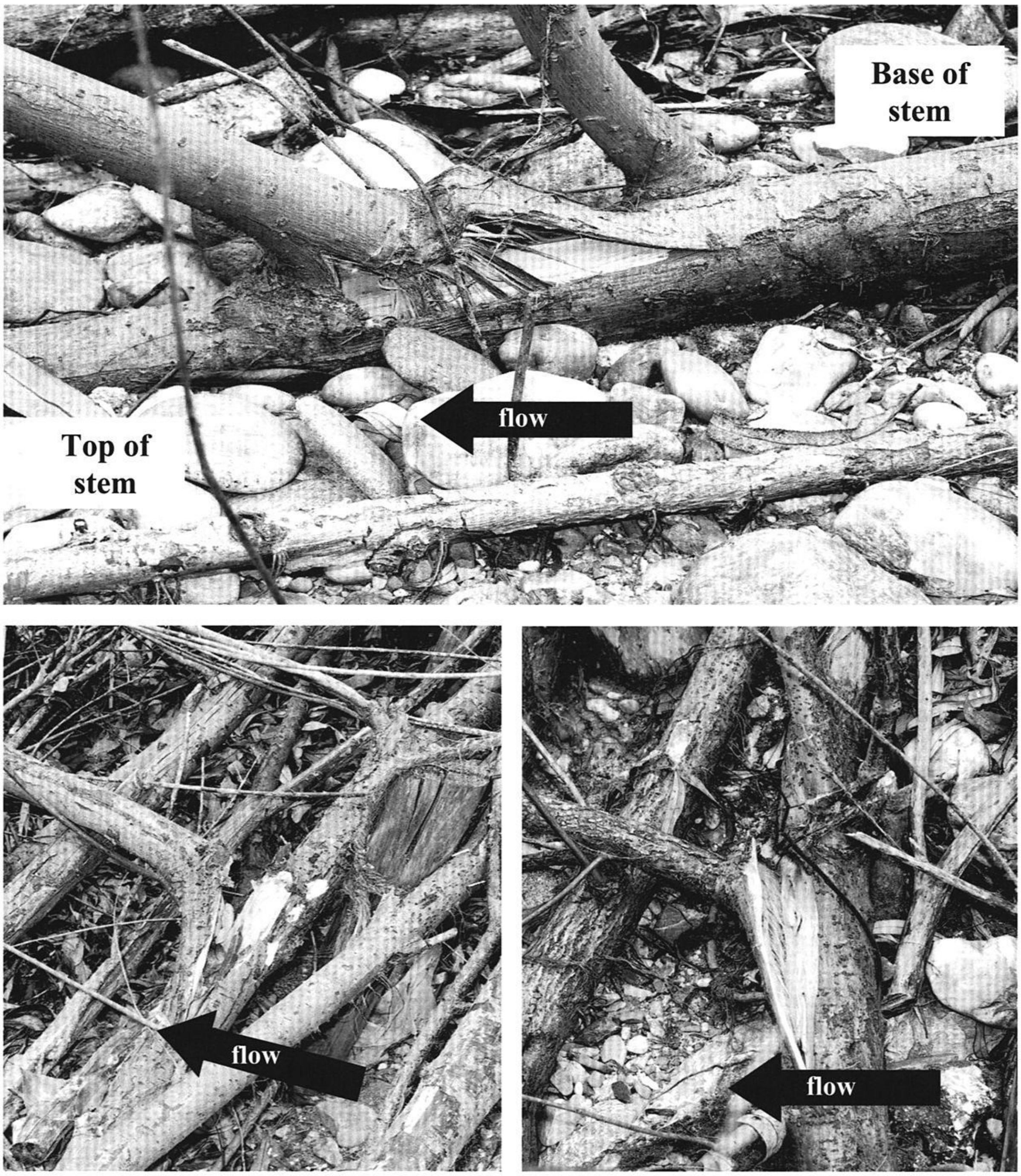


Fig. 50-52 Damage due to floodings: breaking of willow branches due to longitudinal (Fig.50, top) and transversal (Figs.51/52, below) stress exerted by the flow

3.3 Field Work at the Fersina (FS4) and Enz River (FS2)

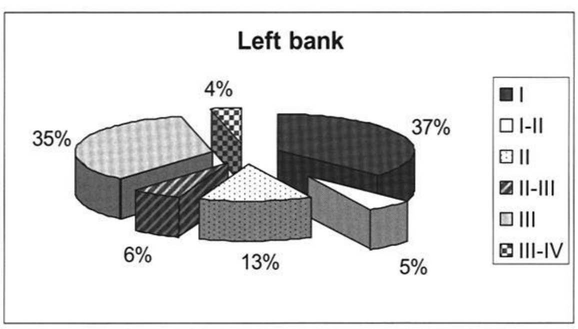
FFI (Fluvial Functioning Index) of the Fersina
The aim of the research is the assessment of the whole ecological conditions of the fluvial functioning of the Fersina. The Fluvial Functioning Index (FFI) method allows the collection of information about the main ecological characteristics of the watercourse and is able to find eco-functional aspects and interrelations between eco-topes within en eco-mosaic. Through the description of morphologic, structural and biotic parameters of the fluvial ecosystem, the watercourse functionality is evaluated. The method gives completely different information from other methodologies that are applied using other indicators or indices (i.e. biotic indices, chemical and microbiological analysis etc.).

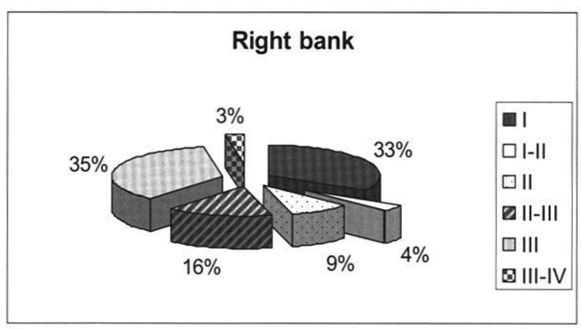
For the Fersina, the results are shown for both banks in Figs.53-54. On the right river bank there is 16540 m length of I functionality level (33%), 650 m of I-II intermediate level, 1410 m of II level, 2560 of II-III intermediate level, 5890 of III level (35%) and 480 m of III-IV intermediate level. It is possible to observe a majority of the III level. On the left bank there is a predominance of the I level (6120m, 37%), then III Level (5780 m, 35%). The other levels are divided as follow: 900 m of I-II intermediate level, 2220 of II level (13%), 940 of II-III level and 580 of III-IV intermediate level.

The findings show that there is a relevant percentage of I level stretches located mainly in the upper part of the Fersina river basin. The results analysis was carried out associating the questions in groups that represent a functional characteristic, the structure of the FFI form allows to investigate different environmental sectors:

- questions 1-4: vegetation condition and land use near the river course
- questions 5-6: wet river channel width and physical and morphological structure of the river bank
- questions 7-11: river channel structure
- questions12-14: biological characteristics

Questions 1-4
There is a general worsening of the right river bank comparing with the left bank, in the upper part of the river basin there is a relevant variability of conditions for both banks: the worst stretches are those where there is a noticeable presence of weirs and longitudinal infrastructures (flood defences, stone and concrete walls) and with a small and discontinuous riparian strip. The percentage score decreases going downstream according to the land use and the artificiality of river bed with the formation of secondary riparian vegetation.





Figs. 53-54 Fluvial functioning indices of the right and left bank of the Fersina torrent

	Cumulative number of leaves			
Time (minutes)	July 2000	November 2000	February 2001	June 2001
1	55	0	0	0
2	145	10	0	0
3	180	393	0	15
4	212	602	0	349
7	249	668	218	459
10	271	696	309	514
15	295	719	371	571
20	308	732	401	589
40	343	758	445	623
60	372	773	460	666

Tab.8 Cumulative number of leaves at the Fersina torrent

Question 5-6
In the upper part of the river basin there is a certain variability due to the presence of stretches with artificial infrastructure. The analysis of this question group allows to suppose that there is a variation of hydraulic regime which can compromise the river bank stability in few critical points.

Question 7-11
The score for both banks is quite high for the upper part of the Fersina catchment which reflects a good depuration capacity. In lower part of basin, the stream Fersina looks like a typical valley bottom river which influences the functionality also because of the canalisation and straightening of the river bed.

Question 12-14
The biological characteristics are fairly good especially in the upper stretches. In the lower part the artificial infrastructure do not guarantee the presence of a stable macrobenthonic community.

Short Term Retention Measurement
Small headwater streams in forested areas have been observed to be heavily dependent on the input of organic material (CPOM, leaves and sticks) coming from the surrounding terrestrial system that acts as an energy source. Retention mechanisms, which retain CPOM in the system, are very important, because they allow it to be processed rather than transported downstream in a coarse particulate form.

The knowledge and the measurement of retention stream features constitute an important step to understand the dynamics that regulate the formation of specific macroinvertebrate community; moreover retention can be related to the colonisation dynamics of substrates and to organic matter demolition. Four monitoring campaigns were carried out in July 2000, November 2000, February 2001 and June 2001.

Mathematical elaboration permitted to define the equation of each curve based on the following relation:

$$f(x) = \frac{ax}{1+bx}$$

where: x = time (minutes), y = cumulative number of leaves arrived

The results for Fersina site are:

2000, July $y = 76,2x / (1 + 0,19x)$

2000, November $y = 283,7x / (1 + 0,35x)$

2001, February $y = 76,4x / (1 + 0,15x)$

2001, June $y = 128,4x / (1 + 0,17x)$

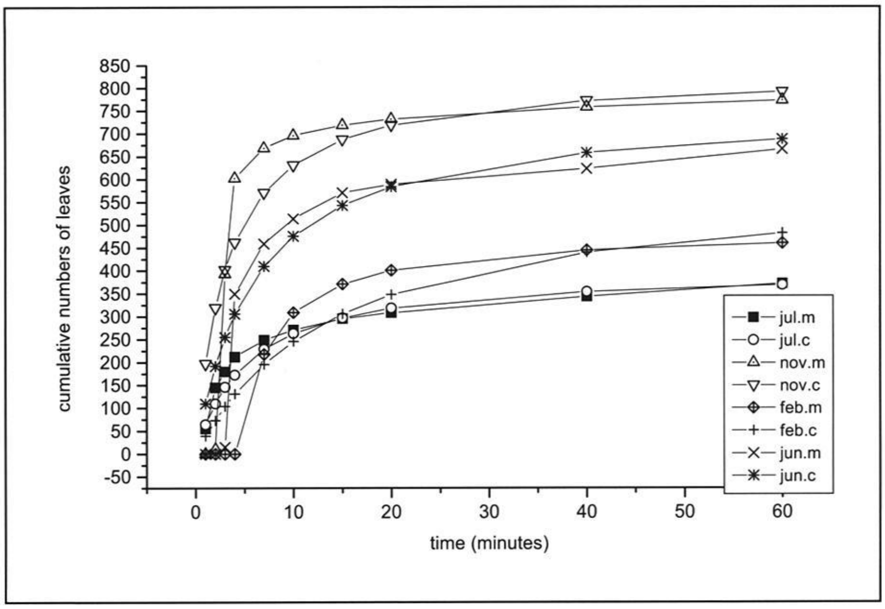


Fig. 55 Cumulative number of leaves captured in the four monitoring campaigns

Short term retention of organic matter is related to the hydrology and the substrate typology. The stretch showed different retention capability in all periods: in July it were retained 62.8% of the leaves released; in November only 22.7% of the leaves were retained, while in February 54% of the leaves were retained; in June 33.4% of the leaves were retained.

The graphs in Fig.55 represent the data of leaves captures in the four monitoring campaigns. The lines named with the month and a "-m" indicate the values observed on site (real data) and the lines with the label "c" are the calculated data using the above formula. Several different mathematical relations were tested but the formula fits better the real data path. The formula coefficients were worked out using the minimum squares method. From a statistical point of you, the correlation between real and calculated data is quite high for $p<0,005$. Therefore the algorithm $f(x) = ax/(1+bx)$ can be considered adequate to represent the retention process of the organic matter and the asymptote.

The graph show the cumulative number of leaves captured at different times, assuming an asymptotic curve. The asymptote of each curve may indicate the maximum retention capability for each period, characterised by different hydrological regimes. The highest asymptote is peculiar for the low retention because many leaves released were not trapped under the stones or other CPOM traps. This kind of investigation seems to be a useful method for evaluating the ecological aspects of alpine streams and gives important information for river management.

Leaf-packs

In this analysis the CPOM demolition processing was investigated using a defined amount of natural autumnal leaves called normally leaf packs. It is possible to evaluate the CPOM demolition capability of a river, observing the weight lost from a leaf pack during a fixed time period. The starting date for leaf pack positioning was June 27, 2001 (about 25 packs). Three leaf-packs were collected weekly (for a period of 5 weeks). In the laboratory leaves were washed to remove sediment and animals, and dried at 50°C for 24 hours. Animals were collected, sorted, classified at Genre or Family level and preserved in non-denatured 70% ethanol. In the following graph (Fig.56) is shown the pattern of leaf degradation expressed as weight loss against day-degrees, as the temperature

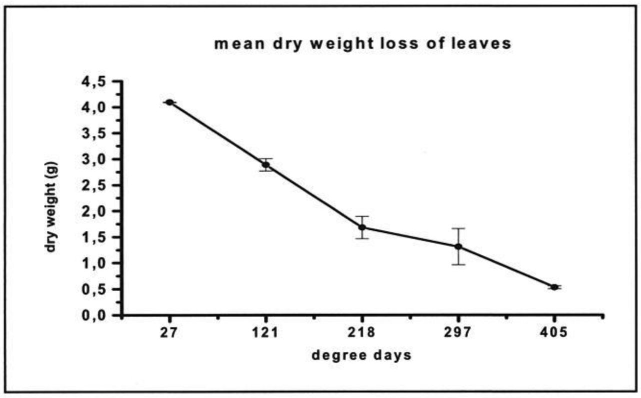


Fig. 56
Leaf degradation expressed as weight loss against day-degrees

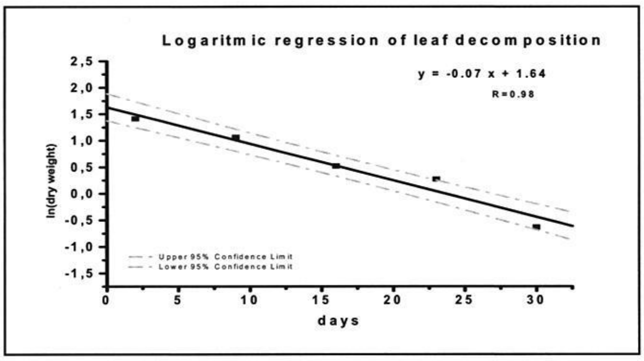


Fig. 57
Logarithmic regression of leaf decomposition

can influence the bacterial process. The values of water temperature have been recorded at the same time of the leaf collection and transformed in day-degrees multiplying the temperature by days spent by the leaves in the water. The log regression of leaf degradation is shown in the Fig.57, where the time is in abscissa and the *ln* of remaining leaves weight in ordinate.

The coefficient *k* represents the slope of the regression straight line. The linear correlation between remaining weight of leaf packs has a very high significance with a correlation coefficient of r= 0.98. The results show that the presence of macro invertebrates is related to their food preferences.

It is possible to note that the colonisation process is characterised by the dominance of collectors group already starting from 9th day and the predator group appears only after 23 days. Along the quali-quantitive analysis of benthonic organisms, it was measured the dry weight of the collected macrobenthonic matter. Collector group biomass increases progressively from 66 of total benthic weight % after 9 days to 87% after 30 days, while filterers decrease from 30% at 9th day to 1% at 30th day.

Benthos Quantitative Sampling

With this methodology abundance of macrobenthonic community can be correlated with a fixed area of the riverbed. Quantitative sampling allows estimation of population dynamics and productivity.

Three monitoring sampling were made, in July 2000, in February 2001 and in June 2001. In the following table are shown the abundances of collected macroinvertebrates; for each monitoring sampling three samples were collected (C1, C2, C3).

In July each sample had a mean of 1232 individuals; so macrobenthos community in Fersina river had in July a density of 12320 organisms/m2 (Surber sampler is an aluminium frame that defines a fixed area of 0.1 m2 of riverbed).

In winter in each sample a mean of 1413 individuals were counted and classified (14130

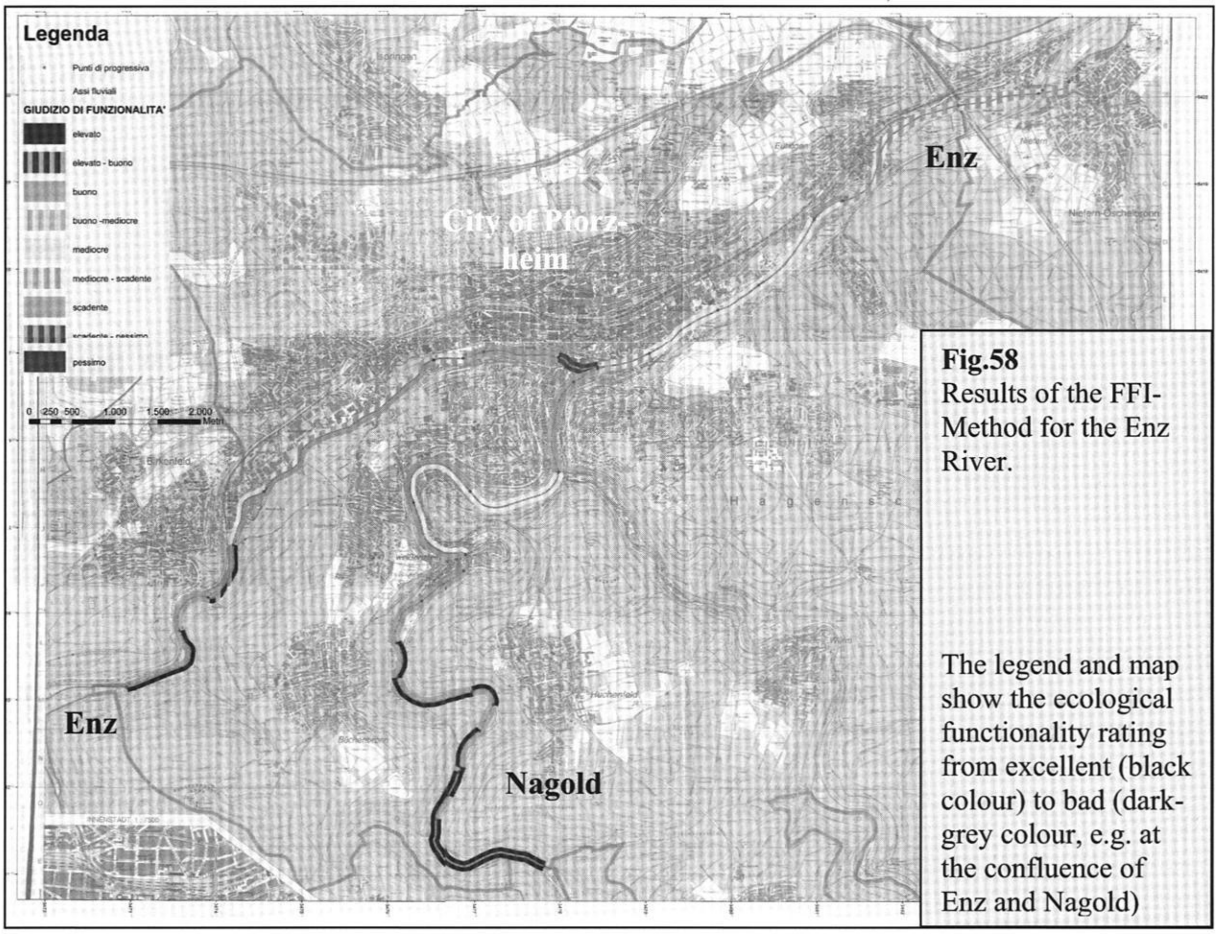


Fig.58
Results of the FFI-Method for the Enz River.

The legend and map show the ecological functionality rating from excellent (black colour) to bad (dark-grey colour, e.g. at the confluence of Enz and Nagold)

organism/m2). In June each sample had a mean of 3339 individuals (33390 organism/m2).

In July the plecoptera are the dominant group (42%), the diptera are also quite numerous (32%), ephemeroptera are less frequent along with trichoptera, oligocheta, coleoptera and irudinea. In February and June (56% e 66%) the presence of macrobenthos are quite similar: the diptera group is very abundant.

The other taxa are present but not very numerous. Community in July showed a clearly dominance of detritivore organisms (91%), in February and in June too (75% and 68%). Collectors are dominant in the three samplings, with 54%, 69% and 43% respectively. In July the second abundance is represent by shredders, in February by scrapers and in June by filterers.

FFI (Fluvial Functioning Index) of the Enz River

In the same way as for the Fersina, the FFI method was applied to the Enz river and its tributaries (Fig.58). The results show the broad applicability of the FFI method to different types of streams and land-use functions (especially for urban surroundings as in the case of the river Enz at the city of Pforzheim).

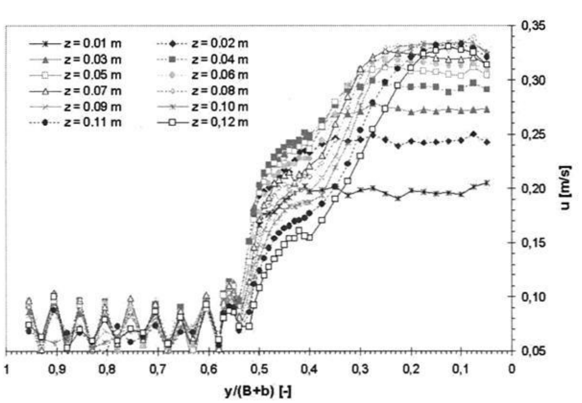
3.4 Flume Experiments on Riparian Flow Field

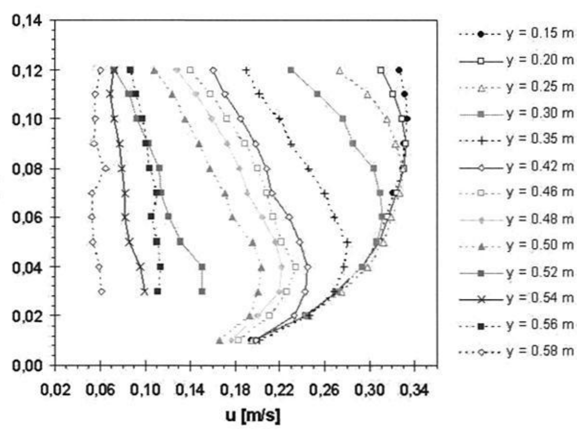
Momentum Exchange Processes

The results clarify the strong influence of turbulent secondary currents on the exchange of momentum in the interaction zone between main channel and floodplain. The secondary currents have the structure of a significant main channel vortex generated close to the junction with a horizontal axis in flow direction and clockwise rotation similar to the results of Nezu et al. (1999) and Tominaga et al. (1989). The main channel vortex caused an intrusion of faster velocities from the main channel into the floodplain in the lower regions of the flow. This effect was counterbalanced by a dispersion of lower floodplain velocities into the main channel in the upper regions close to the water surface. The secondary currents were observed in all runs and their influence on the velocities is shown in Figs.6a-c exemplarily for a complete spatial and temporal averaged data set of S4q20 (flexible cylinders with a density of 5*10cm² per plant).

Fig.59a shows horizontal profiles of the primary mean flow velocity as a function of water depth z [m]. The cross section can be subdivided into three regions: main channel ($0<y/(B+b)<0.2$), interaction zone ($0.2<y/(B+b)<0.52$) and floodplain ($0.52<y/(B+b)<1$). The so called "cooperating width" (Pasche, 1985) where the floodplain flow and velocities are influenced by the momentum exchange with the main channel is not distinct.

The floodplain velocities show a stepped distribution starting right at the first row of cylinders. The maximum and minimum of each step are almost constant across the floodplain. This is due to the data location that





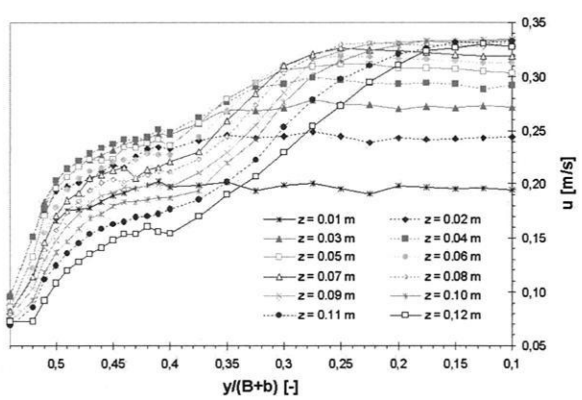


Fig.59a (top left) Horizontal profiles of primary mean velocities for setup S4q20

Fig.59b (left) Horizontal profiles of primary mean velocities for setup S4q20 for the interaction zone

Fig.59c (top right) Vertical profiles of primary mean velocities for setup S4q20 were between two cylinders (e.g. $y/(B+b)$=0.605) or in the wake behind one cylinder (e.g. $y/(B+b)$=0.63). The floodplain is characterized by strong lateral mixing and deceleration of the flow whereas between two cylinders the velocity increases.

The interaction zone demonstrates the influence of momentum exchange that goes far into the main channel (Fig.59b). Close to the water surface (z=0.12m), the mean velocities are influenced up to $y/(B+b)$=0.15 by the momentum exchange and close to the bed (z=0.01m) up to a value of $y/(B+b)$=0.4. The impacts of the secondary currents can also be seen in the deflections of the vertical mean velocity profiles for different locations across the channel in Fig.59 c. The profiles in the main channel close to the wall are showing the characteristic logarithmic shape (y=0.15m). Whereas the mean floodplain velocities are almost constant over the water depth (u=0.06m/s at y=0.58). In the interaction zone, an adaptation of undisturbed main channel velocities towards the vegetation-dominated floodplain velocities occurs and results in horizontal as well as vertical deflections in the velocity profiles. As a consequence, the velocities close to the junction reach a maximum in the lower regions of the flow and not close to the surface as in usual open channel flows.

Depth-averaged and Lateral Velocity Profiles

In Figs.60-63, depth-averaging of the complete data sets of the 18 runs was carried out to differentiate the influence of vegetation properties, density and relative water depth in the interaction zone. Figs.60 and 62 are horizontal profiles of the depth-averaged mean velocities $<u>$ [m/s] made non-dimensional by the maximum depth-averaged velocity $<u>_{max}$ [m/s] of each data

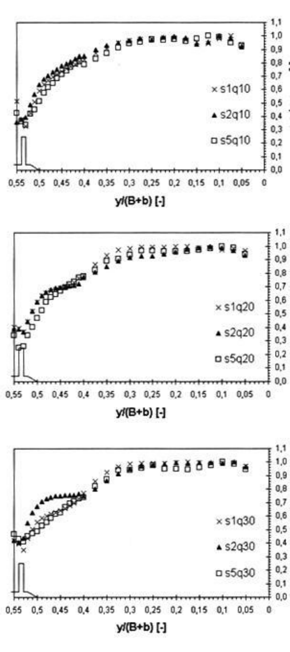


Fig.60a-c Horizontal profiles of depth-averaged primary mean velocities for the interaction zone (low plant densities)

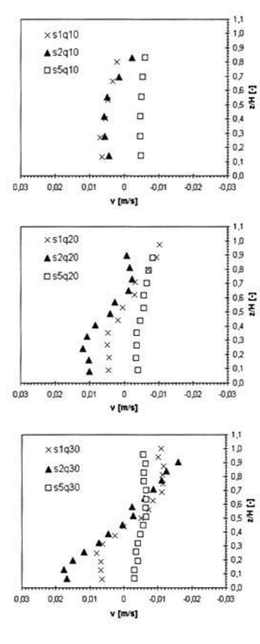


Fig.61a-c Vertical profiles of lateral mean velocities at location $y/(B+b)$=0.48 (low plant densities)

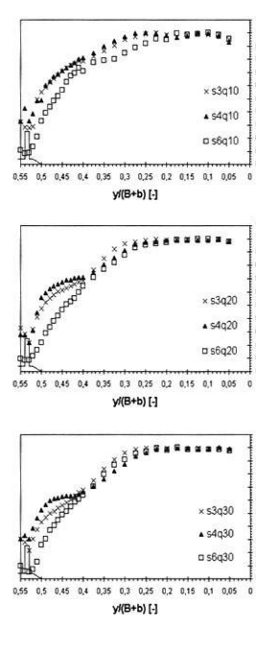


Fig.62a-c Horizontal profiles of depth-averaged primary mean velocities for the interaction zone (high plant densities)

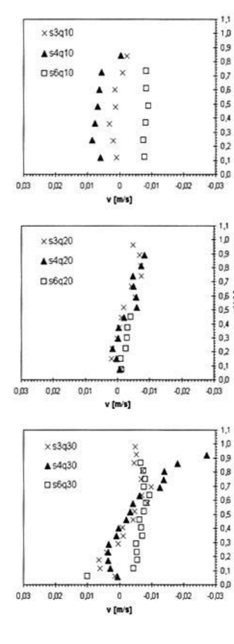


Fig.63a-c Vertical profiles of lateral mean velocities at location $y/(B+b)$=0.48 (high plant densities)

set and classified into the different discharges. Herein, (a) refers to 10l/s, (b) to 20l/s and (c) to 30l/s. Fig.60 contains the low floodplain density data (S1, S2, S5), and Fig.62 the denser installations (S3, S4, S6). Furthermore, in Figs.61 and 62 vertical profiles of the appropriate lateral mean velocities v [m/s] are displayed as a function of the dimensionless water depth y/H [-]. The vertical profiles refer to a single location $y/(B+b)=0.48$ in the main channel close to the junction. Positive values of v characterize lateral flow directed towards the floodplain ($v>0$) and negative values towards the main channel ($v<0$).
The influence of secondary currents on the depth-averaged profiles is small for a width up to $y/(B+b)=0.35$ in the main channel and the horizontal profiles for all runs are in good agreement. Only the leafy cylinders (S6) in Fig.62a show a stronger deceleration in this region which is related to the higher plant density and the resulting wake structure behind the cylinders.
For a relative width $y/(B+b)>0.35$, the velocities are strongly affected by secondary currents and show deflections of the horizontal velocity profiles. These deflections are correlated with the lateral velocity distribution in Fig60 and 63. The steeper the gradient in the lateral velocity profile, the stronger is the deflection of the horizontal profile. Obviously, the gradient and the deflections increase with increasing relative water depth but also differ for the varying floodplain vegetation. Taking the rigid cylinders (S1, S3) as a reference, the flexible cylinders (S2, S4) cause an enforcement of the lateral gradients and deflections. Whereas the leafy cylinders (S5, S6) show a damping effect and have an almost linear distribution of lateral velocities over the water depth. Comparison between the two densities in Figs.60 and 62 indicate only small differences except for the leafy cylinders (S6). This setup appears to cause significantly lower velocities at the junction which is related to the wake structures as already mentioned above. The higher plant density and foliage generated larger wake structures behind the elements where the mean velocities locally reached a minimum.

Floodplain Vegetation
The measurements of physical parameters of the flexible and leafy cylinders are presented in Figs.64 and 65. Compressed width, waving frequency and amplitude of the leafy cylinders are displayed as a function of the stem Reynolds-number Re_s [-] ($Re_s=d_s \cdot u_{veg}/\nu$, where d_s [m]: stem diameter, ν [m²/s]: kinematic viscosity of water, u_{veg} [m/s]: depth- and width-averaged mean velocity above the floodplain). It shows that the flexible properties of the foliage in this case are mainly dependent of u_{veg} and do not change with the water depth.
In the case of flexible cylinders only the waving frequency is independent from the water depth and a function of Re_s-number, whereas the horizontal deflection (Fig.65a) and the waving amplitude (Fig.65c) are dependent of the Reynolds-number Re [-] ($Re=h \cdot u_{veg}/\nu$, where h [m]: floodplain water depth) involving both the water depth and the average mean velocity. In all runs, the increase of the plant density was found to have no significant influence on the properties of an individual plant. Only for low Re_s-numbers ($Re_s<1000$) the compressed width is smaller for the lower density (S5) (Fig.64a). The waving amplitude for leafy cylinders shows larger scattering due to the small elongations of the swings that were between 5 and 13mm. For these measurements, the accuracy of the calliper gauge technique was not high enough.

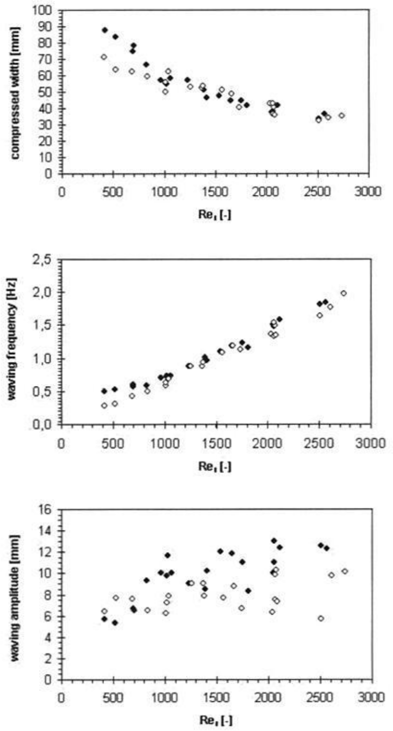


Fig.64a-c Properties of leafy cylinders as function of Re_s-number: (•) S6 and (○) S5

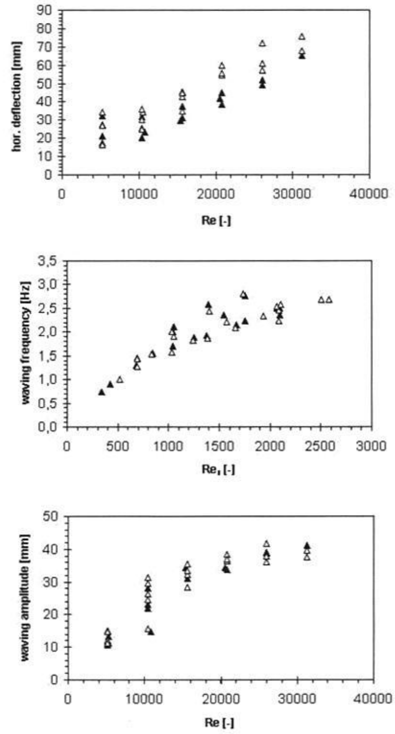


Fig.65a-c Properties of flexible cylinders as function of Re and Re_s-number (▲) S4 and (Δ) S2

In Fig.66 the drag forces F_{drag} [N] exerted on individual plants per unit of water depth are shown as a function of the depth- and width-averaged mean velocity u_{veg} [m/s] above the floodplain. The drag forces were calculated from the momentum equation applied to the entire head-loss of the floodplain. The data of rigid and flexible cylinders of both densities (S1-S4) are in good agreement. Thus, bending and waving effects of the flexible cylinders had no influence on the exerted drag forces and integral resistance. For the leafy cylinders, two effects were determined. Primary, the exerted drag forces were significantly higher due to the increased frontal area of the additional foliage. Secondary, the higher density of (S6) caused smaller drag compared to (S5). The spacing for (S6) was twice as high and the flow structure on the floodplain was more homogenous with smaller gradients of the horizontal velocity distribution between the plants. In case (S5) the wakes behind the plants were isolated from each other causing a winding flow pattern with higher local velocities in front of the cylinders.

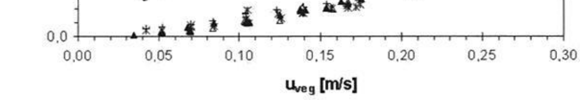


Fig.66 Head-loss data: Drag forces per plant as function of averaged mean velocity on the floodplain

3.5 Flume Experiments on Riparian Morphology

Influence of Emerged Rigid Vegetation on Bed Load Transport in Trapezoidal Channels of Variable Width

Laboratory experiments were carried out by SPECHT (2002) to investigate the influence of emerged rigid vegetation and channel width on bed load transport in sandy rivers. As no new transport formula should be developed, existing formulas had to be modified to describe these processes. Dimensional analysis

$$= \frac{m_F}{\rho_F \sqrt{\rho' g\, d_{ch}^3}}$$

ϕ^*_0 = transport rate which neglects the influenced macro turbulence caused by vegetation. It can be computed e.g. with the transport formula of MEYER-PETER/MUELLER (1949)

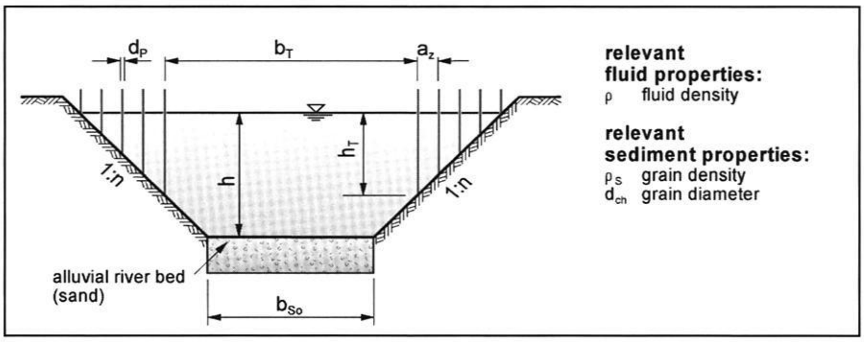


Fig. 67 Definition sketch of the parameters which influence bed load transport in a symmetrical trapezoidal channel with rigid vegetation (b_{So} = width of the river bed)

showed that bed load transport in vegetated channels is influenced by the relative width b_T/h_T (b_T = width of the main channel without vegetation, h_T = water depth at the boundary of the main channel and the vegetation zone, Fig.67), the relative water depth h_T/h (h = water depth at the main channel) and by a vegetation parameter B, which describes the arrangement of the plants, see Fig.67:

$$\phi^* = \phi^*_0 \cdot f\left(\frac{b_T}{h_T}, \frac{h_T}{h}, B\right) \qquad (1)$$

with: ϕ^* = transport rate (defined by EINSTEIN) which takes into account the influence of bank vegetation on the flow

B = vegetation parameter, according to BERTRAM (1985)

$$= \left(\frac{a_x}{d_P} - 1\right)^2 \left(\frac{a_z}{d_P}\right)$$

a_x = distance between trunks in flow direction

a_z = distance between trunks lateral to the flow direction

d_P = diameter of the trunks

The influence of vegetation on bed load transport, expressed in Eq. (1) as a function of b_T/h_T, h_T/h and B, were combined in the vegetation coefficient σ_B:

$$\phi^* = \sigma_B \cdot \phi^*_0 \qquad (2)$$

The vegetation coefficient σ_B was determined from the experimental results by the relationship of bed load transport rates for the cases without vegetation to the one with vegetation:

$$\sigma_B = \frac{\phi^*_{R,oB}}{\phi^*_{R,mB}} \qquad (3)$$

with: $\phi^*_{R,oB}$ = calculated transport rate in the experiments without vegetation by using a common transport formula e.g. MEYER-PETER/MUELLER (1949)

$\phi^*_{R,mB}$ = calculated transport rate in the experiments with vegetation on the banks by using a common transport formula as well.

In Fig.68 the vegetation coefficient σ_B for a symmetrical vegetated channel is plotted as a function of the relative width b_T/h_T and water depth h_T/h. The discharge q was varied as well (see Fig.68) whilst the vegetation Parameter B was kept constant (B = 80). Bed load transport was calculated with the MEYER-PETER/MUELLER formula. A σ_B coefficient of 1 means that the existing bed load transport formula has not to be corrected by the influence of channel width and vegetation whilst in the case of $\sigma_B > 1$ bed load transport rates are underestimated and have to be corrected according to the distributions in Fig.68.

The influence of vegetated banks on bed load transport in trapezoidal channels of different width can be summarized as follows:

- In narrow channels ($b_{WSP}/h < 3{,}5$) with the same vegetation arrangements on both banks ($a_x/d_P = a_z/d_P = 5$; B = 80) the bed load transport increases in some extend up to more than 100% (b_{WSP} = width of the water surface).
- In channels with vegetation on one bank only, the cumulative effect of the macro turbulences of both interfaces disappears. For rivers with $b_{WSP}/h < 6{,}5$ the influence on bed load transport decreases up to 35% (remember: Vegetation arrangements with the same height h_T at the interface were compared, e.g. the bed load transport in a channel with vegetation on one bank (totally vegetated) is 35% lower than in an channel with vegetation on the upper half of both banks only).
- In the case of a density of the vegetation of $a_x/d_P = a_z/d_P = 10$ (B = 810) bed load transport is 20% less than in the case of the standard vegetation with $a_x/d_P = a_z/d_P = 5$ (B = 80). The influence of the vegeta-

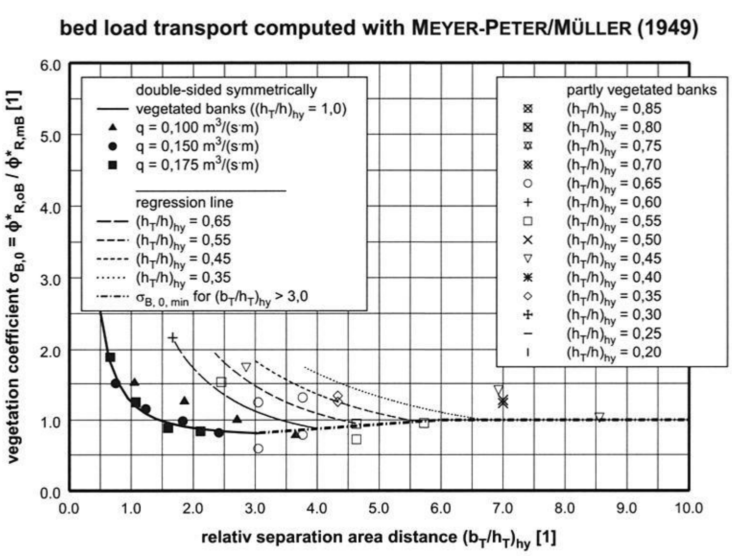


Fig.68
Vegetation coefficient σ_B for a symmetrical vegetated channel based on the transport formula of MEYER-PETER/MUELLER (1949)

tion on bed load transport decreases with increasing distances between the plants.

- Increasing bed load transport rates causes changes in the morphological system of alluvial channels. Due to these changes the bed will erode and the slop will increase, see MERTENS (1994). As a consequence, the water level upstream the vegetated zone will increase and result sedimentation zones.

Influence of Emerged Rigid Vegetation on Bed Forms in Trapezoidal Channels

The influence of rigid vegetation on bed forms is comparable to the influence on bed load transport. In narrow channels this influence is much more pronounced than in wide rivers. In the laboratory experiments of SPECHT (2002) the bed forms mainly consisted of dunes.

Due to the macro turbulences caused by the vegetation the shear stresses on the alluvial sand bed close to the vegetation increased and caused a non-uniform profile in the cross-section, see Fig.69. Especially the dune vales close to the vegetation zone depend significantly. As the dune crests are dominated by the water level the influence of the vegetation dominated macro turbulences was not significant.

In Figs.70 and 71 the two main parameters of the dunes, vale and crest, are plotted as a function of the relative distance z'/h from the vegetation zone for different configurations of bank vegetation and channel width. In the series without vegetation the dune crests and vales were horizontally distributed over the width. Especially, the dune vales close to the vegetation zones are scoured in the series with vegetation. The dune crests were tilted in the cross-section of the channel in the series with vegetation on one bank only.

As a result of the deeper dune vales the steepness of the dunes increased. The steepest dunes occurred not in the series with fully vegetated banks but in the experiments with a relative height of $h_T/h \approx 0{,}8$.

Due to the deep dune vales close to the banks, caused by high shear stresses, bank failure can occur in this region. As the changes in dune crests and vales are not quantified by SPECHT (2002) more research should be carried out in this field.

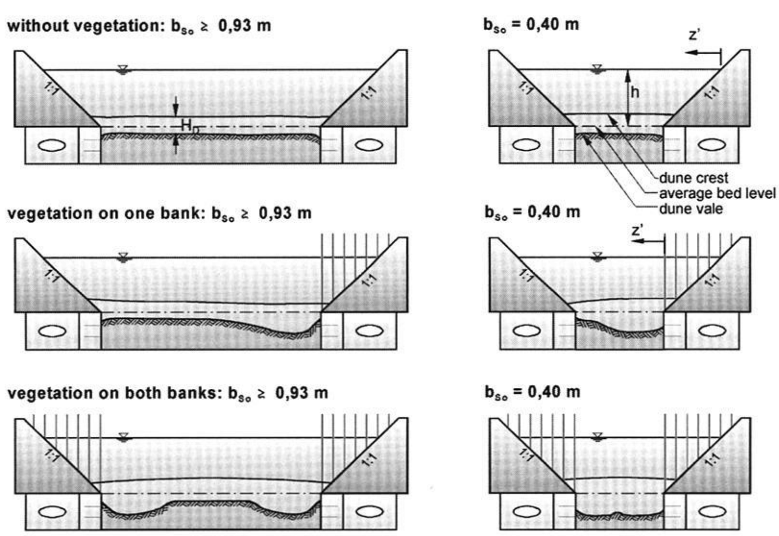


Fig. 69 Definition sketch of the dune formations depen-ding on the vegetation zones on the banks

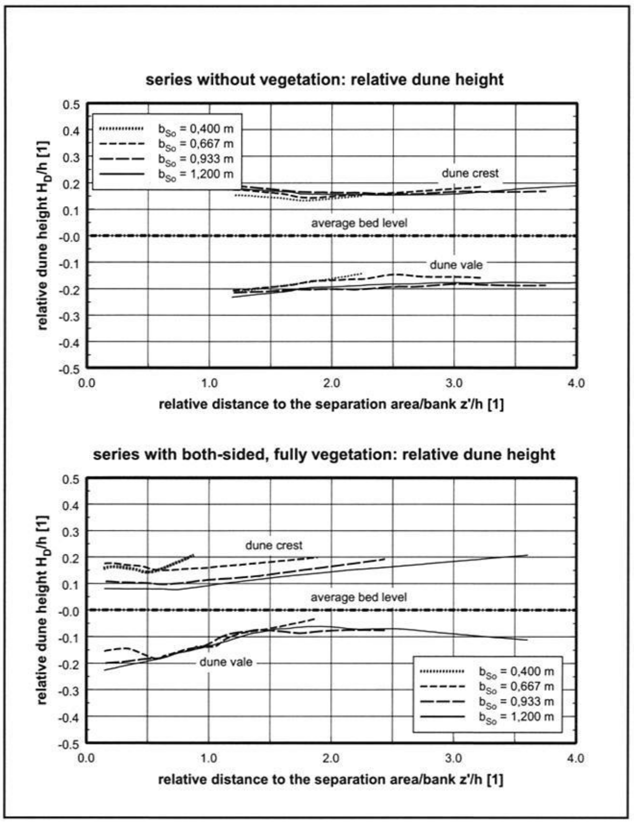


Fig. 70 Averaged dune heights separated in dune crests and vales in the series without vegetation and with vegetation on both banks (the whole bank is vegetated)

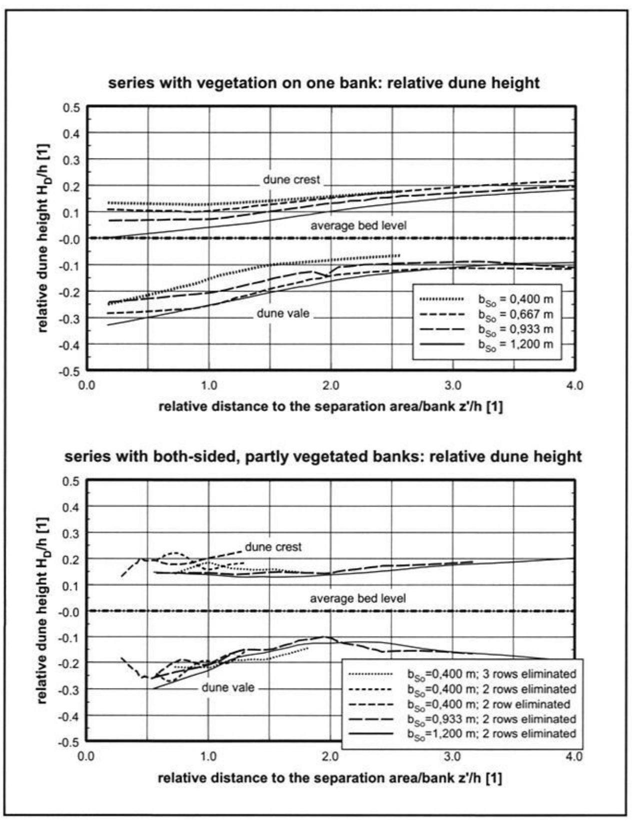


Fig. 71 Averaged dune heights separated in dune crests and vales in the series with vegetation on one bank only (the whole bank is vegetated) and with partly vegetated banks

Transportation/Sedimentation Processes at the Boundary of the Floodplain and the Main Channel ("Rehnen"-formation)

"Rehnen"-formation is an important transport phenomenon on the flood plain at the interaction zone with the main channel of alluvial rivers. To simulate the complex "Rehnen"-formation and transportation processes in the laboratory, a few assumptions have been made which are explained in detail in the report. One assumption is that vegetation on the flood plain was limited to trees, simulated by rigid sticks. To improve our understanding of the influence of vegetation on the processes in general, a run without vegetation was carried out as reference. Two additional runs with bush-like vegetation on the boundary to the main channel gave an indication of the importance of the macro turbulence at this interactive zone.

The sedimentation and transport processes on the flood plain are strongly dependent on the macro turbulence at the transition zone of the main channel and the flood plain. As this vegetation induced turbulence dominates the characteristic dimensions of zone II in Fig.16, the width of this zone is supposed to be the important parameter to determine the distance b_{Boe} (see Fig.74) of the "Rehne" to the boundary of the flood plain. The distance b_{Boe} is in addition to the width and the height of the "Rehne" the main parameter to describe the process of "Rehnen"-formation.

The experiments were carried out in a 30 m long and 2,0 m wide tilting flume. The vegetation was made of rigid PVC-sticks of 10 mm diameter (emerged) and arranged in a pattern of $a_x = a_z = 10$ cm (a_x and a_z are the distances in flow and lateral to the flow direction, respectively). A typical cross section of the investigated situation is shown in Fig.73. The "Rehne" was produced by a sediment field (d_{50} = 0,28 mm) of 4 mm thickness and 1,0 m length spread over the whole width of the flood plain that was transported by the flow as bed load. The flow itself was steady and uniform.

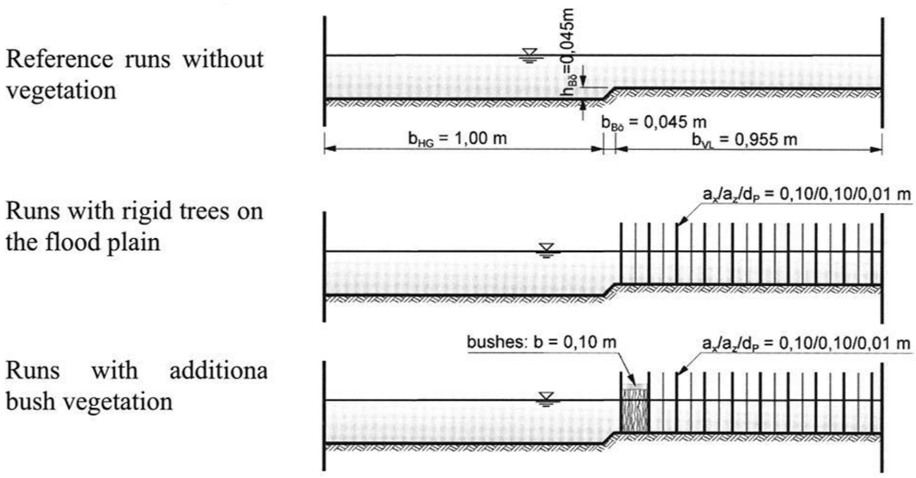


Fig. 72 Definition sketch of the conducted experiments

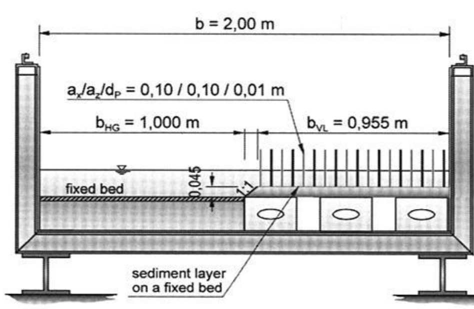


Fig. 73 Cross section of the tilting flume

The transport processes of the "Rehnen"-formation are illustrated in Fig.74. At the beginning of each run the "Rehnen"-

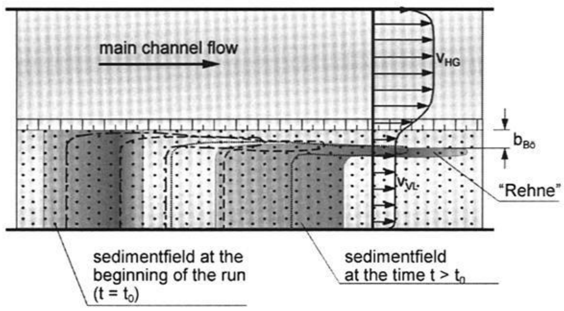


Fig. 74 Definition sketch of the transport processes with rigid sticks on the flood plain

formation developed very quickly and after a few hours the transportation process as well as the shape of the "Rehne" became steady. The longitudinal extension of the sediment field increased during the run as a result of the transportation processes on the flood plain. Due to secondary currents close to the bed of the flood plain the "Rehne" was formed in the distance b_{Boe} from the boundary of the main channel (see Fig.74). After a few hours this formation came to an end-stage with b_{Boe} = constant, where b_{Boe} was slightly larger at the front of the "Rehne" than in the region of the sediment field. Typical transport velocities of this front are given in the report. As mentioned before, the interactive width of zone II on the flood plain, $b_{m,\,II}$, is supposed to be the main parameter that determines the distance b_{Boe}. According to PASCHE (1984), the width $b_{m,\,II}$ is mainly influenced by the water length h_T at the boundary between the vegetation on the flood plain and the main channel and thus strongly dependent on the water depth h_{VL} on the flood plain. As a consequence the depth h_{VL} was the main parameter that was varied in these experiments.

In Fig.75 the distance b_{Boe}, made dimensionless by the water depth h_{VL}, is plotted as a function of the width $b_{m,\,II}$, made dimensionless by the water depth h_{VL} as well. According to Fig.75, a strong correlation exists between b_{Boe} and $b_{m,\,II}$. The grain diameter of the sediment and the density and the arrangement of the trees were not variied. However, the density and the arrangement of the trees are included in the parameter $b_{m,\,II}$, and it follows from theoretical considerations that b_{Boe} increases with decreasing diameter of the sediment.

An often in the nature occurring bush-like situation was investigated by two runs in the experiments as well. Very densely packed sticks were located on the floodplain close to the boundary to the main channel to damp the macro turbulent influence (see Fig.72). The sediment settled down at these locations due to low velocities and damped turbulence. A distinct "Rehne" can form between the densely packed sticks.

3.6 Flume Experiments on Floodplain Vegetation and Sediment

Hydrodynamic Resistance of Isolated and Group of Real Plants

The last schematisation has been suggested firstly by Petryk & Bosmajian (1975); according to them, in case of rigid plants, partially submerged and uniformly distributed along the bed channel, the resistance produced by the single plant is equivalent to:

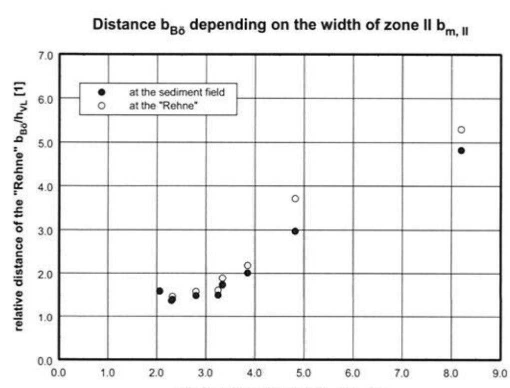


Fig.75 Distance b_{Boe} plotted as function of $b_{m,\,II}$

$$F_i = C_d A_{pi} \rho \frac{V^2}{2} \qquad (1)$$

where F_i = drag force absorbed by the *i-th* plant; C_d = drag coefficient; A_{pi} = area of the *i-th* plant projected in streamwise direction; ρ = mass density of water; V = mean channel flow velocity. In Fig.76 the measured values of the parameter C_dA_p, evaluated from eq.(1), once the force F is measured, is reported as a function of the square of the flow velocity, for plants both partially and fully submerged conditions; other than partially submerged conditions, all curves decrease rapidly and illustrate a large decrease of the parameter C_dA_p , with the increase of velocity, as already shown by Fathi-Moghadam & Kouwen (1997), this reduction with velocity is due to plants bending under the action of the flow. Analogous considerations can be developed for the drag coefficient C_d, (Fig.77) considering as plant cross sectional-area for each test the portion of the trunk and of the principal and 2nd order branches that was submerged, excepting the foliage area.

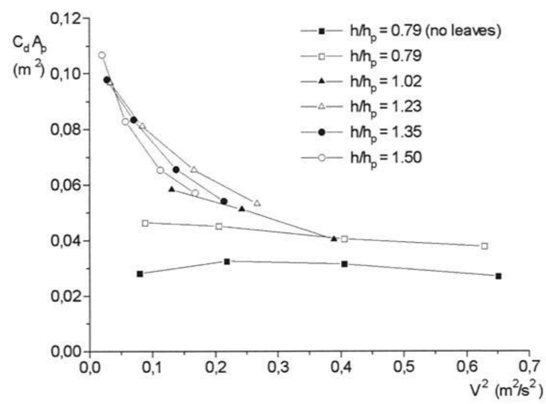


Fig. 76 Variation of the parameter C_dA_p with square of velocity and flow depth

From Fig.77, considering the experiments run on the plant with leaves, the drag coefficient assumes values between 3 and 1.5, the higher values for the lower Re_p. The considerable decrease of the drag coefficient relating to partially submerged tests with the increase of Reynolds number, is justified observing that, in the evaluation of C_d through the drag equation (1), the resistant area has been considered constant and equal to the value assumed in the undisturbed conditions. In this way the effect of the elasticity of the plant is shifted completely on the drag coefficient. On the contrary, in case of partially submerged conditions, the drag coefficient results almost constant, as already verified in all the experiments run on the willows of the group "tall Salix". These values are anyway significantly higher than one, the expected value that a rigid, smooth, indefinite cylinder more or less assumes for $Re > 10^3$. This is probably due to the influence of leaves on flow resistance. In order to verify this assumption, the experiments in partially submerged conditions (h/h_p = 0.79) were repeated after the removal of the leaves. A reduction of the strength up to 40% and consequently a reduction of drag coefficient up to values closer to one (Fig.77b) has been observed. It is then clear the great contribution given by the foliage shear stress to the total hydrodynamic drag resistance of the plant and hence the importance that the vegetative state assumes in the flow resistance predictions.

The ratio between the plants' "shear stress" (i.e. the plants' drag divided the bed surface) and the overall bed shear stress evaluated by momentum equation is reported in Fig.78 as a function of relative submergence; it can be noted that this ratio increases with plants densities and flow depth, the rate of increasing is higher for higher vegetation densities, this could be probably due to the fact that, once fixed the relative submergence, for higher densities the single plant is affected by a lower velocity, so the bending is less marked. In Fig.79 the values of K_{Seq}, evaluated by means of eq.(5), are reported as a function of the relative submergence h/ h_p (where h_p is the not deformed vegetation height) for both the vegetation densities: for the sparse

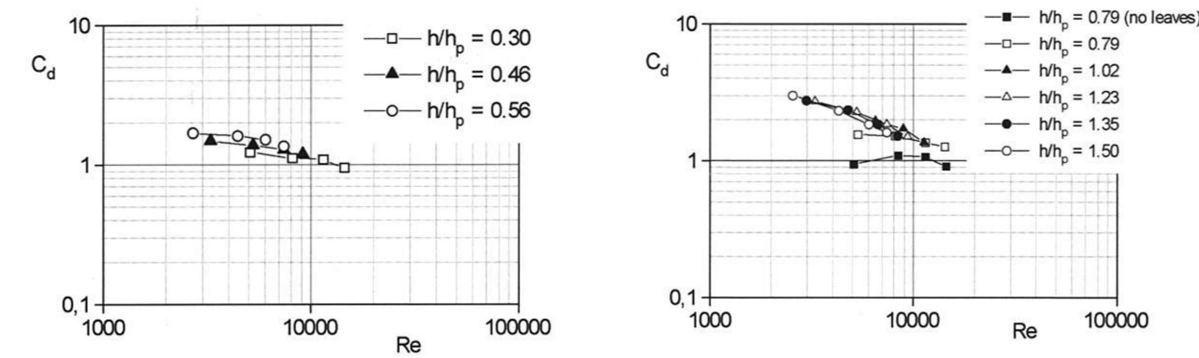


Fig. 77 Variation of the drag coefficient C_d with plant Reynolds number and flow depth a) (left) partially submerged conditions; b) (right) fully submerged conditions.

configuration the minimum value of K_{Seq}, that is achieved when the flow depth is equal to the (bended) vegetation height, is reached for lower values of h/h_p.

Effect of Vegetation on Sediment Transport

One possible rational approach on the quantification of the solid discharge in vegetated bed is to modify the classical solid discharge formulae (e.g. the Meyer-Peter-Müller formula for the bed load) introducing suitable coefficients that can take into account the plants presence. Following this procedure, the M-P-M formula can be considered:

$$\Phi = 8\left(\vartheta' - \vartheta_{crit}\right)^{3/2} \tag{2}$$

where: $\Phi = \frac{q_s}{d\sqrt{g\Delta d}}$; q_s is the solid discharge per unit of width; $\vartheta = \frac{(u_*)^2}{g\Delta d_s} = \frac{h\, i_f}{g\Delta d_s}$ is the mobility parameter of the flow, h is the flow depth, i_f is the bed slope; g is the gravity acceleration, d_s is the grains diameter, Δ is the relative density of the grains; $\vartheta' = \frac{(u'_*)^2}{g\Delta d_s}$ is the net

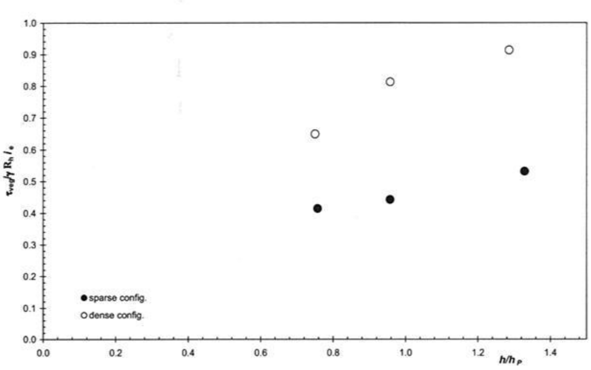


Fig.78
Ratio between the plants' drag per unit bed surface and the overall bed shear stress evaluated by momentum equation ($\gamma R_h i_e$).

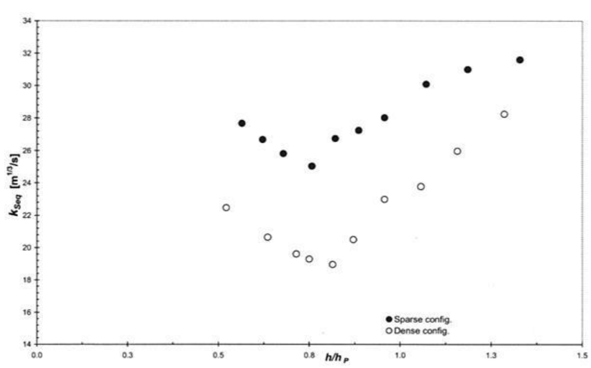


Fig.79
Estimated K_{Seq} as a function of relative submergence, for the *dense* and *sparse* salix configurations.

mobility parameter, that refers only to the grain resistance (see e.g. Yalin., 1977), usually it is experimentally evaluated and can be expressed as a function of ϑ (Engelund, 1966).

The M-P-M formula can be generalized as follows to the situation of vegetated beds:

$$\Phi = 8(1-C_v)\,(\xi_v\vartheta-\vartheta_{crit})^{3/2} \qquad (3)$$

where: C_v is the ratio of bed surface occupied by the plants; ξ_v is a suitable correction factor that has to be experimentally evaluated.

The dimensional analysis rule (see e.g. Yalin, 1977; Lopez & Garcia, 1998) suggest that, for vegetated bed, this factor could depends to various dimensionless parameters, among them the vegetation density $\lambda_{VEG} = A_{Pi}/a_X\,a_Y$ (where a_X, a_Y are the streamwise and transversal distances between adjacent plants respectively), and/or the density of plants, $\lambda = d_P^2/a_xa_y$ (that is surface occupied by the single plant per unit bed surface) play a crucial role. Nevertheless also other dimensionless parameters have to be taken into account (see e.g. Lopez & Garcia, 1998), that can take into account also other characteristics of the plants and of the sediment. A series of experiments has been performed in order to quantify the correction factor and its dependence on the various dimensionless parameters.
The main results of the experiments on sediment transport are reported in Fig.80: the measured dimensionless solid discharges Φ (as defined in eq. (2)) are reported as a function of the mobility parameter θ, together with the classical M.P.M. formula (eq.(2)) for non vegetated bed. The measurements clearly show a significant decrease of bed load in vegetated bed, following equation (3) the correction factor ξ_V is evaluated by best fitting the experimental data; the sensitivity analysis shows that the most affecting parameter is the density of plants, $\lambda = d_P^2/a_xa_y$, (Fig.81) as previously defined, an exponential law is proposed, as follows:

$$\xi_v = \alpha\, e^{-\beta\lambda}$$

The estimated values for the parameters are: β=4,8 and almost independent on density of vegetation, α= 0,38 for *fine* sediment and 0,34 for *coarse* sediment; these values of α are very close to the expected values that allows to evaluate the net mobility parameter ϑ' as a fraction of ϑ (see eq.(2)) for channels without vegetation (Engelund, 1966).

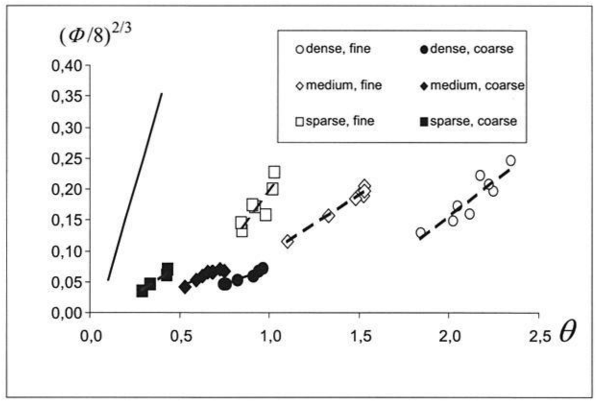


Fig. 80 Dimensionless solid discharge for the various experiments with vegetated bed.

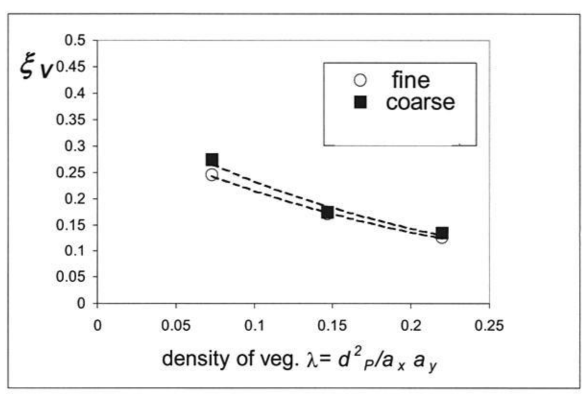


Fig. 81
Experimental values of correction factor of ξ_V as a function of vegetation density.

3.7 Physical Model of the Wien River (FS3)

Flow Resistance of Vegetated Banks and the Wienfluss Physical Model

The discharge curves estimated for different runs in the field site are reported in Fig.82 and compared with the discharge curves measured in the model (related into prototype scale, at Froude similitude) for the different densities of flexible and rigid "plants". The comparison between prototype and model data allows to assume that the intermediate configuration (density of plants $\lambda=d_P^2/a_x a_y=1.17*10^{-1}$) of flexible "plants" can be a fairly good approximation of the Wienfluss hydraulic conditions.

plants bending significantly affects the velocity distribution in the cross section, causing a faster upper layer in the bank that is not so pronounced in the rigid configuration (Fig.83a).

Figs.84a and 84b refers to the transversal double averaged turbulent dimensionless shear stress distribution in the cross section, for the same plants configurations as in Figs.83a and 83b respectively. The rigid plants are characterized by a higher drag with respect to the flexible one and they cause higher values of the shear stress close to the interface between vegetated and non-vegetated region. Moreover, for flexible configuration, the shear distribution is affected by the bending and fluctuating of the plants, so its distribution is less uniform along the

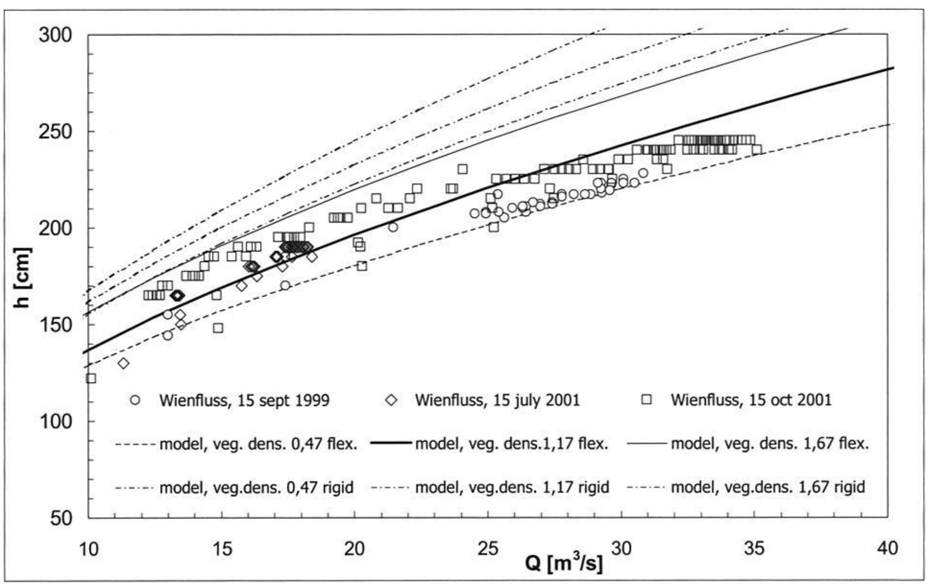


Fig.82 Discharge curves for various simulated flood in the Wienfluss (dots, as evaluated by BOKU) and for the laboratory simulation for rigid and flexible simulated plants (lines), at different densities of plants.

In Fig.83a the dimensionless stream wise velocity distribution in the cross section for discharge Q=31 m^3s^{-1} (prototype scale) and rigid intermediate density configuration is reported, the same in Fig.83b but for elastic plants. As can be observed (Fig.83b) the vertical and –with respect to the rigid configuration- a larger region of the vegetated bank is affected by relatively higher transversal shear stresses; this behaviour is confirmed for all the analysed vegetation densities. The stresses has been averaged along

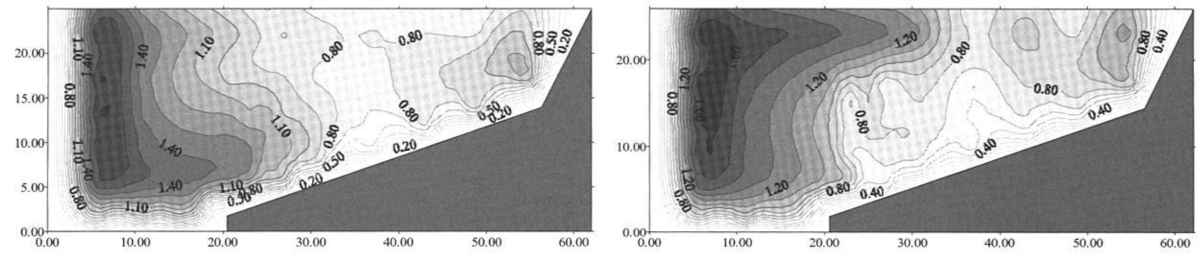


Fig.83 Dimensionless streamwise velocity distribution in the cross section $U_{(y,z)}/U_{mean}$, (where $U_{mean} = Q/A$) for intermediate density $\lambda = d_P^2/a_x a_y = 1.17*10^{-1}$, at discharge Q=31 m^3s^{-1} (prototype scale). Measured with microADV. a) (left) rigid plants; b) (right) flexible plants.

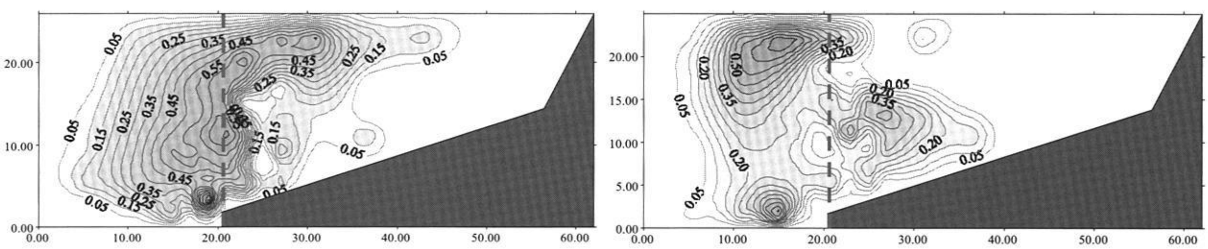


Fig.84 Dimensionless transversal double averaged turbulent stress, $\tau_{turb}/\tau_0 = <\overline{u'w'}>/\gamma R_H i_f$, distribution in the cross section for intermediate density $\lambda = d_P^2/a_x a_y = 1.17*10^{-1}$, at discharge Q=31 m^3s^{-1} (prototype scale). Measured with microADV. a) (left) rigid plants; b) (right) flexible plants

vertical lines, an example of the transversal distribution of such averaged shear stresses is reported in Fig.85 for rigid, dense configuration; the maximum values is locate close to the separation line between vegetated-non vegetated region (dashed line in Fig.85).

Fig.86 reports the maximum values of the dimensionless transversal turbulent stresses, averaged along the vertical, measured in the different configurations analysed (rigid, flexible; sparse, interm., dense), as a function of vegetation of plants, λ. The maximum shear decreases as the vegetation density and -at the same density- the flexible plants are characterised by lower values of this shear, with respect to the rigid.

The method proposed by Trento-UniTN group (as reported in the paragraph above) has been applied to various configuration of

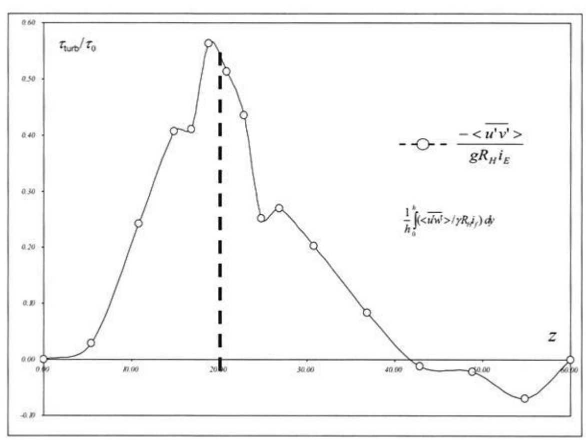


Fig.85 Dimensionless transversal turbulent stress, averaged along the vertical distribution for rigid dense config.

$\frac{1}{h}\int_0^h (<\overline{u'w'}>/\gamma R_H i_f)\, dy$, $\lambda = d_P^2/a_x a_y = 1.67*10^{-1}$,

at discharge Q=31 m^3s^{-1} (prototype scale)

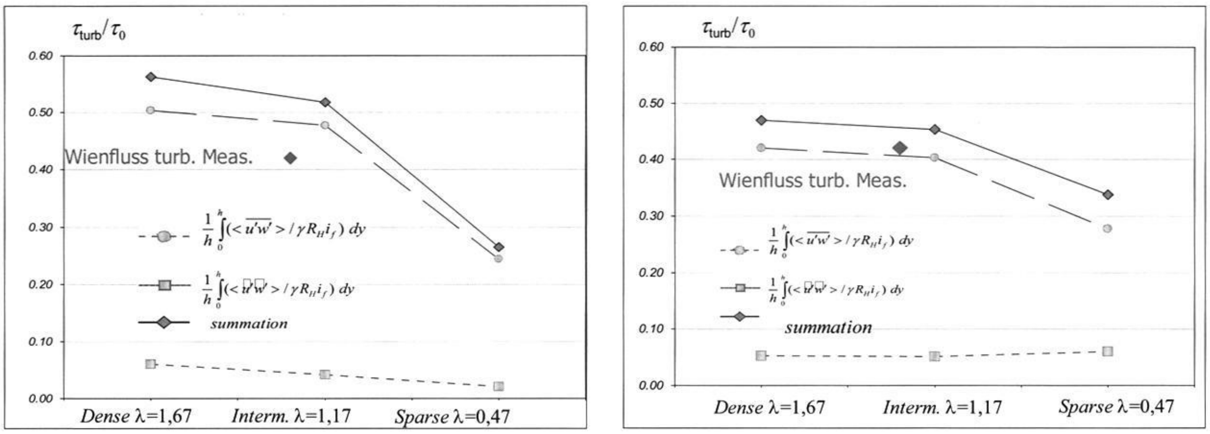


Fig.86 Maximum dimensionless transversal turbulent stresses , averaged along the vertical, measured for different density of plants at discharge Q=31 m^3s^{-1} (prototype scale). a) (left) rigid plants; b) (right) flexible plants

the vegetated bank for the Wienfluss model and also for other trapezoidal cross sections(in this last case not only the discharge was varied, but also the slope of the flume). The best fitting approach to the stage-discharge measurements allows to evaluate the optimal values of n coefficient (as reported in Eq.(6)): it's values ranges between 0.2 and 0.4, as a function of h/h_P. Fig.87 reports, just as an examples, the comparison between the evaluated data of K_{Seq} by direct measurements and the evaluated data obtained applying Trento-UniTN method (for n=0.2 and 0.4) and the classical EH method. Finally, Fig.88 refers to the estimation of the shear at the interface for flexible plants, intermediate density, Q=31 m^3s^{-1} (prototype scale), as results applying Pasche (1984) and the method proposed by Trento-UniTN group for discharge prediction in streams with vegetated banks (in the Trento-UniTN method a constant value of n=0.4 leaded was

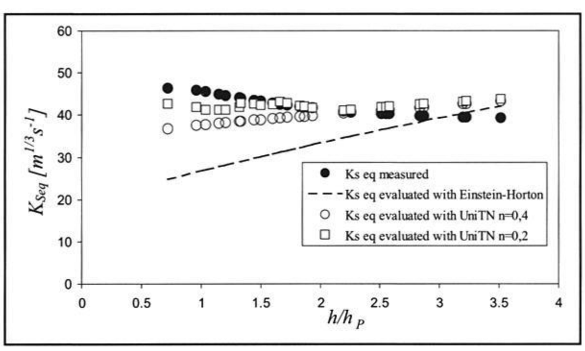


Fig.87 Comparison between measured K_{Seq} in section with vegetated bank, as obtained by eq.(5), and the estimation of K_{Seq} using the classical E-H approach and the Trento-UniTN method (eq.(6) with n=0.2 n=0.4)

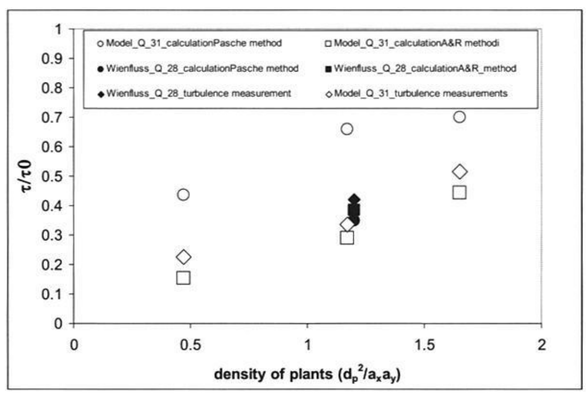


Fig.88 Shear between vegetated and not vegetated banks, calculation by Pasche and Trento-UniTN methods for (model) flexible, interm. density at discharge Q=31 m3s-1 (prototype scale) and the corresponding direct measurements; also the direct measurements in Wienfluss using ADV (filled symbols), for a discharge Q=28 m3s- 1 , are reported for comparison.

used in order to obtain the best fit of the flow level measured data). The theoretical predictions are compared with the corresponding turbulent shear stress measurements in the model, and with the turbulence measurements made in one of the field experiments (Mertens approach is not reported because it does not lead to correct predictions). It can be argued that the proposed method (as well as Pasche method) gives a fairly good estimation of also the shear at the interface.

3.8 3D Numerical Modelling of Riparian Flow Field

The results of the numerical simulation were tested against data of a physical model study carried out in the scope of the current project. The flume consists of a half of a sym-

	Discharges [l/s]						
5 x 5 cm	-	-	**20**	-	**50**	**75**	-
10 x 5 cm	**5**	10	20	30	**50**	**75**	**100**
10 x 10 cm	**5**	10	20	30	**50**	**75**	**100**
20 x 20 cm	-	-	**20**	-	**50**	**75**	-

Tab. 9 The simulated combinations of discharges and vegetation densities. Number in bold are simulated

metrical compound channel with vegetated floodplain. The vegetation density and the kind of vegetation were varied as well as the discharges. In Fig.89 the plan view of the

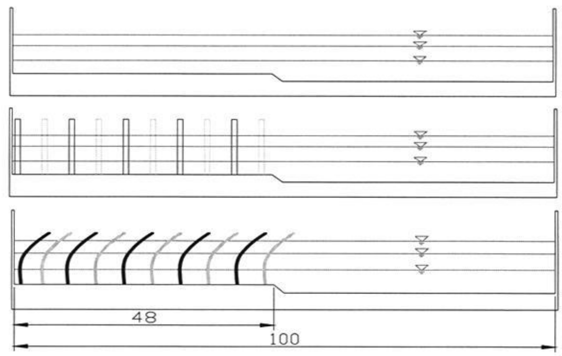


Fig.89 Cross section of laboratory flume at different discharges and vegetation densities

cross section of the laboratory flume is illustrated. The investigations were focused on the case with the rigid density. In Fig.90 the measured and the simulated velocities are shown. In the case of 10 l/s, 20 l/s and 30 l/s, were measured data have been available, the numerical simulation showed good agreement. The mean velocities in the main channel and on the floodplain could be reproduced. Based on validation and on a generated rating curve of the physical model study (Fig.91), it was now possible to simulate various flow scenarios. During the project the flow of four different discharges in combination with two additional vegetation densities are investigated. In Fig.92 it can be seen that the results in case of the increased vegetation density is illustrated for three dif-

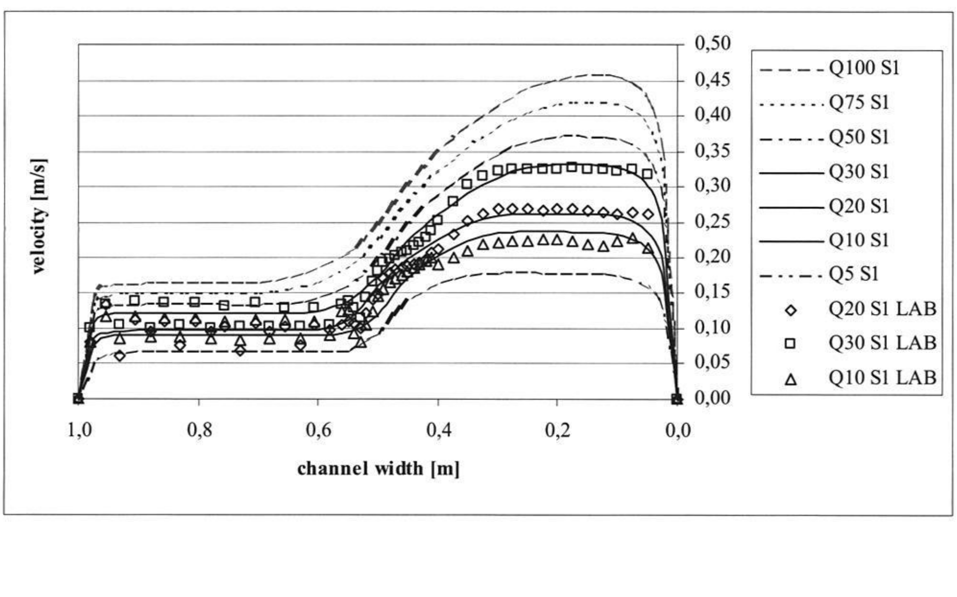


Fig.90 Horizontal velocities in a cross section at different discharges, vegetation density 10 cm x 10 cm (S1)

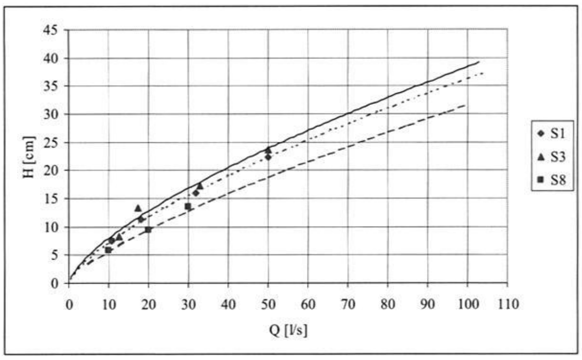


Fig.91 Rating curve of the physical model S1 10x10 cm, S3 10x5 cm, S8 5x5 cm

ferent discharges. Using this procedure, any other variation can be modelled.

In addition to the rigid vegetation the investigation were also focused on the modelling of flexible ones. In this context the numerical model was tested against data from an experimental setup where the floodplain vegetation consisted of flexible cylinders. Therefore the code was enlarged with a new routine which takes into account the drag resistance of bent vegetation under a certain, hydrodynamically correlated angle. The results were not matching to the observations due to the fact that the modelled material had physical properties which were not transferable to the numerical model. Different approaches were tested against the bending behaviour of the material which was used in the physical model, and showed no agreement with the measurements. It was not possible to describe the bending numerically by universal and consistent physical laws and therefore the model for the flexible vegetation could not be fully developed and implemented in the code.

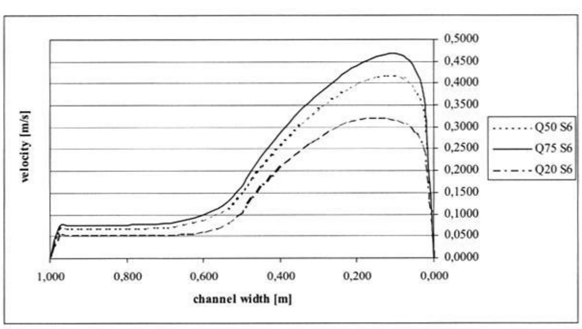


Fig.92 Horizontal velocities in a cross section at different discharges; vegetation density 5 cm x 5 cm (S6)

3.9 1D Numerical Modelling of Flood Wave Propagation

Validity of the Flow Simulation Programme

The hydrographs measured at Rheinweiler and Hartheim as well as one simulated at Hartheim for the actual flood event in May 1999 are plotted in Fig.93. The aforementioned figure shows that both measured and simulated hydrographs at Hartheim have the peak discharge at the same time. A time lag of the peak discharge is approximately 3 hours between the hydrographs measured at Rheinweiler and simulated at Hartheim. The temporal course of the simulated hydrographs is almost similar to those measured. However, there are some discrepancies of the discharge between the measured and simulated hydrographs when the discharges are over 2500 m^3/s. An error index is defined by Eq. (6):

$$RE_p = \left| \frac{Q_{mes,p} - Q_{sim,p}}{Q_{mes,p}} \right| \quad (6)$$

where RE_p = relative error of peak discharge, $Q_{mes,p}$ = measured peak discharge, and $Q_{sim,p}$ = simulated peak discharge.

The relative error of the peak discharge RE_p is approximately 3 %. The error of measurement could be at least 10%, thus, a good agreement between the measurement and simulation was reached from an engineering point of view. However, there is some uncertainty of the influence of the submerged canopies on the flow resistance in the model. When the flow discharge is over 2500 m^3/s, the discrepancies between the measured and simulated discharges grow

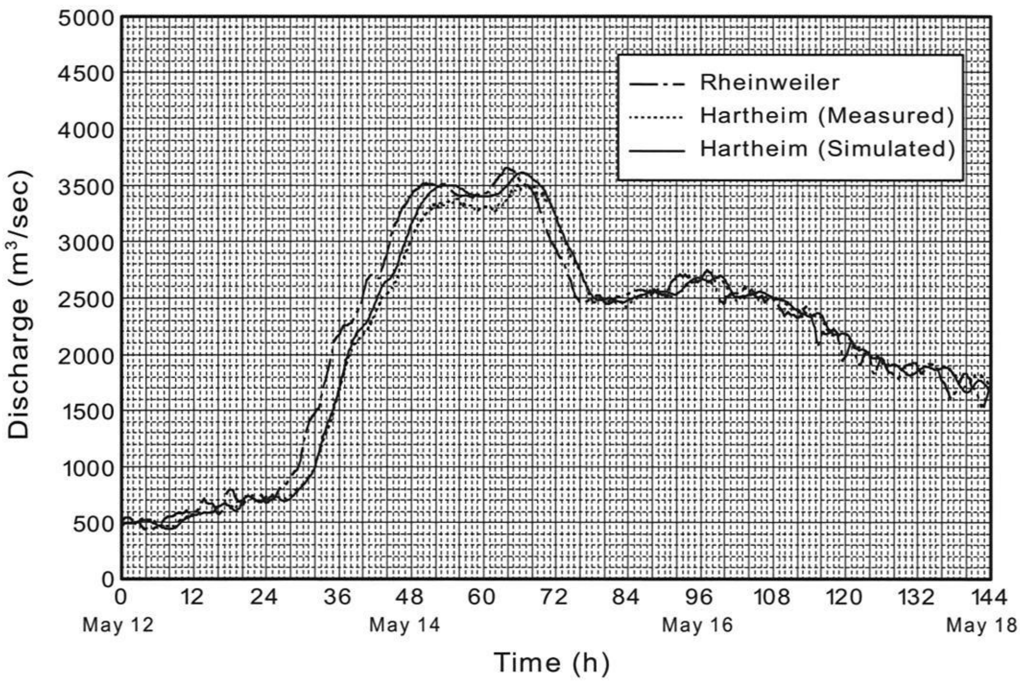


Fig. 93 Comparison of hydrographs between measurement and simulation at Hartheim during the course of the flood event in May 1999

larger. This fact suggests that the submerged canopies seem to have a great effect on the water table, especially on the floodplains and promote more energy dissipation which results in the measured discharge smaller than the simulated one.

Retardation of Flood Waves

The influence of the riparian forests on the retardation of propagation of the flood waves was investigated through the simulations. The results of some simulations, which show more retardation effects than the other cases, are shown in Figs.94 and 95. The biggest time lag of the propagation of the flood waves is 1 to 1.5 hours, and the riparian forests developed on the specially-enlarged floodplain actually has no significant effects on the retardation.

Retention Volumes in the River Course

The temporal courses of the retention volumes in the river course are shown in Fig.96. The riparian forests developed on the enlarged floodplains show a significant influence on the retention volumes in the river course. The increments of the retention volumes in comparison with the present condition are also shown in Fig.97. The riparian forests can, at most, lead to the additional retention volumes of 30 million m^3 between Rheinweiler and Hartheim.

3.10 Riparian Succession at the Upper Rhine (FS1)

It could be shown that the decisive factor for the present vegetation development is not the flood duration but primarily the flow velocity, the depth of inundation also plays an important part to some extend. Moreover, the sites are also changed by accretion. For most of the sites, the flood duration would allow the development of hardwood floodplain forests.

However, the enormous flow velocity of extreme flood events causes the breaking up of the vegetation cover and new sedimentation areas arise that are exempt of vegetation. The extraordinary flood of May 1999 even knocked down a very considerable number of older white willows. Succession does thus hardly get beyond the stage of softwood floodplain forests. Small-scale hardwood floodplain forests may merely be determined along the border of the former river bed of the Rhine. Even the large-scale regeneration of softwood floodplain stands appears difficult given that herbaceous plants may arise almost everywhere. These plants do not allow the regeneration of white willows (Salix alba), black poplars (Populus nigra) etc., as these tree species require virgin soils and full light for their germination. The present vegetation is thus dominated by stages that are to a limited extend attention has also been drawn to the future development of vegetation.

The broadening of the river bed will cause a reduction of the flow velocity depending on the extension of the new flood prone area. Its importance as main regulative factor will thus be considerably reduced. In the beginning the floodplain area will be situated some decimetres above the long-term groundwater level, later, as a result of accretion, it will on a large scale be situated more than half a meter higher. Moreover, an ap-

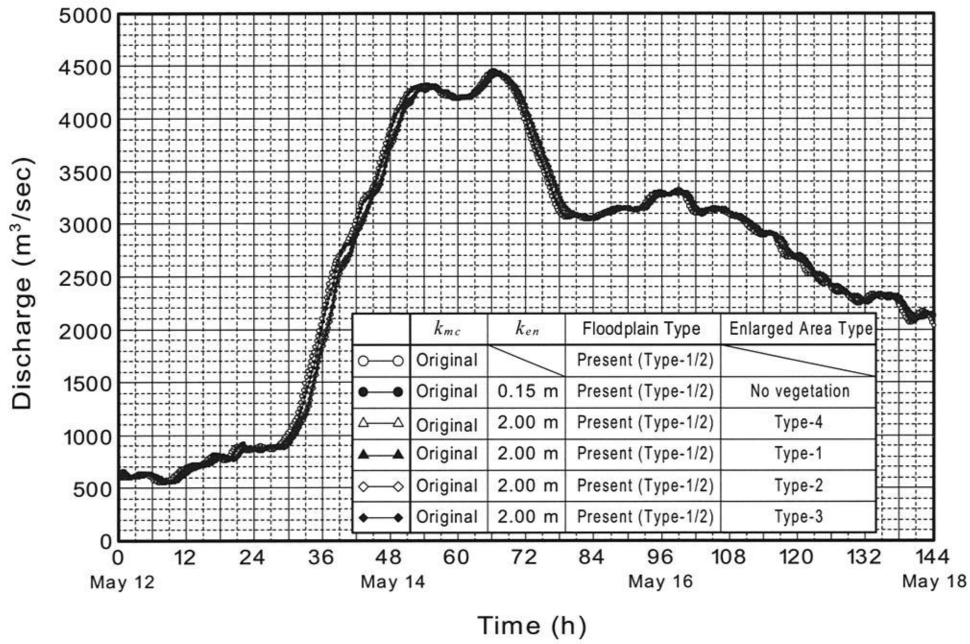


Fig. 94 Simulated hydro-graphs during the course of the designed flood at Hartheim in Cases 0, 1, 2, 11S, 12S and 13S (Tab.1)

determined above all by flow velocity, germination conditions, settlement effect and sedimentation, rather than by flood duration and competition.

Altogether the conditions of the present sites in the former river bed of the Rhine are absolutely unnatural and are not known to exist in this form in any other place. A broadening of the river bed will bring about more near-natural ecological conditions. This is why general knowledge on the regeneration in river floodplains and the behaviour of a number of key species have been considered, propriate seed potential is available in the surroundings and the flood duration will allow the existence of hardwood floodplain forests on almost the total surface of the area. These are the reasons why, in the long term, vegetation will develop towards hardwood floodplain forests on a large scale. This process is obstructed by a flow velocity that is still high, by sediment input on the digging area, a lacking soil maturity as well as an unnatural depth of inundation at high discharge rates. Moreover, the development of vegetation of course takes time.

It is thus to be expected that, in a first step, communities of softwood floodplain forests in which the white willow (Salix alba) will be predominant, will develop on the newly created inundation areas.
They will form tall and relatively compact white willow stands as can be observed in some places along the French river bank and this will become true especially if the uncovering of the new surface occurs during the spreading of the willow seeds (late May/ early June). If this is not the case, river reeds extraordinary flood events. This is why the development of a nitrophile herb layer (tall herbaceous vegetation) is to be expected in the willow forests. For the ash (Fraxinus excelsior) as well, it will not be easy to become firmly established on such sites.

In the medium term, however, on the higher situated and relatively stable sites as well as from the edges of the digging area, the English oak (Quercus robur), the elm (Ulmus spec.) and further species of the hardwood

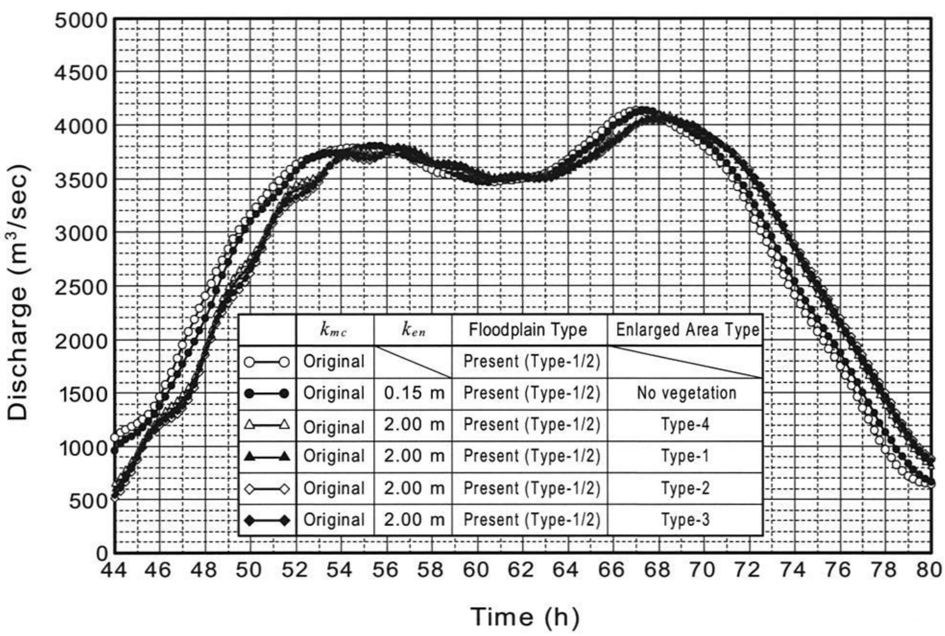


Fig. 95 Simulated hydro-graphs around the time of peak discharge at Hartheim in Cases 0, 1, 2, 11S, 12S and 13S (Tab.1)

e.g. of Phalaris arundinacea may establish themselves and form permanent communities that persist in the long term and that will only be replaced very slowly by ligneous plants.
It is not supposed that gravely (and sandy) pioneer sites will remain exempt of vegetation over a longer period and that they cover larger areas. In the willow forests the development of a shrub layer emerging from elements of the hardwood floodplain is obstructed by too high depths of inundation at floodplain will force their way into the area.
Altogether, the vegetation conditions on the broader digging areas will become more near-natural as is the case at the present time. However, these conditions will not be characteristic of the floodplain which is why finally no succession model allows making true predictions on the future development.

The most reliable knowledge has thus to be drawn from the present condition of the river bed of the Rhine.

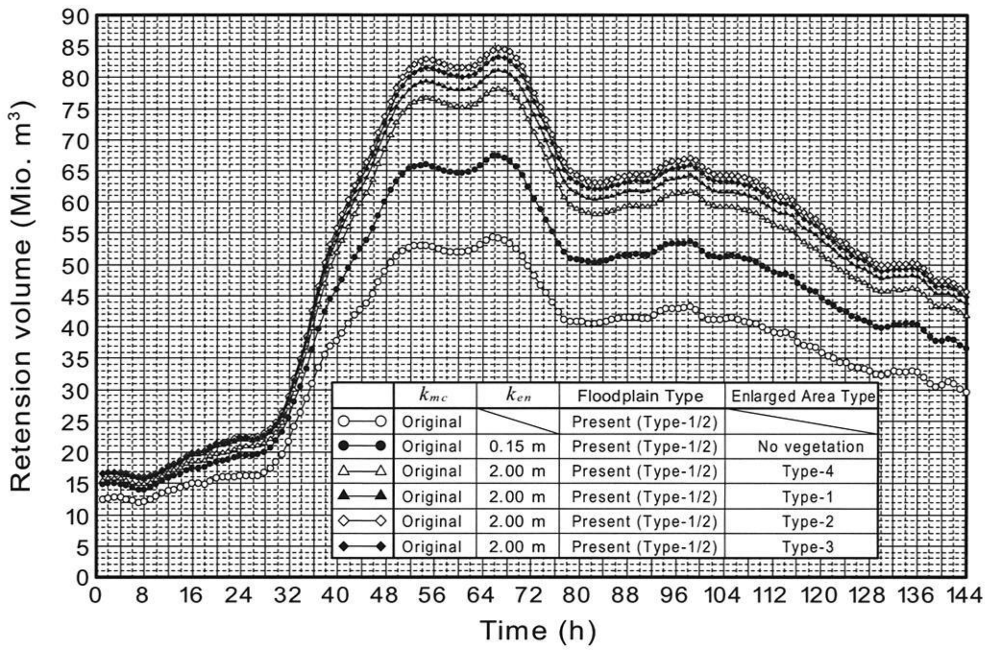


Fig. 96 Temporal courses of retention volumes during the course of the designed flood event in Cases 0, 1, 2, 11S, 12S and 13S

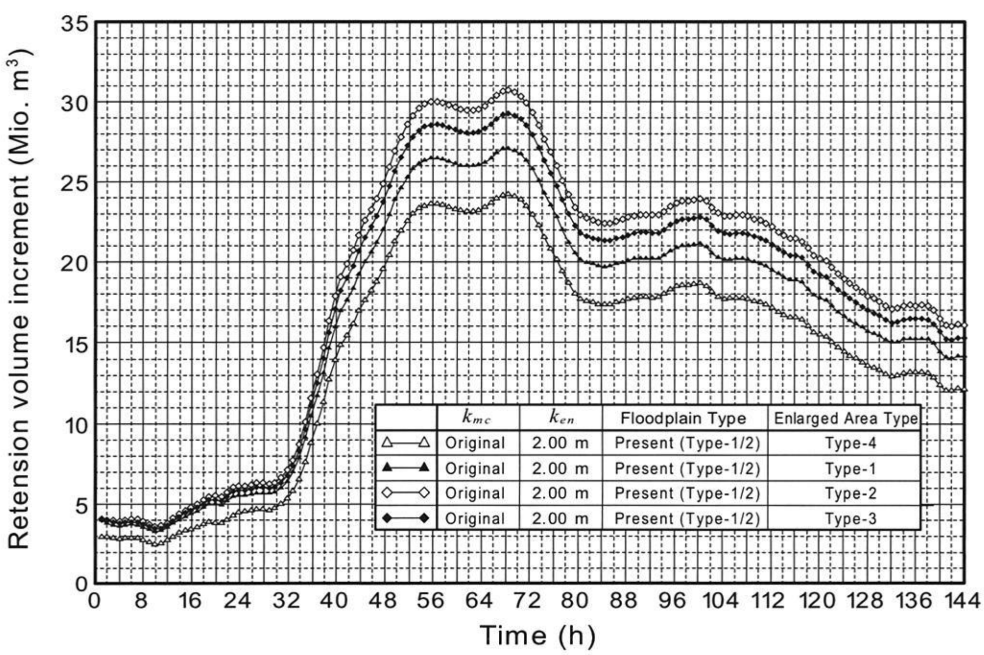


Fig. 97 Temporal courses of retention volumes around the time of peak discharge in Cases 0, 1, 2, 11S, 12S and 13S

4. CONCLUSIONS

4.1 Individual Workpackages

Field Work at the Upper Rhine (FS1)

The installation of new floodplain areas at the Upper Rhine will initially be dominated by sedimentation and distribution of fine silty material unless no bigger flood events respectively higher velocities occur. Willows lead to higher rates of sedimentation compared with grass areas at the Upper Rhine. Whereby at willow areas there is a tendency for erosion of bed material with rising water level. Grass seems to protect the bed also at rising water level. The critical point of system instabilization could not be observed but it needs ground near velocities higher than 950mm/s. Up to a water level of 2.3m these velocities only occurred during the peak of discharge and only inside the willow grove. Future investigations at the test site will give more information about the boundary conditions for erosion processes (e.g. type and habitus of vegetation) and about velocity and discharge values which could lead to destabilization of morphology and erosion. Furthermore it has to be discussed which influence the initial situation of topography and grain size distribution have on the succession of vegetation and the shift of roughness.

Young flexible willows decelerate the mean flow velocity in order to their roughness compared with the grass area and therefore the discharge at the wooden areas is lower compared with the grass covered. Since the distinct differentiation of vertical distribution of flow velocities leads to a proposal of a partition of four zones of roughness value for flexible tree this should be investigated for a longer time. In order to check these phenomena more measurements have to be carried out at different stages of water level and at different stages of vegetation period. Due to these results it also has to be investigated if the local flow field measurements can be transferred on larger areas with similar boundary conditions and if these data can be used to calibrate and improve numerical models. Therefore new field campaigns are necessary to investigate the overall flow field inside different floodplains and different rivers. The future investigations will give more detailed information on the interaction of vegetation, flow field and sedimentation and will take into account the application and verification of formulas for discharge, sediment transport and shear stress on vegetated floodplains.

Field Work at the Wien River (FS3)

The experiments in the natural-scale test-flume at the river Wien showed the strong influence of vegetation growth and succession on the hydraulic roughness, flow velocities and shear forces. For the experiments, natural willows were planted in the flume and stressed periodically by artificial floodings. Willow succession and growth were monitored over a four year period. In this period, the willows had become taller, more shrubbier and although less numerous and had grown to maximum basal diameters of about 5 cm. At this stage, flexible plant properties still dominated and lead to bending of the willows and thus fully submerged conditions during the flood peaks.

The analysis of the measured flow velocities showed that there are significant differences between the vertical velocity profiles in the un-vegetated main channel and those above the vegetated banks with submerged willows. First, the maximum velocities at peak discharge conditions were decreased by the willows of about 35-45% close to the water surface.

This decrease was generated by the increased roughness of the plants and influenced also the velocities and consequently shear forces close to the bed. Hereby, the velocities were decreased of up to 50%. As a result, the willows had stabilising effects on the bed and banks and protected it from erosion

The additional vegetative roughness and the decrease of flow velocities was associated with an increase of the water level in the test flume. At peak times, the difference between two stages of succession (1999 compared to 2001) was quantified at a maximum difference in water levels of 20cm (an increase of 10%).

Furthermore, the basic mechanisms of willow damage were observed. It could be shown, that breaking occurs primary when the direction of flow attack differs from the anatomic load direction (for undisturbed growth this means mainly the self-weight of the plant and thus vertically downwards). This effect plays an important role for submerged willows, where the flow attack causes load that is directed opponent to the anatomic load (for bending in flow direction). On the other hand, the breaking of willow branches did not cause the damage of the entire plant, because the sites of fracture were able to re-lignificate. In such way, the plants were able to "learn" from the fractures and to adapt to the hydrodynamic stresses.

Field Work at the Fersina (FS4) and the Enz River (FS2)

Ecological studies are very important to evaluate environmental quality and integrity, in addition to plane the management of riparian and perifluvial areas. In this project, four methodologies were applied to study the ecological and biological situation on project site on the Fersina and one (FFI) on the Enz. All the four methodologies permitted to evaluate the biological aspects in different ways and showed the ecological importance of riparian areas to increase the river quality and functionality.

The FFI (Fluvial Functioning Index) permitted to evaluate the general functioning of riverbed, of riparian areas and of riparian territory adjacent to the floodplains. The Index was applied to the rivers Fersina and Enz. Different land-use, hydrology and geology at the two test sites proved the good applicability of the method covering a wide range of scenarios.

Organic matter retention analysis permitted to study the riverbed morphology with regard to organic matter retention, demolition and depuration capacity. Information of demolition and depuration was complemented by leaf-pack analysis. The linked information of both methods gave an exact description and quantification of the self purification capacity of the river system. Additional benthos quantitative sampling consented to analyse the macrobenthonic community as direct indicators of the water quality and river functionality.

In such way, parameters for the ecological functionality of different stream types as well as practicable methods for their evaluation and monitoring were presented. These parameters are easy to determine and of high practical relevance and integrate essential ecological information for end-user (such as public or private river managers, landscape planners, agencies for flood protection) about the management of the riparian vegetation respecting the requirement of river biota.

The urban and landscape planning should consider the riparian forest ecosystem with management strategies developed as an integral part of the community plan. In order to create some effective buffers strips in developing urban areas, land-users and planners must understand the importance of the real functions of riparian ecosystem within their watersheds. This objective needs to know the nutrient control and sediment flow processes in accordance to the hydrologic regime.

Flume Experiments on Riparian Flow Field

The aim of the laboratory study was to characterize the flow field and momentum exchange processes in a compound open channel with vegetated riparian floodplains making use of a LASER Doppler Velocimeter (LDV) and head-loss tests. It was found that secondary currents are the primary mechanism for momentum exchange between the main channel and the floodplain. The magnitude of the secondary currents increases with increasing water depths and causes significant deflections of the horizontal and vertical velocity profiles. Near the junction between main channel and floodplain, a strong intrusion of main channel velocities into the floodplain was found at lower regions of the flow, whereas slower velocities were dispersed from the floodplain far into the main channel at the upper regions of the flow close to the water surface.

By varying the floodplain vegetation it was found that the flexibility has a primary influence on the secondary currents. Therefore, physical parameters were introduced to characterize the flexibility in terms of bending, waving and compression. The results show that waving and bending of flexible stems without leaves have no impact on the integral floodplain resistance but enforce the generation of secondary currents. Strong waving motions as they occurred for the tested flexible cylinders enforced the generation of secondary currents. In contrast, leafy cylinders with compressible foliage had a damping effect on the exchange processes. The same effect was observed and measured for a higher plant density. Thus, the plant density is only of secondary importance for the momentum exchange process.

Finally, the magnitude of the secondary currents has only minor influence on the discharge capacity of the entire channel system, but has to be considered with regard to morphological aspects including bed-load transport, sedimentation or aggregation processes that form natural rivers.

Flume Experiments on Riparian Morphology

Experiments in a physical model investigated the interactions between sediment transport and morphology and the floodplain vegetation. It could be shown that the macro-turbulent vortices and secondary currents that were generated at the junction between main channel and floodplain influence the sediment transport significantly. In general, these exchange processes caused higher shear stresses at the near bed region and consequently the mobilisation of sediment and an increase of transport rates. For compact cross sections with vegetated banks, the width to depth ratio was found as primary parameter to characterize the strength of these macro-turbulent exchange processes. Thus, narrow channels with smaller width to depth ratio and vegetation on both banks are influenced stronger by the macro-turbulent exchange and have higher sediment transport rates compared with wider or only partially vegetated channels.

Additionally to the sediment transport rates, the morphological phenomen of sand-ridge formation (so called “Rehne”) has been investigated in the physical model. Rehnen are longitudinal aggretions (in flow direction) of fine sediments at the edge of the floodplain towards the main channel. It could be shown, that the magnitude of macro-turbulence and consequently the distance of the Rehne from the edge are strongly correlated with the width of the turbulent mixing zone inside the floodplain. With increased macro-turbulence, the zone

of lateral exchange as well as the Rehne was shifted away from the main channel.
Afterwards, additional experiments with bush-like vegetation strips at the edge of the floodplain towards the main channel were carried out. The very dense vegetation decreased the flow velocities and the macro-turbulent exchange at the edge of the floodplain significantly and caused the deposition of sand only within the strip.

Flume Experiments on Floodplain Vegetation and Sediment and Physical Model of the Wien River (FS3)
Two problems have been faced: the first was the problem of hydrodynamic behaviour of flexible bushes as usually employed in remediation work with bio engineering techniques; in order to have a deeper insight on this field, a series of laboratory experiments with real plants has been performed and a new method for hydraulic resistance of vegetated banks has been proposed. The knowledge on the behaviour of flexible plants has been useful for physical model construction of the River Wien field site. The method has been successfully tested on the field and laboratory data concerning River Wien: this method is easy to apply, and gives to an almost correct estimation of the stage-discharge relation and of the momentum exchange that take place at the interface between central bed and vegetated banks.
Moreover the problem of sediment transport in vegetated bed has been faced and a modification of the classical formula of Meyer-Peter-Mueller for bed load prediction has been proposed and tested on the data from a laboratory open channel simulations.

3D Numerical Modelling of Riparian Flow Field
A three dimensional numerical model, where the turbulence structures are calculated with the k- ε closure scheme, was used to determine the flow pattern in open channel flows. To simulate the additional flow resistance of non-submerged rigid vegetation the drag force on a rigid cylinder is implemented into the Navier-Stokes equations. Preliminary results have shown that the numerical model using the k-ε scheme is not able to reproduce the turbulence structures in detail. However it provides good estimation about mean velocity distributions in all parts of the channel. The results showed good agreement to the measurement and enabled the researcher to predict the waterlevels and the flow field at different discharge/ vegetation configurations. In contrast to this, it was not possible to simulate the distinctive secondary currents occuring in the interation zone. But the measurement of the physical model showed that these currents do not have a large influence on the total flow capacity. Summing up, it turned out that the used model is a useful tool to describe the flow in open channel flow with vegetated floodplain.

1D Numerical Modelling of Flood Wave Propagation
The 1D unsteady-state flow simulations investigated the large scale impact of riparian forests on the flood retention exemplarily for the Upper Rhine near Breisach. For the simulated scenarios, it could be shown that the influence of different stages of riparian forest succession on the retardation of the propagation of the flood waves is limited. In the study site (ca. 28 km), the retardation of the propagation is at most 1.5 hours in comparison with unvegetated floodplains. On the other hand, the succession of riparian forests resulted in an additional maximum retention volume in the river course of 30 million m^3 (densest vegetation) in comparison with the present condition (narrow floodplain with only sparse vegetation). Hereby, about 12 million

m³ were gained by enlargement of the floodplains and between 11-18 million m³ by riparian forest at different stages of succession.

The above-mentioned facts mean that one cannot expect the riparian forests to play a role of decelerating the propagation of the flood waves but the retention volumes in the river course. The resulting increments of the retention volumes may cause higher watertables and consequently higher hydrostatic pressure on the banks and also the rise of groundwater tables.

Riparian Succession at the Upper Rhine (FS1)

Based on comparative botanical studies, the riparian forest succession at the Upper Rhine has been investigated. It could be shown that flow velocities respectively shear forces and short-term erosion and sedimentation are the determining factors for the succession at the investigated river reach.

Compared to other riparian forest systems, flood duration and competition of the vegetation were found to be only of minor importance. The stronger hydrodynamic forces induced by the flow suppress the succession of hardwood floodplain forest and allow only the development of softwood communities in which white willows will be predominant.

This fact implies the importance of direct vegetation-flow-interactions especially when resctrictive boundary conditions such as width limitation (e.g.by levees as in the case at the Upper Rhine) and consequently higher hydrodynamic forces have to be considered.

4.2 Synthesis of Individual Workpackages

Floodplain Stability

The results from field and laboratory measurements prove the importance of vegetation properties for the bank and floodplain stability. In this case, stability means a balance between sedimentation and erosion of sediments where the initial cross sectional profiles are maintained. First it could be shown, that a static equilibrium with no sedimentation or erosion does largely not occur at natural or restored rivers and riparian systems. Instead, continuous morphological changes take place that depend mainly on the properties of the flow interacting with the properties of the vegetation. Hereby, the most important classification was found to be the flow condition arising from the vegetation height, flexibility and the present hydraulic conditions such as water depth and velocity. The results of the experiments showed that the flow conditions can be classified in four categories (see also Figs.98a-d):

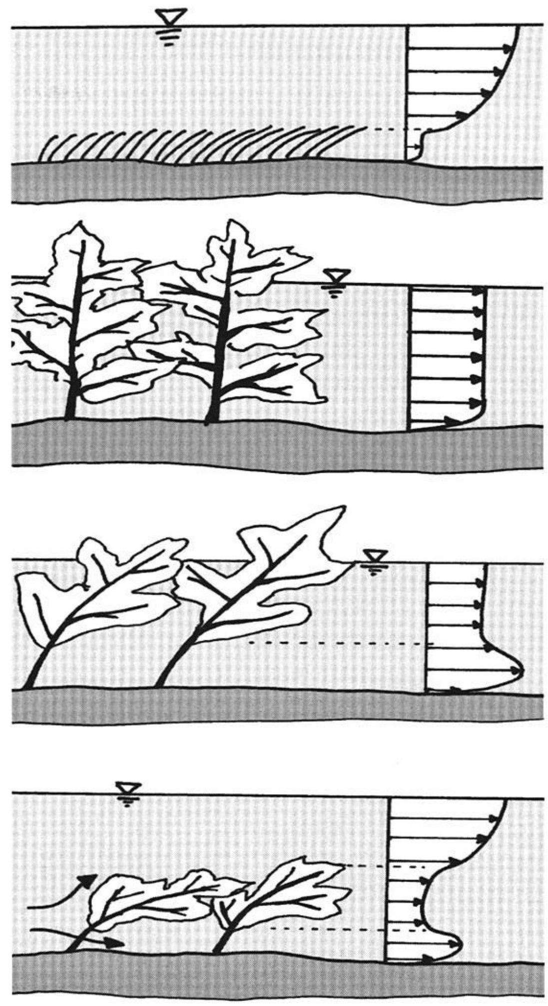
a) Submerged conditions, in which the plants are tall compared with the water depth and/or have flexible properties that allow biological drag reduction by bending in flow direction. The resulting flow field can be separated into the flow inside the vegetation close to the bed and the flow above the vegetation that shows the classical logarithmic mean velocity distribution (Fig.98 a).

b) Non-submerged (or emerged) conditions, in which the plants are taller than the water depth and/or rigid enough to withstand the flow. In this case the flow is almost constant over the water depth and can be characterized by classical friction laws (Darcy-Weisbach or Gauckler-Manning-Strickler formula) (Fig.98 b).

c) Emerged conditions with canopy and bottom flow. In this case the plants are too rigid to bend completely so that their canopies still protrude the water surface. The flow can be separated into decelerated canopy flow through the foliage and accelerated bottom flow underneath the canopies (Fig.98 c).

d) Submerged conditions with canopy and bottom flow. Contrary to the emerged case, the water depth is higher than the bent plant height. The vertical velocity profile resembles condition c) up to the canopy flow but has an additional logarithmic distribution above the canopy layer (Fig.98 d).

These categories are closely related to the sedimentation/erosion effects within floodplains and river banks. Hereby, local effects have to be differentiated from large-area processes. Fully *submerged conditions* lead to a decrease in velocities near the bottom and within the vegetation (see *Fig.98 a)*. In such way, they protect and stabilize the floodplain bed as observed for the fully submerged and bend willows at the river Wien and grasses at the Upper Rhine. If the vegetation grows homogenously in density and height, large areas can be affected by sedimentation. *Emerged flow conditions* occur with older vegetation such as trees that have highly rigid plant properties (e.g. woody stems, see *Fig.98 b)* and low vegetation densities due to the shading effects of their canopies. These rigid structures generate wake flows and tend towards local scouring around the plants. When *bottom flow* occurs, the flow is contracted underneath the vegetation canopy and causes increased velocities close to the bed and consequently increased local erosion around the plants. This effect was observed for young willow trees at the Upper Rhine (*emerged conditions* with canopy flow as shown in *Fig.98 c)* and for spherical bushes in the flume experiments at Trento (*submerged conditions* with canopy flow as shown in *Fig.98 d)*. The canopy in both cases was compact and dense with a rigid stem-structure at the bottom that anticipated a full bending of the plants. Considering in general the large-area effects on the floodplain stability, the vegetation increases the hydraulic roughness significantly and reduces the flow and the velocities. Consequently, less sediment can be transported



Figs. 98a-d Flow conditions for vegetation

by the flow and sedimentation predominates on the floodplains. Experiments at Trento showed that the total shear forces have to be increased up to 200 percent in presence of dense vegetation to get equal transport rates as for non-vegetated floodplains. This mechanism is important for long-term floodplain elevation and transition between softwood riparian forest that grows on the lower levels of the floodplain with higher and longer periods of inundation and hardwood riparian forest. Besides the vegetation-induced flow conditions, the strength of the flood waves characterized by their peak discharge has an influence on sedimentation/erosion. The rates of sedimentation within the submerged grasses at the Upper

Rhine increased with higher-discharge flood events and with declining water depths and flow velocities in the run-off phase of the flood wave. Simultaneously, the local erosion within the willows with bottom flow increased with higher discharges. Furthermore the accumulation of woody and floating debris influenced the sedimentation/erosion strongly. The trapping of floating debris by the vegetation close to the water surface enforced the occurrence of bottom flow conditions and consequently local scouring, whereas the accumulation of woody debris on the floodplain caused local protection of the bed and sedimentation to a large extent.

River Bed and Bank Stability

In general, the bed stability of rivers can be characterized by the grain size distribution and the effective hydraulic stresses acting on the river bed sediments. In the case of rivers with riparian floodplains, the hydraulic stresses are a result of interactions between the flow and the vegetation. Therefore, laboratory studies investigated the influence of floodplain vegetation on the flow field, sediment transport and sedimentation/erosion processes. The results of the physical models show, that strong interactions between the floodplain flow and the flow in the un-vegetated river channel (or main channel) occur. The interactions are characterized by a strong turbulent exchange and secondary currents. These effects are generated at the edge or banks of the floodplain and expand far into the open main channel. As a result, the turbulent shear stresses and erosive forces acting on the river bed are increased. In the experiments on riparian morphology, the sediment transport rates in the main channel were increased up to more than 100 percent in the case of a narrow main channel with dense vegetation on both banks compared to a scenario without vegetation. The strength of the exchange processes is related to the plant properties as shown by the experiments at Karlsruhe. Waving motions of emerged flexible vegetation caused an increase of the strength of secondary currents, whereas the compression and waving of foliage had a damping effect. Besides, local morphological changes such as sand ridge ("Rehne") formation on the banks are generated by the flow interacting with the vegetation. In nature, sand ridge formation has been observed as an important initial state of riparian succession. Willows find excellent growth conditions on the ridges and stabilize the sediments by their roots. Therefore, additional experiments investigated the influence of dense vegetation strips on the banks. It was found that significant damping of momentum exchange and sediment transfer between main channel and floodplain occurred. In such way, the sand ridge formation is a self-stabilizing reaction of the bed and floodplain morphology towards an equilibrium stage.

Roughness and Flood Protection

According to the classification in Figs.98 a-d, the roughness of single plants is dependent of the plant properties interacting with the flow. Hereby, the flexibility of stem, branches and foliage plays a determining role because it enables the plants to streamline and reduce their frontal area and consequently the exerted hydraulic forces biologically. This phenomenon was investigated at large-scale flume experiments with natural willows at Trento, at the River Wien and at the field measurements at the upper Rhine. The willow is a typical and frequent representative of softwood riparian forest and highly adapted to the flow and sediment dynamics of its habitat and was therefore chosen as the ideal test plant. In general, all measurements could prove that vegetation causes an increase of roughness and consequently decreased mean velocities and the discharge capacities. The maximum reduction of flow velocities at the river Wien (*submerged conditions*) and at the Upper

Rhine (*emerged conditions with bottom flow*) was found to be 30-45 percent compared to un-vegetated conditions. Even if the flow conditions were different, the flow was decelerated significantly for both cases and in the same order magnitude.

This deceleration can also be expressed as a Strickler resistance coefficient that covered a range between 19 and $32m^{1/3}/s$ in the Trento flume experiments. The spread of the values proves that the resistance is not constant but a function of the relative submergence and plant density. Higher values of relative submergence and lower plant densities caused lower hydraulic resistance. In the experiments, bending started at flow velocities of about 0.15 m/s until the plants reached their maximum submerged compression at about 0.6 m/s. This streamlining effect lead to a reduction in total drag forces of about 80 percent for a single plant. Furthermore, it could be shown that a removal of leaves reduced the drag forces up to 25 percent for maximum compression and 75 percent for low velocities before bending occurs. This implies the significant contribution of foliage to the overall plant resistance and its seasonal dependency. Besides, the vegetation vitality and properties were observed to change in short-term during flood events. Submerged grasses at the Upper Rhine decreased their flexibility and roughness due to longer inundation and showed stronger bending at the run-off phase of the flood wave. Furthermore, the trapping of driftwood and floating woody debris by the vegetation were found to influence the streamlining. The accumulation of floating debris increased the frontal area and the drag of willows and caused bending at earlier stages of the flood. In the case of rigid emerged plants where no bending occurred, the accumulation lead to a significant increase of roughness and induced in some cases bottom flow conditions below the debris that was deposited in the height of the water level. Models to predict the streamlining effects of various types of vegetation and the reduction of frontal area and drag forces have not been established yet. Hereby, the biggest difficulty is a physically-based description and quantification of the complex vegetation properties and structures. Therefore, flood prediction focused on large-scale models and roughness estimations that integrated the above mentioned local effects. For this purpose, a 1D unsteady numerical model was developed and tested at a 28 km long reach of the Upper Rhine. In the model, the calculated from vegetation density and stem diameters as well as the width of the vegetated floodplain were varied. The results could show that denser floodplain vegetation has no significant influence on the flood hydrograph and peak discharges and causes only a small retardation of the flood wave. The reason for this is that floodplains with riparian forests that are adjacent and directly connected to the river are already inundated when the flood peak arrives and thus do not contribute as storage reservoirs. Consequently, the value of riparian forests as flood protection measures is strongly dependant of their lateral and longitudinal extensions and the resulting inundation dynamics.

Floodplain Ecology and Riparian Succession

The ecological importance of riparian forests and floodplains as buffer strips for wildlife habitats, groundwater protection and prevention of pollution is well known from literature. Therefore, one part of the ecological work within the project was directed towards the determination of the ecological functionality as a key aspect of riparian forest. The analysis of leaf-pack processing, short-term retention of organic matter and benthos sampling introduced quantitative and practicable methods to fulfill these objectives. Additionally, the fluvial functioniong index (FFI) was introduced to include descriptive qualitative analysis of larger river systems. These methods provide a broad insight in riparian ecology, its actual state and deficits and were applied succesfully for the rivers Fersina and Enz. The second ecological workpackage was the characterisation of stages of succession of riparian forests and its prediciton exemplarily at the Upper Rhine. In such way, the hydraulic and morphological field investigations were complemented with botanical studies of the vegetation. These studies showed that the succession of riparian floodplains with limited lateral extensions (below 150 m) is strongly influenced by the flow and sediment dynamics in exchange with the river. Hereby, different factors were identified: primary the flow velocity and water depth, secondary the formation of virgin soils by sedimentation, settlement and germination conditions. Only flow-adapted species were able to withstand the direct hydraulic stresses and drag forces. The most frequent one was the white willow. These species is able to streamline and to decrease the exerted stresses biologically. Nevertheless, damages and fractures occurred after exceeding critical stresses but due to the secondary mechanism of re-lignification the willow mortality was low. But it shows that the succession at the Upper Rhine gets hardly beyond the stage of softwood riparian forest even if the flood duration would allow formation of hardwood forest. Additionally, the formation of dense reed layers on the virgin soils where erosion/sedimentation occurred was found to prevent the succession of trees. Reeds establish at many sites and were even able to form permanent communities supported by the sedimentation and decrease of bed shear as already mentioned above for submerged flow conditions.

Closing Words

It is easy to imagine, that the work of five partners within a project period of three years is limited considering the spatial and temporal extensions of natural riparian forest and the complexity of the involved physical and ecological processes.

In that light it was necessary to put the focus on some of the most relevant processes, knowing that it was impossible to cover all. This meant for example, that the areas under investigation were narrowed down to the floodplains directly adjacent to the river channel where the determining interactions between flow, sediment and vegetation occur and ground water is only of minor importance.

On the other hand, this methodology made possible to carry out investigations in much more detail and on a scientific level involving basic research and essential steps forward to solve problems that had not been faced before. In the RipFor-Workpackages, the primary objective was the identification and quantification of relevant parameters to describe the mechanisms behind riparian forests. Moreover, the gained knowledge and experiences were put in the development and realisation of measurement techniques, calculation methods and numerical prediction models.

Beyond the research, the basis for a sustainable riparian forest management was provided by development of the RipFor-guidelines. The guidelines contain practical aspects and recommendations for maintenance and restoration of riparian forests derived from the undertaken research work. Hereby, the practical applicability was kept in mind and supported by the introduction of case studies of different field sites.

Thus, RipFor as a pioneer project on the field of riparian forest research contributed to the scientific progress as well as further developments of management practices even if many open questions remain.

Some of these questions will be answered by ongoing research activities of the partners, based upon the experiences and knowledge gained within RipFor.

5. EXPLOITATION AND DISSEMINATION OF RESULTS

First of all, RipFor is a scientific research programme working on a field where physical basics are known only fragmentary up to now: the complex interacting processes between sediment, vegetation and flow in riparian forests.

Publications, Conferences and Workshops
RipFor contributed to the scientific progress and filled important gaps with new material, methods and results as introduced in the previous Chapters 3-5 of this report. Presentations of the current state of the research were given at different international conferences. In particular three general assemblies of the European Geographical Society (EGS) at Nice between 2001 and 2003 (see Chapter 8) and one workshop "Arbeitskreis Hydrologie" at Berlin, March 2002. Herein, partners of each group contributed to introduce the entire RipFor project and discuss it with experts from the scientific community.
On the other hand, RipFor always incorporated the practical applicability of the research and decision support for potential end-users working in administration (e.g. forestry and flood control) and professionals (e.g. landscape planning and engineering). At the final RipFor meeting at Trento, 2003, end-users were invited to a workshop with presentation and discussion of the RipFor Guidelines to make the practical aspects of the research work available for the community.
Publications in scientific research journals were done or are in preparation (see Chapter 8, "PUBLICATIONS AND ABSTRACTS"). Furthermore, work on PhD theses based upon project-related topics is carried out by the partners of UNIKARL and BOKU. This shows the up-to-date relevance and importance of the RipFor topics and is confirmed by the fact that all partners worked on proposals for future research, particularly in the 6th frame programme of the European Commission. In such way, the experiences gained within the project will be directly incorporated in ongoing research and found a basis for further steps and insights in riparian forest management.

Teaching and Lectures
The research was incorporated in teaching activities at the different universities, such as guided tours at the laboratory facilities and field excursions to the RipFor test sites. Hereby, it was important to include the students in the project work and to teach awareness of the necessity of riparian forest systems.
In April, July and August 2002 field and lab lectures were given about "Ecomorphology of rivers and floodplains" at the Upper Rhine test site and at the experimental flume of the Federal Environmental Agency in Berlin. Together with 12 undergraduate students experiments were carried about the interaction between vegetation, flow velocity, discharge, sediment transport and geomorphology. The results of the lab experiments will be published at the annual report 2002 of the Federal Environmental Agency.

Public Presentations and Exhibitions
Public Presentation was given at the floodings of the Wien River, the first one in October 2001. In March and September 2002 the RipFor-Project presented problems related to flood retention and river restoration to general public at the Science Fair Exhibition of the Freie Universitaet Berlin and at the Exhibition "Planet Water; Year of Geosciences in Germany".

Guidelines
The chapter on flow field measurements was prepared as a part of the guidelines with respect to methodological aspects and case studies

Technical improvements
To investigate the interaction between floodplain vegetation, flow field and sediment transport under naturally boundary conditions two Acoustic Doppler Current Profilers (ADCP) were mounted inside a willow grove respectively at a grass covered location on a floodplain at the Upper Rhine. In addition to that the monitoring of vegetation and flow field was realized by a digital video camera mounted on the embankment. In January 2002 an ISDN based remote control between a computer in Berlin and at the test site "Upper Rhine" was installed. In February 2002 the remote control via PC and ISDN telephone network was started successfully. This installation enables to control, check and adjust the video camera and the ADCPs and to transfer data via ISDN. In addition the online operation of the ADCP makes it now possible to record three dimensional flow fields of entire flood events for several hours, days and weeks for all stages of water level and discharge. The data which can be obtained by these measurements will lead to an improved knowledge about non stationary flow conditions inside vegetated floodplains. In combination with the geodetic survey and the installed sediment traps the design of experiment gives the opportunity for a comparative long term monitoring of flow fields, sedimentation and erosion under the influence of different types of riparian vegetation and with respects of natural boundary conditions and different stages of succession.

6. POLICY RELATED BENEFITS

Initial Intentions and Objectives
Looking back at the initial proposal, seven goals were defined:

1. *creation and utilisation of river floodplain vegetation for sustainable retention purposes,*
2. *resistance and transportation of fine sediments,*
3. *description of the plant succession to make prognosis of the retention effects,*
4. *protection of river banks,*
5. *improvement of water quality,*
6. *formation of habitats for plants and animals,*
7. *Use as recreational areas for local population.*

The objectives and achievements deduced of the goals were (with link to the goals):

a) *description of the flow field inside riparian forests (1, 2, 3, 4),*
b) *description of roughness of riparian forests (1, 2, 3, 4),*
c) *description of sedimentation inside riparian forests (1, 2, 3, 4),*
d) *reduction of flow velocities in combination with plant parameters (1, 2, 3),*
e) *effective resistance of individual plants (1, 3),*
f) *interactions between vegetation and sediment transport (1, 2, 3),*
g) *resistance of flow through riparian forest (1, 2, 3, 4),*
h) *ecological studies of organic matter retention and processing (1, 5, 6),*
i) *macroinvertebrate habitat studies (1, 5, 6),*
j) *mapping of the ecological functionality of streams (1, 5, 6, 7),*
k) *riparian forest management concerning interactions between rivers and floodplains (1-7),*
l) *Guidelines for optimisation of riparian forest management (1-7).*

The work carried out by the partners covered all of the above. The initial intentions and objectives were fully met by the following results (see Chapter 3, "RESULTS"):

a) description of the flow field inside riparian forests:

FUB:	field work at the Upper Rhine (FS1) Flow field measurements Spatio-temporal changes of flow field under impact of floodplains vegetation
BOKU:	field work at the Wien River (FS3) Flow velocity distribution
UNIKARL:	flume experiments on riparian flow field Depth-averaged and lateral velocity profiles
UNIKARL:	3D numerical modelling of riparian flow field

b) description of roughness of riparian forests:

BOKU:	field work at the Wien River Relationship between discharge and water level

UNIKARL: flume experiments on riparian flow field floodplain vegetation

UNITN: flume experiments on floodplain vegetation and sediment
Hydrodynamic resistance of isolated and group of real plants

UNITN: physical model of the Wien River (FS3)
Flow resistance of vegetated banks and the Wienfluss physical model

UNIKARL: 3D numerical modelling of riparian flow field

UNIKARL: 1D numerical modelling of flood wave propagation

c) description of sedimentation inside riparian forests:

FUB: field work at the Upper Rhine (FS1)
Sedimentation and erosion

Spatio-temporal changes of sedimentation and erosion under impact of floodplain vegetation

UNIKARL: flume experiments on riparian morphology

UNITN: flume experiments on floodplain vegetation and sediment
Effect of vegetation presence on sediment transport

d) reduction of flow velocities in combination with plant parameters:

FUB: field work at the Upper Rhine (FS1)
Spatio-temporal changes of flow field under impact of floodplains vegetation

BOKU: field work at the Wien River (FS3)
Flow velocity distribution

UNIKARL: flume experiments on riparian flow field
Floodplain vegetation

UNITN: flume experiments on floodplain vegetation and sediment
Hydrodynamic resistance of isolated and group of real plants

UNITN: physical model of the Wien River (FS3)
Flow resistance of vegetated banks and the Wienfluss physical model

UNIKARL: 3D numerical modelling of riparian flow field

UNIKARL: 1D numerical modelling of flood wave propagation

e) effective resistance of individual plants:

UNIKARL: flume experiments on riparian flow field
Floodplain vegetation

UNITN: flume experiments on floodplain vegetation and sediment
Hydrodynamic resistance of isolated and group of real plants

f) interactions between vegetation and sediment transport:

UNIKARL: flume experiments on riparian morphology

UNITN: flume experiments on floodplain vegetation and sediment
Effect of vegetation presence on sediment transport

UNIKARL: riparian succession at the Upper Rhine (FS1)

g) resistance of flow through riparian forest:

BOKU: field work at the Wien River (FS3)
Relationship between discharge and water level

UNIKARL: flume experiments on riparian flow field
Floodplain vegetation

UNITN: flume experiments on floodplain vegetation and sediment
Hydrodynamic resistance of isolated and group of real plants

UNITN: physical model of the Wien River (FS3)
Flow resistance of vegetated banks and the Wienfluss physical model

UNIKARL: 1D numerical modelling of flood wave propagation

h) ecological studies of organic matter retention and processing:

APPA: field work at the Fersina (FS4) and Enz River (FS2)
Short-term retention measurements
Leaf-packs

i) macroinvertebrate habitat studies:

APPA: field work at the Fersina (FS4) and Enz River (FS2)
Benthos quantitative sampling

j) mapping of the ecological functionality of streams:

APPA: field work at the Fersina (FS4) and Enz River (FS2)
FFI (Fluvial Functioning Index) of the Fersina
FFI (Fluvial Functioning Index) of the Enz River

k) riparian forest management concerning interactions between rivers and floodplains:

APPA/ BOKU/ FUB/ UNIKARL/ UNITN/ BMLF: See stand-alone document « Riparian Forest Management Guidelines»

l) guidelines for optimisation of riparian forest management:

APPA/ BOKU/ FUB/ UNIKARL/ UNITN/ BMLF: See stand-alone document ”Riparian Forest Management Guidelines”

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8. PUBLICATIONS AND ABSTRACTS

European Geophysical Society, General Assembly 2001, Nice (France)

INVESTIGATION ON THE INTERACTION BETWEEN FLOOD EVENTS, VEGETATION AND SEDIMENT DISTRIBUTION AT FLOODPLAINS OF THE UPPER RHINE

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The investigation is embedded in the framework of the EU-Research Project Riparian Forest Management taking into consideration the hydraulic, sedimentological and ecological problems of a multifunctional riparian forest management at different scales. The aim of the project is the restoration of riparian forests and the activation of retention areas. The tasks of this survey focus on the impact of morphology and vegetation on the flow field and the processes of sedimentation and erosion during flood events in a floodplain at the upper Rhine, south of Breisach. The test site is located near the community of Hartheim, at river kilometre 210 in a silted groin field. The area is covered with different kinds of trees, bushes, shrubs, perennial plants and grass. Flow velocity, topography, morphology and vegetation are investigated. Furthermore the transport of suspended- and bed load, sedimentation and erosion are surveyed. Grain size analysis and its distribution over the floodplain are also taken into account. The morphology is characterised by a distinct separation into an upper and lower floodplain level. The varying types of vegetation show differences in height, morphology and succession. Their dissemination is closely related to the topography. Texture and organic content of sediments show remarkable differences in their horizontal and vertical distribution. Both multiple changes of texture classes and organic content in soil horizons and the thickness of the horizons indicate a great variety in flow and sedimentation conditions during former flood events. Additional results of a field-campaign after a single flood event in summer 2000 show that no erosion has taken place in the floodplain, however sedimentation of 3cm on the lower floodplain level could be observed. The fresh sediment is dominated by silt, clay and organic material. The present results demonstrate the need of a better understanding of interactions in floodplains between morphology, vegetation, flow conditions and sedimentation. The investigation must also include the influence of morphology and succession of vegetation on changes in the hydraulic conditions and thereby on sedimentation and site properties. Guidelines for sustainable riparian forest management with consideration of flood retention and river restoration will be worked out.

SOME EXPERIMENTAL RESULTS ON THE EFFECT OF VEGETATED BED ON SEDIMENT TRANSPORT

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The main results of an experimental investigation on the role of vegetation (bushes)on sediment transport phenomena are reported. The investigation was made in an open channel flow, where the presence of bushes on the bed was reproduced. Different grain sand size and different density of vegetation were considered. For each grain size and vegetation density values, various runs were performed, for different vegetation submergence, Froude and Reynolds number values. The aim of the experiments is to have a better insight on the mechanics of sediment transport in vegetated bed. A modification derived from the original relationship by Meyer-Peter-Muller is proposed and calibrated on the measured data. The proposed formula treats the vegetation as a reduction of the available bed surface for sediment exchange. This parameter in the formula acts a special hiding factor.

FLEXIBILITY OF RIPARIAN WOOD

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Covering the soil by plants bent down to the ground when flooded is one of the most efficient ways to protect riverbanks by riparian vegetation. Material properties of typical riperian timber describe their suitability for this mechanism. By means of bending tests mechanical properties were established for various species‘. Their dependence on the tree's diameter and the

species delivers clues to suitable species', types of bioengeneering construction and their maintenance. The flexibility of plants, i.e. their ability to bend down when overflown, to cover the embankment and protect it from erosion, is described on the basis of empirically established material properties. Five tree species were examined, i.e. Acer pseudoplatanus, Alnus glutinosa, Fraxinus excelsior, Salix alba and Salix caprea. It is shown:

- The deformation of all examined materials is not elastic. Their deformation behavior is rather elasto-plastic with a very long transient section.
- The plastic deformation section is predominating the elastic part with all tree species'.
- The commonly applied resistance to deflection (E. I) appears to be in-sufficient, in order to describe the deformation behavior of young woody stems.
- The tree species' Acer pseudoplatanus and Fraxinus excelsior show higher ultimate stresses, and also higher moduli of elasticity than Alnus glutinosa, Salix caprea and Salix alba.
- Concerning riverbank protection that means that ductile tree species such as Alnus and Salix are more easily bent to the ground by the streaming water in order to cover the soil and the riverbank whereas higher loads are needed to bend Fraxinus and Acer.

PHYSICAL MODELING OF RIPARIAN FOREST VEGETATION

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Riparian forest vegetation has a main effect on the decrease of flow velocities on floodplains, the resistance of the interface plane interacting with the main channel and therefore the retention capability of river systems during flood events. Due to the high complexibility of vegetation structures a parameterization from an hydraulic point of view has not yet been developed succesfully. Different species of trees and bushes occur simultaneously and in different stages of forest succession. The behaviour of these plants under flow conditions can range from completely rigid (like old trees with fixed stem diameters) to highly flexible with compressible stem, branch and leaf structures and the ability to get streamlined (such as young willows). Laboratory experiments will be carried out at the University of Karlsruhe to determine the flow and interaction resistance, turbulence structures and the deposition of suspended sediment in different stages of riparian forest succession. With this aim three types of artificial vegetation will be used: (a) rigid cylinders, (b) bendable/non-compressible PVC-twigs and (c) flexible/compressible PVC-twigs. At the EGS -conference first results are presented which later on will be included in the "RipFor"-project guidelines about the management of multifunctional riparian forest. This project is directed to a better understanding of the linked processes between morphology, hydraulic and vegetation in riparian forests.

1-D NUMERICAL SIMULATION OF THE WATER LEVEL OF A RIVER SECTION WITH RIPARIAN FOREST AND SENSITIVITY ANALYSIS OF ROUGHNESS PARAMETERS

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In the frame of the Integrated Rhine Programme retention basins of different types and size are planned. The aim of the measure south of Breisach consists in the creation of a retention volume of 25 Mio m3. It is realised by increasing the width of the River Rhine by about 90 m and by dredged floodplain up to 6 m. In the process of natural succession the dredged floodplain will be covered by a riparian forest. A modified 1-D steady-state numerical model was applied to the reach between Basel and Breisach in the River Rhine and the roughness parameters were identified by different discharges. A sensitivity analysis was carried out in many combinations of the roughness parameters due to the floodplain surface and the density of the vegetation on it. The roughness parameter due to the floodplain surface varied in the range of ± 20 %. The five kinds of density of the vegetation were chosen from several sites in the present River Rhine. In the sensitivity analysis the influence of the enlargement of the floodplains were also considered. The results showed that if the surface roughness is larger and the vegetation of the floodplains is denser, then the higher water level is obtained. Certain combinations of the parameters can realise the expected or even more retention volume of 25 Mio m3.

European Geophysical Society, General Assembly 2002, Nice (France)

FLOOD EVENTS, DISCHARGE AND SEDIMENTATION ON FLOODPLAINS

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The activation of retention areas and the restoration of floodplains have great importance for flood protection and the ecological function of river landscapes. Complex interactions take place between flow velocity, sediment transport, morphology and vegetation within floodplains. This investigation, which is embedded in the framework of the EU Research Project Riparian Forest Management, focuses on these interactions and will give more detailed information about the impact of vegetation on flow field, discharge and sediment transport. Under the aspects of flood retention and river restoration the improved knowledge of these parameters is expected to assist in generating measures for the optimisation of riparian forest management. Hence the objective of this investigation is the description and analysis of:
a.) duration and level of inundation
b.) spatio-temporal variation of flow velocity and its intensity within the floodplain
c.) roughness in the form of substrate, vegetation, morphology and its spatiotemporal variation
d.) impact of morphology and vegetation on flow velocity and discharge within the floodplain
d.) morphology, vegetation, substrate, sedimentation and erosion before and after subset flood events.
The selected area of investigation is located at the upper Rhine, near Freiburg. The test sites within the investigated floodplain differ in the type of vegetation, morphology, substrate, aspect and height. These parameters were investigated before and after a longer period of floods. The spatio-temporal variations of flow velocity in the stream and on the floodplain were recorded using Acoustic Doppler Current Profilers. Simultaneously data were collected about the suspended load above the ground and below the water surface. Using a digital video camera, a first attempt was made to monitor the deformation of trees during a single flood event.

SEDIMENT TRANSPORT ON THE VEGETATED BANK OF THE SOIL BIOENGINEERING TEST FLUME AT THE WIEN RIVER

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Soil bioengineering structures are frequently used to protect river banks. Studies by WEITZER / DOPPLER / FLORINETH (1998) on measuring the pull-out resistance and by OPLATKA (1998) on the effective flow acting on willows show that a high hydraulic load by itself does not lead to failure or dislodging of the plants but that the slope's instability is caused by the erosion of bed material. The onset of erosion is indicated by a critical shear stress, determined by the combination of a number of factors such as flow velocity, lift force, turbulence, grain size, grain shape, stratification of the river bed material and the type and density of the vegetation. Investigations into the stability of a variety of soil bioengineering structures (brush mattress with willows, branch layers, fascine layers) are carried out at the soil bioengineering test flume along the Wien River, where artificial flooding runs expose the plant/soil complex to extreme hydraulic loads. Marked, surveyed and weighed gravel material of different grain diameters (10, 20, 40, 60, 80 and 100 mm) and variable layer arrangements is put into the bed or bank of the test flume to determine the critical shear stress. The exact grain position is identified before and after each artificial flooding, so that the mean sediment transport path can be determined for each grain diameter. By comparing sediment transport paths for different grain sizes, a critical grain diameter can be defined for each soil bioengineering structure. The critical grain diameter thus obtained is used as an input parameter in calculating the critical shear stress from bed load transport equations. Based on the data thus collected and their analysis it is possible to present and interpret initial findings.

DEVELOPMENT AND HYDRAULIC ACTION OF VEGETATION GROWING FROM SOIL BIOENGINEERING STRUCTURES

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In 1997 and 1998 a test flume was laid out at the Wien river near Vienna, to investigate soil bioengineering methods and their hydraulic effects. Four different soil bioengineering methods were used for bank protection, i.e. brush mattresses with willows, fascine layers, branch layers and willow cuttings. Four and five years after construction, important differences between methods are now becoming visible in terms of growth, functionality and damage. The development of individual

plants and the entire population is described by: the number of shoots per plant and per m2 (i.e. density), their basal diameter and the diameter at a height of one metre, their length, the shape of their crown.
Differences between the soil bioengineering methods are mainly related to the plant's water supply, which leads to a variation in the density of the populations. Typical deficiencies and losses are described phenologically and explained by the drag force of the water acting along different axes of the plant. Growing plants serve as a roughness element in the cross-section, by becoming taller, more rigid and shrubbier although less numerous. This hydraulic influence is described by the comparison of water levels, which were measured over a period of four years at the same profile and discharge volume. It is shown that the growth of the bank vegetation has a damming-up effect and thus causes the observed water levels to rise significantly.

HYDRODYNAMIC BEHAVIOUR OF FULLY AND PARTIALLY SUBMERGED PLANTS IN OPEN CHANNEL FLOW: A PROTOTYPE SCALE EXPERIMENT.

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The hydrodynamic behaviour of partially and fully submerged tall vegetation is of great interest in the river management. Only recently some researchers (Kouwen, 1999, Oplatka, 1998) analyzed the hydrodynamic resistance of bushes, taking into account also the plants elasticity in the classical Petryk & Bosmajian approach. In the present work, an experimental investigation is performed, where the hydrodynamic resistance of isolated and grouped salix alba bushes is measured, in a laboratory channel at prototype scale. This kind of plants has particular interest because they are often used in bank stabilization and remediation works for mountain streams. The tests are performed using young plants, ranging from 1 m up to 2 m high, in a 100 m long, 2 m deep and 2 m large open channel flow, the discharge ranges up to 1,3 m3/sec. A suitable strain gauges system has been realized in order to directly measure the force exerted on the plant by the flow. The results are compared with analogous measurements of Oplatka and Kouwen, confirming the influence of elasticity and leaves on hydrodynamic resistance; in particular the effect of smaller branches bending and the influence of foliage on drag has been analyzed, comparing the drag of the same bush with and without leaves. Moreover an approach for drag evaluation, alternative to that of Oplatka and Kouwen is proposed.

PHYSICAL MODELLING OF COMPOUND CHANNEL FLOW WITH RIGID AND FLEXIBLE CYLINDRICAL FLOODPLAIN VEGETATION

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In recent years, nature rehabilitation of river floodplains and riparian areas has become an important task for river and environmental management. As a consequence, the strong effects of natural vegetation on the hydraulic roughness and the shear layer between the main channel and the floodplains had to be taken into account. Across this shear layer, vortices with vertical axes develop that are considered as the driving force of momentum transfer. Due to this turbulent interaction process, the velocities are d ecelerated in the main channel and accelerated on the floodplains and lead to a change of the channel discharge capacity. In the present study, flexible cylinders were used as physical model of nonsubmerged floodplain vegetation in a half-trapezoidal compound channel constructed at the Theodor Rehbock hydraulic laboratory. Additionally, comparative experiments were performed with rigid cylinders of identical diameter. For both setups, experiments for uniform flow conditions and three discharges (respectively three depth ratios) were carried out. Flow velocities were measured by a laser Doppler velocimeter (LDV) within multiple cross sections. The resulting horizontal velocity profiles were analysed and compared to theoretical boundary-layer approaches. The main objective of this study is to get a better idea of the influence of natural vegetation on compound channel processes.

THREE DIMENSIONAL MODELING OF THE FLOW IN A COMPOUND, VEGETATED CHANNEL

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There is an increasing interest and research concerning floodplain management of river and natural waterways. The fact that the vegetated floodplains in terms of riparian forests can be used as flood retention space, it becomes of major interest to understand the hydraulic effects of non-submerged vegetation in these areas. The aim of the present work is to introduce a three dimensional numerical model which is able to predict the hydrodynamic behaviour of the flow in a compound open channel with vegetated floodplains. A three dimensional numerical model, where the turbulence structures are calculated with the *k-e* closure scheme, was used to determine the flow pattern in open channel flows. To simulate the additional flow resistance of non-submerged rigid vegetation the drag force on a rigid cylinder is implemented into the Navier -Stokes

equations. Preliminary results have shown that the numerical model using the *k-e* scheme is not able to reproduce flow as well as turbulence structures in detail. However it provides good estimation about mean velocity distributions in all parts of the channel. The model was validated with the experimental data of the physical model situated at the Theodor Rehbock Laboratory, University of Karlsruhe. The flume, designed as half trapezoidal compound channel where the floodplain taking the half width of the flume, is covered with vegetation simulated by rigid cylinders with a constant diameter and a specific spatial density. Based on already existing data, one significant mean velocity of the flow on the floodplain as well as in the main channel is obtained, to enhance the validation of the numerical model.

"New Trends in Water and Environmental Engineering for Safety and Life: Eco-compatible Solutions for Aquatic Environments", 2002, Capri (Italy); International Congress "Interprävent" 2002 in the Pacific Rim, Japan

THE SOIL BIOENGINEERING TEST FLUME VIENNA: METHODS AND RESULTS

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In the last decades the demand for ecological studies of flowing waters grew significantly. The aim and the purpose of such studies is on the one hand to assess the human impact on flowing water ecosystems and on the other hand to make an attempt for fully understanding the complex natural river structures. This knowledge is very important and can be very useful for river restoration and for the application of soil bioengineering methods.
Soil bioengineering is an appropriate soft engineering method for bank protection using native materials such as living plants or plants in combination with auxiliary materials. However, the stress on, and the resistance of soil bioengineering constructions depends on various factors which are subject to dynamic change.
In general, soil bioengineering methods are not pulled out of the bank by the water, rather they are eroded. The stability of soil bioengineering methods depends mainly on the interaction between the factors water – plant – soil.
In a hydraulic laboratory it is not possible to simulate these complex structures and to get the important and necessary data. Therefore the Department of Soil Bioengineering and Landscape Construction (University of Agricultural Sciences, Vienna) have constructed a soil bioengineering test flume in cooperation with the local authorities of Vienna in 1996. The resistance of different soil bioengineering methods has been tested by artificially generated floods and during natural floods. The length of the test flume is 170 meters with 3 different soil bioengineering methods (brush mattress, branchlayer, fascine layer) for the bank protection. The main focus of the investigations of the soil bioengineering test flume can be described by the following:

- measuring the flow velocities of different parts of the cross sections (different methods of flow measurements)
- succession of bank vegetation
- the hydraulic impact of the vegetation in different stages of succession (flow capacity, sedimentation, erosion, flow distribution in the vegetation).

After four years of observation it is possible to show the developing of the vegetation of the different soil bioengineering methods and present first results regarding the flow field distribution inside and outside of the covered flow area.

European Geophysical Society, General Assembly 2003, Nice (France)

A SIMPLE METHOD TO ASSESS THE SHEAR FORCE AND FLOW VELOCITY ACTING ON THE BED SURFACE AND VEGETATED BANK

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Properly used, riparian vegetation can reduce the flow velocity, mainly near ground level, and thus provide protection from erosion. Acoustic velocimeters are unsuitable to measure near-ground velocity because of their signal reflection. A simple device measuring the shear force $F = \tau \cdot A$ acting on a known sectional area A allows to calculate the bed shear stress $\tau \cong p \cdot g \cdot rhy \cdot I$ resp. $\tau \cong p \cdot g \cdot h \cdot I$ and thus the flow velocity by empiric calibration. A water-filled floating body ($p \cong 1g / cm^3$) serves as a surface for the shear force to act on in the main flow direction. Attached to an anchor, by a rope, the body floats just above the bed surface or bank slope. A dynamometer integrated into the rope measures the shear force acting on the body and transfers the data, collected with variable frequency, by cable to a signal amplifier and a data logger. The entire measuring unit was calibrated in a hydrometric vane calibration channel by measuring the shear force at exactly known flow velocities, i.e. the speed of the cart across the channel. The measured shear forces were related to the defined velocity for generating a calibration curve. In this manner, it is possible to deduce the flow velocity from measuring the shear force. Bodies of different cross-sections are used in order to adapt the measuring range to the velocity expected. When applied to a stream in Vienna rehabilitated by soil bioengineering methods, the measuring device found that the shear force is close to zero within the dense bank vegetation just above the river bed. In the transition area between the vegetated bank and the open channel, shear forces were observed that corresponded to flow velocities of approx. 1.4 m/s. Upon flooding of a paved river path, shear forces were observed which were equivalent to flow velocities of 2.5 m/s.

NUMERICAL MODELLING OF VEGETATION FLOW INTERACTION: THE WIENFLUSS TEST CASE

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We apply a three-dimensional computational fluid dynamics code based on a finite volume discretisation to a 170m test reach of the a river in Vienna. One of the primary aims of this paper is to test various methods for representing the flow resistance of natural vegetation. The two approaches considered vary in complexity and could be practically implemented and applied within 2D and 3D flood modelling tools. The first approach uses empirical relationships derived from the laboratory data and modifies the existing friction term in the momentum equations. While the second approach introduces a drag related sink term in addition to the bed friction term. The roughness closure models considered do not modify the turbulence model (in this case the k-e model) and hence do not require re-calibration for each application.
The test reach is straight and comprises an asymmetrical compound channel that is vegetated on the floodplain by willows and unvegetated within the main channel. The development of the willows has been monitored over a four year period and plant parameters which characterise the dimensions of individual trees and their distribution have been quantified. Further, streamwise velocity data of high-spatial resolution has been collected at one cross-section for a series of flood events. The performance of each approach is quantified in terms of its ability to reproduce the streamwise velocity distribution in a partially vegetated channel. Different parameter tests are conducted to allow the sensitivity of the computed velocities against mesh resolution, and other important plant properties to be examined. For both flow resistance approaches, reasonable agreement is found between the measured and computed floodplain velocities.

HYDRAULIC BEHAVIOUR OF VEGETATED BANKS OF RIVERS: A FIELD AND LABORATORY INVESTIGATION

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The hydraulic behaviour of a river bank vegetated with flexible plants is substantially different from a bank with plants serving as rigid elements. At the soil bioengineering test flume in Vienna it is feasible to conduct field measurements to investigate the hydraulic behaviour of flexible plants under defined flood conditions. The length of the test flume is 170 m and the width of the whole cross section is 7 m, whereas the width of the vegetated zone is 4,5 m. This vegetated bank is constructed using different soil bioengineering methods. Doppler ultrasonic velocimeters are monitoring the flow field within the momentum exchange area during artificial floods with a maximum discharge of 33 m3/s. In order to provide a deeper insight into the hydrodynamic behaviour of the vegetation and the interaction between the banks and the non-vegetated main channel a laboratory model of the field test flume with a scale of 1/12 was realized. The field and the laboratory measurements show similar results in terms of mean velocity profiles and in terms of turbulence structures, showing a strong dynamic interaction between the vegetated and the non-vegetated zones. Further measurements in laboratory scale allow to distinguish between rigid and flexible plants in regard to their hydraulic action and to investigate the influence of different densities of plants on the flow resistance and the dynamic interaction, both in terms of turbulent and dispersive shear stress. The experimental results are compared with different analytical models commonly used for flow resistance estimation.

THE CASE OF THE UPPER RHINE: UNRAVELLING THE PAST AND WRAPPING UP THE FUTURE

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The southern Upper Rhine was once the most prominent braided river system in Germany. However it lost its character during the last 200 years and is now a trained river used for electricity and carrying ships to Basel(CH). The river sector between Basel and Strasburg(F) was always different to the Hochrhein (Lake Constance Ü Basel) and to the lower Upper Rhine (Strasburg Ü Bingen(D)). This ancient braided river system changed downstream according to the transition of grain sizes from cobbles to gravel and sand. Between Strasburg and Lauterburg(F) the braids were replaced by meanders and this geomorphological change induced many other changes. At thesed times the ecology, including the use of water and land, riparian forests, the development of flood defence and navigation were different. In addition there was a further problem for people living in the time of enlightment: how should the boundary of a state be defined within a braided river? In the German language braided rivers were and are still called "verwildert" and this means the river is going wild. As such, somebody who was able to improve this situation would gain merits. This happened to Johann Gottfried Tulla. He became the responsible engineer for river construction in the Great Duchy Baden. In 1812 he created a memorandum with recommodations for the future development of the river Rhine. Only 5 years later he succeeded with the first cutoff of a meander next to Karlsruhe. After his death a treaty between France and Baden regulated the elimination of the braided system between Basel and Lauterburg. The construction took place between 1840 and 1875. This development was opposed locally and by the Prussian and Dutch authorities who claimed - after the huge flood of 1824 - that the abnormal flood peak was a result of the meander cutoffs created in Baden. Nevertheless the results of training the braided system were technically convincing: a deeper river channel, less floods, a well defined border and finally the first bigger steamboats entering the new harbor of Basel. The new situation was settled by the peace treaty of Versailles with its entrustment of the Rhine to France. This resulted in the construction of the Canal d'Alsace between the wars and after the last WorldWar. Wrapping up the future of the Upper Rhine cannot be a turn back to the past, but should be an attempt to reduce the deficits and to amplify the ecological benefits. As already stated in 1824 the new river system causes more peaky floods and induces a deficit of bedload. The last problem was overcome by a bedload management scheme proposed by Felkel in 1970. For flood protection a German-French agreement defined the "integrated Rhine programm" in 1982 to create more flood storage capacity using the following approaches: - special operation of the power scheme, - construction of more weirs and more flood polders. The largest retention measure so far is planned along the Restrhein between the weir at the entrance of the Canal d'Alsace and Breisach(D). A strip of approx. 95 m width the ancient floodplain on the German side will be excavated down to the groundwater level in order to develop a new artificial floodplain capable of storing approx. 25 million m3 of floodwater. This project will not only create a new river but will be encountered by 50 million m3 of sediments which have to be removed and sold. The development of the Upper Rhine is an extreme example for river genesis during the last 200 years. There is no way back to the future but only the possibility to create an improved and more sustainable river system for the next century.

SPATIAL AND TEMPORAL CHANGES IN FLOW FIELD SEDIMENTATION AND EROSION DURING FLOOD EVENTS AT THE UPPER RHINE

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In order to counterbalance the effects of river control by regulation and straightening different types of measures are planned or under construction leading to a restoration of floodplains and to the installation of new flood retention areas. These measures need a better understanding of the interactive processes between the flow field, morphology, vegetation and sedimentation. The basic scope of this research is the resistance of vegetation to flow field and the impact of different types of vegetation on flow field, sedimentation and erosion. This knowledge is needed for the optimisation of riparian forest management to include flood and erosion/sedimentation mitigation. Both flow fields in riparian forests and its boundary conditions as set by vegetation and geomorphology will be studied during and after high floods. The investigation focus on the description and analysis of spatio-temporal variation of flow velocity and its intensity at different water levels during the entire periods of flood events. Special attention will be given to the flow field at the fringe of the forest against open areas and to typical flow field in riparian forests. Furthermore both the impact of morphology and vegetation on flow velocity and discharge within the floodplain and the processes between vegetation and sedimentation are analysed.

Hydraulic, Sedimentological and Ecological Problems of Multifunctional Riparian Forest Management

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APPENDIX: NAS

"The management of riparian forests in a macrolandscape context"

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A1. INTRODUCTION

By macrolandscapes we mean very large ecological systems, like river basins and ecoregions. Our goal has been to assess the role of the riparian forests in the production of natural services by such macrolandscapes, and to identify management principles for preserving or recovering this role.
The assumptions underlying our approach are related to the systems ecology knowledge base, namely that 1) socio-economic systems and the natural capital have a nested hierarchical structure (Allen and Star 1982, Odum 1993, Vadineanu 1998, Iordache 2002a), 2) the production of resources and services is the result of the structure and functioning of the natural capital (i.e. the natural capital *is not* the natural resources and services), and 3) organizations manage the natural capital in order to maximize the overall production of resources and services (i.e. the natural capital is simply one kind of capital, without any assumption about its intrinsic value).
Natural services depend on the functioning of the ecological systems, and the functioning is depending on their structure and on the connecting fluxes between the structural elements. Consequently we will look at the position of riparian forests in the structure of macrolandscapes, at the abiotic and biotic fluxes connecting them with the other types of ecological systems, and at the management principles arising from this knowledge ("Results" chapter). A case study will also be provided, illustrating the implementation of the principles that we identified.
On the other hand, the maximization of natural resources and services production is not an objective per se, but in view of a heterogeneous set of human goals (economic ones beside others). Promoting this maximisation with success is not possible without having a socio-economic perspective. Consequently we will look at how the management objectives related to the natural capital fits in the problematic of macroregional public institutions, and at the principles for managing macrolandscape arising from here ("Discussion" chapter).

A2. METHODS

The role of the riparian forests has been assessed based on three elements: extensive literature reviews performed within a critical thinking paradigm, processing of own unpublished data, and development of new theoretical elements (in order to surpass the limitations of the existing ones). The literature reviews and data processing involved a larger number of scientists than the authors of this paper; the results of these activities will be included in an editor book devoted to riparian forests, in preparation.
The case study was located in the lower Danube floodplain (macrolandscape). It had been established that, in order to significantly decrease the nutrients input into the Black Sea, as constrained by international agreements, at least 120000 ha should be restored in this macrolandscape (Vadineanu et al. 2002). In order to see how this surface should be structured (which diked microlandscapes to restore, number, surfaces and location) we assessed the resources and services in current floodplain microlandscape of different complexities, and compared the current structure with the reference one (Iordache et al 2002b). An analyses of the socioeconomic constraints towards restoration was performed (Iordache et al. 2002c, Bodescu et al. 2002), as well as an assessment of the eventual undesirable effect of the restoration due land pollution (Iordache et al. 2002d).

These steps allowed the exact delineation of the appropriate microlandscapes to be restored. Then restoration scenarios were developed for one of them, the northern part of Big Island of Braila (Braila is a city near the Danube river, Fig.1). A detailed DTM based on 1:5000 maps and GPS field investigation was developed. Reference state was characterized based on historical maps analyses. Current land use was characterized in detail by remote sensing images, pedological, pedochemical and agricultural maps, and field investigations. The dike-Danube part of the island was analyzed by forestry maps and field investigations.

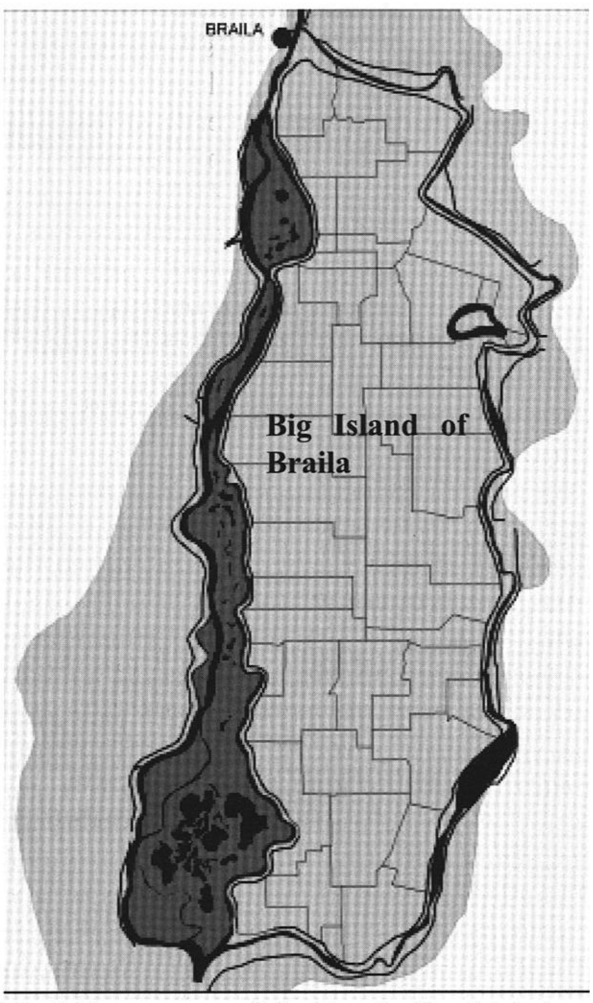

Fig.1 Current state of the Danube floodplain in the Big Island of Braila (BIB) Sector. Grey areas are diked, deep gray areas are not diked. Thin lines within the BIB indicates farms limits.

The current economic efficiency in the diked area was analyzed by crops production distribution maps and investments distribution maps, coupled with local interviews. The scenarios were developed in cooperation with the main current stakeholders, farmers and foresters, and the local public was informed about.

A3. RESULTS

A3.1 The Place of Riparian Forests in the Macrolandscape

The riparian forest is a type of riparian system, which is a type of wetland systems. Tab.1 summarizes the types of riparian forest from the point of view of the hierarchical level, as well as the systems integrating riparian forests. We could identify the following situations:

1. The riparian forest is an ecotone between an aquatic ecosystem (lake or river), and a terrestrial one. Thus, it belongs to a terrestrial-aquatic microlandscape (integrating system 1), which in turn belong to a small order basin (integrating system 2).
2. The riparian forest is an ecosystem in its own, with biocenoses different from those of the adjacent ecosystems. Such riparian forest can be found either in the floodplain of medium rivers, or in the floodplain of large and very large rivers. In the first case (2a) the riparian forest will belong to a terrestrial-wetland-aquatic microlandscape, included in the medium order river basin, as well as in a low order ecoregion. In the second case (2b) the riparian forest will belong to a wetlands microlandscape (such as an alluvial island with lakes, marshes and

Type of riparian forest from hierarchical point of view	Integrating system 1 and 2
1 Ecotone	TA microlandscape / small order basins
2 Ecosystem	2a TWA microlandscape / medium order basins, low order ecoregions 2b W microlandscape / fluvial macrolandscape, low order ecoregions, medium order basins
3 Microlandscape	3a fluvial macrolandscape / high order river basins, high order ecoregions 3b medium order basins / high order river basins 3c low order ecoregions / high order ecoregions

Tab.1 The natural capital directly and indirectly relevant for the management of the riparian forests. Explanation in text. *Legend:* TA microlandscape - microlandscape composed of terrestrial and aquatic systems, TWA microlandscape = microlandscape composed of terrestrial, wetland and aquatic systems.

forests), which may be part of larger fluvial macrolandscape (floodplain), part of a medium order river basin, as well as of a low order ecoregion.

3. The riparian forest is a microlandscape, such as an alluvial island covered by different forests (e.g poplar forest on levees, willow forest in depressions). These microlandscapes can be found in the floodplain of medium order (3b) and high order (3a) rivers. In the case 3a, the fluvial macrolandscape, which include the forested riparian microlandscape, is the lower sector of the large order river system. The forested riparian microlandscapes are also directly included in low order ecoregions (3c). In the case of very large rivers the fluvial macrolandscape can be assimilated to a low order ecoregion, or even a high order one, depending on the specific situation.

Fig.2 presents the inclusion relationships discussed above. The included systems are structural elements of those in which they are included. It results form its inspection that at low order ecoregion or medium order river basin level all types of riparian forest should be taken into consideration for the design of the management. At even higher level practically the full river corridor should be considered (a river corridor consists in the TA microlandscapes, the TWA microlandscapes, and the fluvial macrolandscapes of a river basin (notations as in Fig.2).

Not represented, in Fig.2, but relevant, is the inclusion in the ecosphere, with consequences on the services related to the functioning of the climate system. Also not shown is the inclusion in the socio-economic systems. Local SESs usually include by their organisations (in ownership terms) all types of riparian forests, the microlandscapes including riparian forests, and in some cases small order river basins. Institutions at regional (county) and macroregional (country) SESs level are responsible for the management of the macrolandscapes (medium, and high order river basins, as well as low and high order ecoregions) Decision concerning the natural capital at continental and global level are taken usually by international institutions.

A3.2 The Role of Riparian Forests in the Macrolandscape

Tab.2 presents the services performed by macrolandscapes and the complementarity between riparian forests and other macrolandscape components in the production of the services. Tab.3 shows the compatibility matrix between the production of the services at riparian forest and macro-landscape level. And Tab.4 resumes the deterioration pathways affecting the production of services by macrolandscapes. Synergism between the different deterioration pathways may occur, or between chronic and acute stress, which is an important reason for adopting an adaptive management, and the appropriate managerial institutions (see "Discussion" chapter). Elements of the extensive analyses underpinning the information from these tables are not included here due to the limited space.

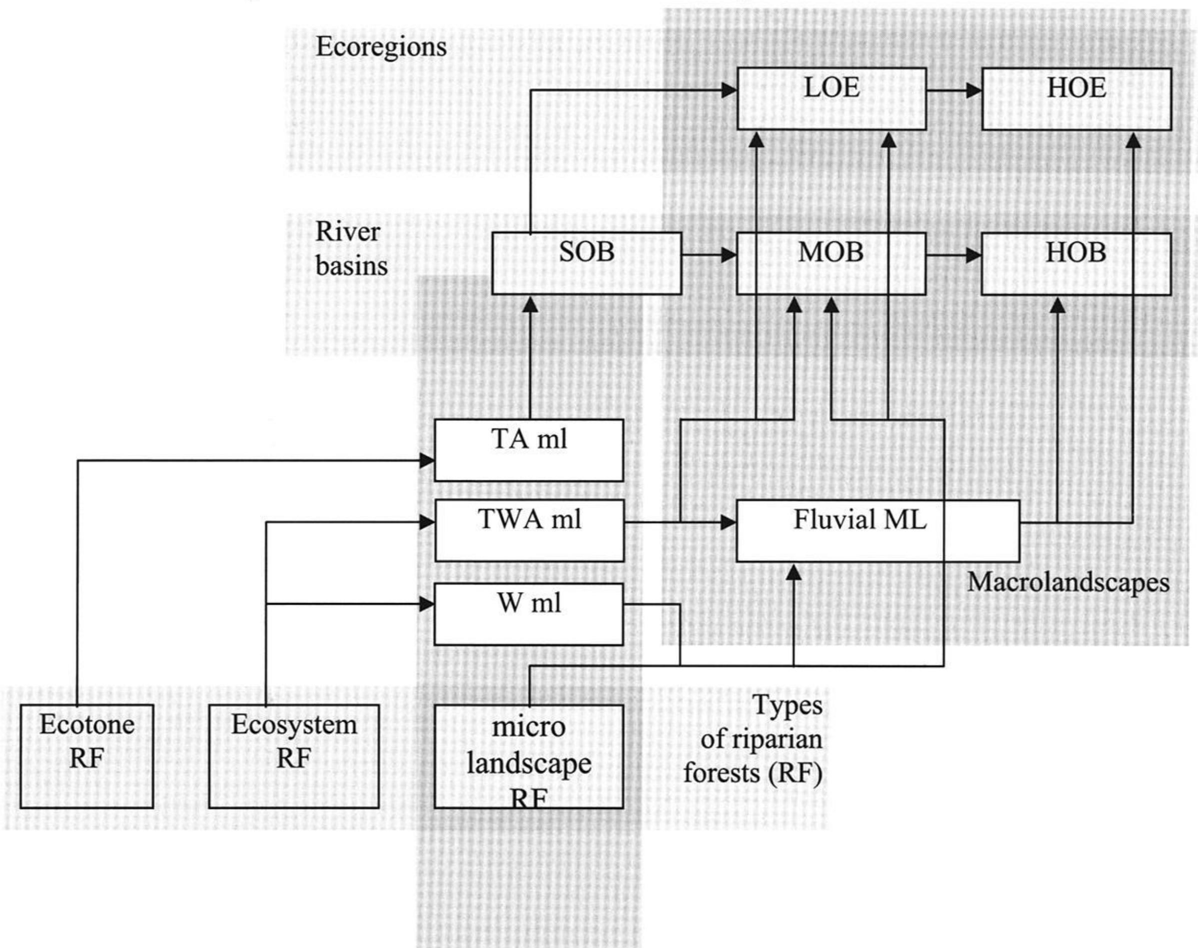

Fig.2 Inclusion relationships (black arrows) between riparian forests and their integrating systems. *Legend*: ml = microlandscape, ML = macrolandscape, TA = terrestrial aquatic, TWA = terrestrial-wetland-aquatic, W = wetland, SOB = small order river basin, MOB = medium order river basin, HOB = high order river basin, LOE = low order ecoregion, HOE = high order ecoregion.

Services	*Complementarity of riparian forests (ecotones, ecosystems, or microlandscapes) with:*
Flood protection	▪ upland forests, especially those natural (in river basins) ▪ all other ecological subsystems (in fluvial macrolandscapes; a full example is provided in Chapter A6)
Groundwater recharge	▪ non-riparian wetlands and upland forests (in river basins) ▪ all other subsystems (in fluvial macrolandscapes)
Regional climate improvement	▪ upland forests (in river basins) ▪ all other ecological subsystems in fluvial macrolandscapes
N, P, toxic substances retention	▪ non-riparian wetlands and hedgerows (in small and medium order river basins in plain areas) ▪ all other subsystems in fluvial macrolandscapes
C sequestration / *wood production*	▪ *upland forests* and non riparian reed marshes (in river basins) ▪ reed marshes (in fluvial macrolandscapes) ▪ bogs, fens (in higher latitude macrolandscapes)
Diversity of ecological systems (1)	▪ other types of microlandscapes, reflecting in their structure succession processes, and subject to large scale/long term dynamic under natural driving forces (in low order ecoregions and fluvial macrolandscapes - river corridors)
Diversity of species	▪ all other ecological subsystems (in fluvial macrolandscapes – river corridors) ▪ other upland ecosystems and microlandscapes (in low order ecoregions)

(1) applicable only to riparian forests at microlandscape level

Tab.2 The complementarity between riparian forests and other types of ecological sytems in the macrolandscapes production of the natural services.

	1	2	3	4	5	6
1 Hydrological services		C (1)	C	C (2)	NR (3)	C
2 Regional climate improvement	C		C (2)	C (2)	NR (2)	C (2)
3 N, P, toxic substances retention	C	C		C (4)	N (4)	N (4)
4 C sequestration / biomass production	C	C	C		N	N
5 Ecological systems diversity maintenance	C	C	C (3)	C		C
6 Species diversity maintenance	C	C	C (3)	C	C	

(1) at local level only microclimate improvement takes place
(2) forests with high floodwater retention capacity (forested depressions) have however lower productivity than sites on levees.
(3) relevant to some extent only for riparian forests at microlandscape level
(4) compatible only within the support capacity of the riparian systems

Tab.3 Compatibility matrix between the maximizations of the production of different natural services at riparian forest level (above the diagonal) and macrolandscape level (below the diagonal). C= compatible, N = not compatible, NR = not relevant

Level	*Deterioration by:*
Macrolandscape	▪ change (+, -) in the abundance of upland / riparian microlandscape types ▪ full removal of upland /riparian microlandscape types ▪ introduction of new upland /riparian microlandscape types ▪ quantitative / qualitative change in the fluxes (abiotic, biotic) connecting the microlandscapes ▪ modification of the natural driving forces controlling the microlandscapes dynamic
Microlandscape	▪ change (+, -) in the abundance of ecosystems types ▪ conversion of ecosystems from natural to human controlled ▪ full removal of ecosystem types ▪ introduction of new ecosystem types ▪ quantitative / qualitative change in the fluxes (abiotic, biotic) connecting the ecosystems ▪ modification of the natural driving forces controlling the ecosystems dynamic
Ecosystems	▪ change of the hydrogeomorphic unit by abiotic resources exploitation or pollution ▪ change of the biocenoses structure by overexploitation, species elimination or species introduction ▪ change of the populations structural parameters (genetic diversity included)

Tab.4 Deterioration pathways affecting the production of services by macrolandscapesm which should be assessed in view of macrolandscape management.

A3.3 Principles for Managing the Forests in a Landscape Context

The maintenance (at publicly desired levels) of the production of the natural resources and services described above will be tactical management objective for the organizations/institutions involved in the management of the macrolandscape. Operational objectives will be the restoration of floodplain, of the main channel, or management and maintenance of existing riparian forests, but coupled with other ones in the upland. The portfolio of managerial objective will differ from one situation to another, and it is essential to be realistic, adapted to existing socio-economic conditions (Ehrenfeld 2000). Not reaching over ambitious objective undermines the credibility of the whole approach at public (non-expert) level. International organizations (e.g. FAO 1990), adopt the same point of view, but sometimes scientists confusing ecology (science) with green activism (ideology), miss the point.

When there are incompatibilities in the maximization of different resources/services production by a riparian forest, they should be overpassed by action on the river basin structure (for objectives related to biogeochemical and regional climate services), on the ecoregion structure (for services related to diversity services), or on both (for C sequestration and timber production).No single riparian systems will provide all services and resources. But an adequate planning of the landscape structure and attention to maintaining its natural dynamic as much as possible will maximize the production of natural resources and services. Such an approach is in tune also with the climate change problems, for the following reasons: it will increase the retention time of water in the river basins, it will improve the regional and micro-climate, and it will facilitate the species dispersion from regions becoming more arid to regions where they find optimal conditions.

As an example, measures for mitigation river basins eutrophication should include: actions at agricultural field level (minimizing the output of nutrients to groundwater and by runoff), actions for minimizing runoff inputs to riparian areas (by maintaining a network of hedgerows), actions by minimizing the secondary input to groundwater (by maintaining non-riparian wetlands), actions at the level of the small streams riparian areas (for transversal buffering), and actions at the level of lower floodplains (for longitudinal buffering). P export may be most efficiently managed by focusing primarily on control of the soil P levels in hydrological active zones most likely to produce surface runoff (Gburek and Sharpley 1998), especially in the area close to the stream channel, < 150m (Tufford et al. 1998).

The specific width of the river corridor depends also on the density of the rivers in the managed macrolandscape: areas with low streams density should have wider river corridor microlandscpes, while in high stream density areas the width should be smaller, but complemented with more extended measures in the upland. When the focus is on species diversity maintenance services, the population ecology of the species intended to be protected should be thoroughly taken into consideration. However, rather than maximizing certain species abundance is better managing to avoid extinction of populations by identifying thresholds of acceptable fluctuations for a wide array of wildlife (Smyth et al. 2002).

Macrolandscapes restoration by acting at forests level is a long term process, thus requiring a stable political and societal will behind him, which can be achieved only by an effective co-management (see next chapter). Hupp (1992) estimates at 65 years the recovery duration of the riparian forest, which is however shorter than the period needed for restructuring upland forests (up to 200 year, in difficult conditions, according to Mayer 1977 apud. Vlad et al. 1997). The feed-back loop practically does not close in the same human population generation. Consequently, for ethic reasons, these plans should reduce the inherent associated risks by using the best available scientific knowledge and adopting the precautionary principle (see "Discussion").

The techniques of restoration to a particular forested condition, and the further forest treatment, use silvicultural practices common in other types of forests (Vlad et al. 1997), and should coupled with the restoration of the hydrogeomorphic unit, where needed. The cutting patterns and treatments maintaining the highest production of natural services, while maintaining also the timber production, are the most expensive ones. At forest ecosystem level, Giurgiu (1988, 1997) puts an accent on silvicultural measures directed toward maintaining the native, as natural as possible, composition and structure, and using biological technologies for the protection from diseases and insects. But the organizations involved in management and harvesting are seldom opened to such elements because of the higher associated costs. The high costs not possible to be covered may undermine the credibility of some landscape restructuring plans, as correctly points out Vlad et al. (1997). However, practices such as focusing on the reduction of the trees harvesting age and modifying criteria for the inclusion of forest ecosystems in different categories (mainly for timber production vs. mainly for services production), are not related to the high costs incurred by intensive silvicultural practices, but rather to short term maximizing behavior. These are not issues easy to tackle and require a healthy democracy, and a well designed co-management, in order to be overpassed. Last but not least, they require adopting a macrolandscape vision, the principles from the "Discussion" chapter, the principles listed at the end of this chapter, and following the steps presented in Tab.5.

Most difficult in the restoration of riparian landscape is the restoration of the geomorphic and hydrologic processes, because of technical reasons and societal commitment to an altered state (Gore and Shields 1995). However, in many macrolandscapes the restoration of river corridor would be more acceptable than that of the uplands, and in this context the management of river corridors appears to be a priority important both from river basin and ecoregional point of view (IUCN 1995, Jongman and Troumbis 1996, Vos et al. 2001, Vadineanu et al. 2001).
Where to propose forest restoration? Which are the most appropriate areas? First of all, the areas where land use changes are easier to accept are those without economic efficiency. For instance, Machedon (1988) points out that the official reforestation plans in Romania envisage especially the "degraded areas". On the other hand, past management decisions concerning the extensive diking of the floodplains have proved to be errors. Some of the areas in this situation are recognized as such, and included in the restoration plans, others are subject of discussion, despite the scientific proofs concerning their inefficiency. They may be still kept at efficient levels by public agricultural subsidies (Iordache et al. 2002c), and usually there are strong lobbies for their maintenance in the current state.
Reforestation and afforestation cannot limit in principle to degraded lands. Beside the fact that many lands are so degraded that the vegetation is affected (Zaharia 1999), the main reason for not limiting the reforestation to such areas comes from preserving the needed production of natural services at macrolandscape level. The solution should be a case specific one, depending on the structure of the natural capital and of that of the local socio-economic systems. For each macroregional landscape one will need modeling studies GIS based to produce the scenario of landscape structure (Opdam et al. 2002, Bodescu 2001) and other decision making tools (Vadineanu 1999, Iordache et al. 2001).
A key issue related to the financing method for landscape restructuring is adopting the incremental cost format (GEF 1995): public sources from a certain (x) hierarchical level will finance at the lower socio-economic (x-1) level only additional actions beyond what is required for making the natural system to produce resources and services manageable at level x-1. In other terms, the management cost for producing natural resources and services manageable at level x-1 will be covered by sources of the level x-1. Of course, for this technique to work one needs recognition of the natural services as having a public character, as well as an acceptance of covering maintenance costs, which is highly variable across socio-economic systems. The utility of this method is indirectly recognized also by foresters interested to promote reforestation for climate change control. Ciesla (1996) recommend that the new forest would produce net benefits separate from those which may ultimately arise in the climate change context.
Another important issue is to overpass the sectoral approach in designing the projects related to macrolandscapes. Each type of public land use (forests, waters) has its own

administrators, and one would need public mechanisms to make them cooperate in view of the macrolandscape management. For instance the restoration of the lower Danube floodplain is subject now to two independent approaches: the Green corridor approach, promoted by administrators of water quality and species diversity services, and the forests restoration, promoted by. Measures designed and negotiated separately are frequently insufficient with respect to the overall restoration of the potentially public services provided by the floodplain (e.g. Schneider, 2002), not last because the lobbying forces interested in restoration are distributed among different categories of interests.

It is time now to mention the concept of multifunctional farming, as tool for overpassing the sectoral approaches in agricultural landscapes. Traditional farmers had maintained on their ownership natural ecosystems (forests, lakes, meadows, wetlands), and used them for producing abiotic and biotic resources within their support capacity. Indirectly and not intended they allowed the microlandscape natural capital of the farm to function in natural conditions, thus providing also natural services, and an enhanced production of natural resources as a result of connecting fluxes between ecosystems (Altieri, 1991, 1995; Denevan, 1995). Curently there is an international institutional trend to promote such multifunctional farming (e.g. FAO, 1999).

Most of the foresters recommendations for the sustainable development of silviculture (e.g. Giurgiu 1995, 1997) are compatible with the management at macrolandscape level: (re)forestation of degraded and economically inefficient lands, hedgerows for agricultural field, and for transportation infrastructure, protection forests for human settlements, and restoration of river corridors. But the proposed measures are not related to all categories of land uses by arguments based on the services provided by the macrolanscapes, and consequently may lead to conflicts with those envisaging the sustainable development of the sectors related to other land uses (mainly water bodies management and agriculture). The same holds at European level, with a not (yet) explicit connection between the ecoregions approach in view of species and habitats diversity maintenance (Natura 2000 network), and the river basin approach, in view mainly of hydrological and biogeochemical services. The adequate interpretation of the respective regulations in order to show the points of conceptual and managerial connection will be a priority for the next future.

It seems that the civil society have still to work hard in order to promote the public interest related to the macroregional services and the sustainable development of the socio-economic system to which they belong. These organizations should compare the publicly recognized services at macrolandscape level with those presented here, identify the differences, and promote their attenuation. There might be a need for related, coherent, public policies concerning the management of different subsystems of the macrolandscapes (riparian forests, included). These policies, by their programs would influence the behavior of the socio-economic actors towards maintaining a macrolandscape structure desirable from public point of view. But without direct action of the macroregional institutions at local level, excepting for the cases of the ecosystems/microlandscape under public property.

Thus, riparian forests management should be explicitly related to:

- the management objectives at the level of local landscapes which include riparian forest ecosystems
- the management objectives at the level of macrolandscapes: river basins (via Water

Framework Directive) and ecoregions (via FFH Directive and Natura 2000 network)
- the global management objectives to which measures concerning forests are relevant (especially carbon sequestration).

And the general principles for designing the macrolandscape structure are:

1. all lotic systems require a natural riparian area with forests in its structure;
2. the natural dynamic in the floodplain should be preserved as much as possible
3. All parts of the restored river corridor should include a portion of forested upland, and eventually an ecotonal grassland at the field limits.
4. The wider a river corridor is, the better is for maintaining species diversity
5. The non-riparian lakes and wetlands should have a similar buffer zone as the lotic systems
6. The non riparian and riparian systems should be connected by a network of structurally complex hedgerows.
7. The upland should include small and large terrestrial forest ecosystems to the highest extent possible.
8. Afforestation/reforestation at ecosystems level should have multiple objectives to the maximum extent possible
9. The portfolios of objectives concerning ecosystems/microlandscapes should be complementary such as to maximize the heterogeneity of the set of objectives at macrolandscape level.
10. Most of the forests for timber production should be in the upland area; the riparian corridor should be dedicated mainly to the production of services and secondary to biological resources.

A3.4 Case Study: Restoration Scenarios in the Big Island of Braila

The scenario maximizing the interest of farmers suppose the maintenance of the current structure of the natural capital, however with large investitions associated to the amelioration of the soil quality in terms of hydrology, salt content, land morphology, drainage network, etc. These measures would lead to higher crops production than before but at very high cost. They will also further deteriorate the hydrogeomorphic structure of the ecosystems, which now from geomorphological point of view is not very far from that of the reference system, excepting for the former lakes which have been filled up 70-100 cm. A scenario with average investitions supposes a partial reorganization of the landscape, maintaining the dikes but allowing hydrological connections to some extent. Shallow lakes (25% of the surface), forests (35%) and agricultural fields (40 %) provided with hedgerows would coexist within the landscape and would be managed based on the concept of multifunctional farming. The scenario with minimal investitions (Fig.2) would envisage establishing similar hydrological conditions with the reference system and it would be based on the recolonisation capacity of the species. Organisms would come from the ecosystems distributed in the dike-Danube area and from small natural remnants of the currently diked area. Investitions would be needed for directing the forests development towards a desired landscape structure. The microlandscape would have the following structure: riparian forests 60%, meadows 12 %, lakes, canals and marshes 28%. Despite the difference from the references system (marshes percent much larger in the reference system), the benefits of such a system is estimated to be comparable with those of the references system. The decision making process leading to a decision about which scenarion to adopt is related to the macrolandscape management (in this case the lower Danube). Elements relevant to this will provided in next chapter.

A4. DISCUSSION

We don't manage ecosystems, we manage natural capital[1]. The reason for which we manage it is the production of natural resources and services. When we can have private control over this production, we don't need to recognize those services as public and to create and pay institutions for managing them. This is the case of the resources produced in small and medium sized ecological systems, which can be owned in the fullest sense. However, the production of resources and services by large and very large natural systems cannot be de facto, in most of the current socio-economic systems, controlled by private actors. When every one is interested in these resources and services, the management of the systems producing them (ecoregions and river basins as public goods) will be a public matter, in the name of the public interest. This management is a public service in itself, and will be performed by public institutions, with resources obtained from the private contributors. Fig.3 presents the relationships between the categories of stakeholders involved in the management of macrolandscapes (private users, public institutions, and the civil society). Specific steps for the elaboration of a management plan for a macrolandscape are presented in Tab.5, and the general principles for managing macrolandscapes in Tab.6.

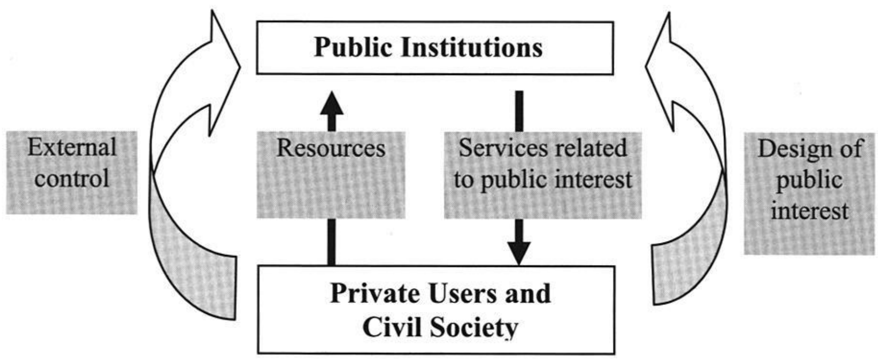

Fig.3 The relationships between the categories of stakeholders.

[1] i.e. ecosystems with value as a relational property resulted by their interaction with humans.

1 Accessing the decision support system (DSS)

The specific information system

1.1.1 The knowledge base. Identification of the natural capital (NC) and socio-economic systems (SESs). Set of rules, laws, models, on which depends the assessment of the natural resources and services, and the strategies, tactics, and operational activities for the natural capital management

1.1.2 The data base. Values of the state parameters describing the natural capital and socio-economic systems on the which depends the same issues as mentions above in the case of the knowledge base

1.2 Applying the methods for the economic valuation of the natural capital

1.2.1 Functional analyses of the natural capital

1.2.2 Monetary analyses of the natural capital

1.3.1 Characterization of the state of the DSS components which cannot be restructured by management at local SES level (legislation, regulations, human resource formation, institutional infrastructure at regional and macroregional SESs level)

2 Designing the set of alternative solutions (packages of management objectives) concerning the restructuring of the natural capital, the restructuring of the SESs or their functional modules, and/or the restructuring of the management practices (concerning SES-NC relationships), with the final goal of using the NC below the support capacity and valorizing its full range of resources and services.

3 Assessment of the set of alternative solutions

3.1 Assessment of the restoration costs

3.2 Cost benefit analyses of the alternative solutions

3.3 Identification of all kind of resources needed for implementation, and design of the set of applications (projects)

4 Preparation of the set of recommendations for the decision makers.

Tab.5 Steps for designing a plan for the management of a macrolandscape

1	The management of the macrolandscape should be seen as the management of a **SES-NC system**.
2	The management objectives, instruments and measures for the macrolandscape should take explicitly into consideration the **conflicting goals** of the involved stakeholders. No one of the extreme goals of economic return maximization, social equity maximization, or natural capital full conservation should be institutionally adopted, but a **publicly accepted balance** of them.
3	The management plan should be **inter-sectoral** (explicitly linked to the relevant sector programs), should address the **cross-cutting issues**, and be subject to **strategic impact assessment**.
4	The management measures (e.g. regulations, economic instruments) taken by public institutions in order to promote a certain landscape structure should be complemented by **full compensations** of the unequally distributed decrease in the benefits of the private owners due to the constraints imposed to their property rights.
5	The management objectives and measures should be based on the **best available scientific knowledge** about the production of natural resources and services **publicly accepted in that socio-economic system**; when this knowledge has established the existence of a resource / service, but there are uncertainties about the human impact on its production, a **precautionary approach** should be adopted.
6	The management measures should take into account the **traditional ecological knowledge** available in the local socio-economic systems.
7	The portfolio of management objectives, instruments and measures at a certain socio-economic level should be adaptive, able to react to the natural relationships between the subsystems of the macrolandscape, to their natural dynamic, to the natural dynamic of the macrolandscape, and to the dynamic of the lower level socio-economic systems (**adaptive management**).
8	The public institutions involved in the macrolandscape management should **institutionalize the process of continuos knowledge and data production** with regard to the SES-NC system.
9	The public institutions involved in the macrolandscape management should be **self-regulative, and open to external control** by the civil society.
10	The public institutions involved in the macrolandscape management should be at **the lowest socio-economic level** relevant for that macrolandscape; when this is not operationally possible due to lack of expertize, the management should be at the lowest most effective level (**subsidiarity principle**), and **capacity building measures** should be promoted by the institutions of the integrating socio-economic system.
11	The public institutions should develop decision-taking mechanisms allowing the involvement of the other stakeholders in **co-management, at the highest possible participation** (that is, should share as much as possible the management rights with the stakeholders); when this is not operationally possible due to lack of expertise, **capacity building measures** should be promoted as a public service.
12	The natural capital at ecotone/ecosystem level owned by public institutions (i.e. private state property, very extended in the Eastern Europe) should function as **pilot areas** for a management maximizing the overall public benefits, including the production of public natural services by the integrating landscapes.

Tab.6 The general principles for managing macrolandscapes.

A5. CONCLUSIONS

Managing forests in a macrolandscape context means managing them such as to preserve their role in the services production, and is inherently done together with the management of other types of ecological systems from the macrolandscape structure. Because these are public services (Chapter A4) the organizations directly interested in designing macrolandscapes management are the public ones, or those parts of the civil society.

However, private local organizations are interested in the rezulting management measures, and consequently those designing the management should involve the local level actors by adopting a comanagement approach within the large set of principles for macrolandscape management (Chapter A4).

Those designing the macrolandscape management should have access to the following knowledge:

- The place of riparian forests in the structure of microlandscapes and macrolandscapes (Chapter A3.1)

- The landscape mechanisms underpinning the role of riparian forests in the production of public services at macrolandscape level, and leading to compatibility between different services production, or lack of it (Chapter A3.2)

- The available instruments and concepts to be used for promoting the restoration of the macrolandscape (Chapter A3.3)

Based on such knowledge one would build a specific information system for the macrolandscape in case and would develop restoration scenarios, as steps in the process of the management design (Tab.6, Chapter A4). After the (co-management based) decision concerning the scenario is taken, specific policies and programs will be developed in order to influence the local actor's behavior towards the desired landscape structure. Sets of projects will be developed by the local actors at riparian forest level as well as at the level of other types of ecologica systems. Then operational measures will be implemented (hydrogeomorphic unit reconstruction, silvicultural measures, Chapter A3.3).

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