Master Thesis

Sediment dynamics and morphological change in the braided Pfynwald reach of the Rhone River

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Abstract

Steep gravel-bed rivers with high sediment supply and streamflow form a braided channel structure. The Pfynwald Rhone River reach between Susten and Sierre, located in the Rhone valley in the Central Alps of Switzerland, has kept its natural braided morphology. The nearby located Illgraben catchment, which is one of the most active torrents in the Alps, has a large impact on the characteristics of the Pfynwald River section. There is large and instantaneous sediment supply to the Rhone River from the Illgraben through debris flows. The underlying research hypothesis of this study is that the interactions of flow regime, sediment supply and channel morphology are fundamental in order to quantify the sediment dynamics in braided rivers.

In this thesis the quantification of sediment transport is addressed by means of a numerical sediment transport model. The one dimensional as well as the two dimensional model of the numerical sediment transport model system BASEMENT are applied to the study reach. In the calibration process sensitive model parameters are identified.

The one dimensional model BASEchain is calibrated on the basis of annually surveyed topographic data for the period of 1995 to 2007. The adjusted 10 grain class model configuration is then used to investigate the sensitivity of the evolution of the longitudinal profile and of the mean annual sediment transport rate through the reach with respect to variable boundary conditions.

The two dimensional model BASEplane is calibrated just hydraulically due to a lack of data for a calibration of sediment transport. The spatial patterns of erosion and deposition in the channel bed for two different scenarios are addressed with the aid of the calibrated 2d-model using a mobile riverbed.

On the basis of a balance of observed and computed sediment volumes in the Pfynwald reach the mean annual sediment supply by the Illgraben and the mean annual bed load transport rate are estimated. For the period of 1995 to 2007 a sediment input of roughly 140'000 m^3/a results. The sediment transport rate in the Pfynwald reach decreases from 150'000 m^3/a at the confluence with the Illgraben to 30'000 m^3/a at Sierre.

This study highlights that the application of numerical models to relatively steep alpine rivers with a braided morphology is a very difficult task and that current nu-

merical models are not yet fully adequate to simulate satisfactorily sediment transport and erosion and deposition in such very dynamic river reaches. While the pure hydraulic simulations yield excellent results, the sediment transport computations need to be regarded with extra care, particularly concerning the one dimensional model, which appeared to suffer from many inconsistencies.

Acknowledgements

I would like to thank all the people who have supported me during the work of my master thesis. The software I was working with was totally new for me and I was very glad to have so many competent people around me. I really appreciated their help and contribution. Special thanks to my supervisor Dr. Peter Molnar for offering this interesting master thesis topic, for his great supervision, for the time he spent for my concerns and for the many interesting discussions we had. Further I like to thank the applied numerics divison at the VAW under the direction of Dr. Roland Fäh for their great effort they have brought up to solve the problems I have encountered. A special thank is dedicated to Renata Müller and Christian Volz for their patience and for fulfilling my numerous software wishes. Without their help I would not have been able to manage the modeling part of this thesis. I also like to thank Roni Hunziker from the engineering company Hunziker, Zarn & Partner AG and Xavier Mittaz from the engineering company sd ingénierie Dénériaz et Pralong Sion SA who provided me with several technical reports about the Pfynwald river reach and the topographical and volumetric data for the calibration of the model. Apart from the above mentioned people, I would like to thank my family and friends outside ETH who have supported and encouraged me in numerous ways during my studies.

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List of Abbreviations

BASEMENT . BASic EnvironMENT for simulation of environmental flow and natural hazard simulation
CFL .... Courant-Friedrichs-Lewy
CS .... Cross Section
DEM .... Digital Elevation Model
DTM-AV .... Digitales Terrainmodell der Amtlichen Vermessung
ETH .... Swiss Federal Institute of Technology
FV .... Finite Volume
HLL .... Harten, Lax, van Leer
HLLC .... Harten-Lax-van Leer-Contact
IVP .... Initial Value Problem
LIDAR ...... Light Detection And Ranging
MPM .... Meyer-Peter Müller (sediment transport formula)
MPMH ...... Meyer-Peter Müller Hunziker (sediment transport formula)
RECORD .... Restored Corridor Dynamics
ROC .... Receiver-Operation Characteristics
SMS .... Surface Water Modeling System
VAW .... Laboratory of Hydraulics, Hydrology and Glaciology

Chapter 1

Introduction

1.1 Motivation

Natural rivers show a large variety of channel patterns. *Leopold and Wolman* (1957) developed a widely used classification scheme for natural rivers based on their planform. They suggest a division of the morphology of a river channel into the three categories: straight, meandering and braided. In a natural environment rivers develop generally from a straight to a braided channel structure with increasing slope and coarser gravel.

Among straight, meandering and braided rivers, the latter are the most dynamic systems. Short-term channel migration is a frequently seen phenomenon in braided rivers, because steep headwater tributaries supply highly variable discharges and sediment supply to the mainstream (*Gray and Hardling*, 2007). A simple and commonly used definition from *Leopold and Wolman* (1957) describes braided river morphology as a river, which flows in two or more anastomosing channels around alluvial islands. Braided rivers can be found all over the world, most frequently they occur in Arctic and Alpine regions that are characterized by high precipitation and steep headwaters (*Gray and Hardling*, 2007).

Braided river morphology is determined to a large extent by the dynamics in gravel-size sediment availability, supply and transport. It is most widespread in gravel-bed rivers where the coarse grains are close to incipient motion conditions during large and relatively frequent discharges, so that the river is subject to permanent changes in the channel bed structure.

In the course of large-scale river corrections in the last two centuries, most Alpine rivers were straightened and channelized. The original meandering and braided river systems disappeared almost completely in Central Europe. The Pfynwald reach of the Rhone River between Susten and Sierre is one of the last morphologically intact braided river section in Switzerland that kept its original dynamics. The natural dynamics of the river has so far not allowed to channelize this section of the Rhone River. The Pfynwald reach of the Rhone River is therefore a very unique place to study extremely active river dynamics and the relevant consequences to river management.

The natural dynamics of the Pfynwald Rhone River section is mainly caused by the large sediment supply by the Illgraben, a tributary that joins the Rhone River near Susten. The Illgraben catchment is one of the most active torrents in the Alps. Every year several thousand tons of sediment are delivered to the Rhone River by debris flows (*Hürlimann et al.*, 2003).

Sediment discharge from a tributary to a main valley can influence the flow pattern of the receiving trunk stream, if the increase in sediment flux exceeds the sediment transport capacity of the river. Studies conducted in other rivers show that an imbalance between stream power and sediment transport capacity occurs at the confluence of two streams with contrasting hydrological properties (*Hammack and Wohl*, 1996; *Tucker and Slingerland*, 1997; *Korup*, 2004; *Hanks and Webb*, 2006).

Investigations of *Jäggi* (1988) and *Bezzola* (1989) show that there is an imbalance between stream power and sediment transport capacity in the Pfynwald reach of the Rhone River. In particular, the large and instantaneous sediment inputs from the Illgraben especially lead to aggradation in the channel bed of the Rhone River. Since the year 1995 annual sediment volume balances of the Pfynwald river reach have been estimated by a local engineering company (*KBM SA*, 1995-2007). In addition the sediment balance as well as the morphology of the respective reach was investigated with the aid of a numerical model (*Hunziker, Zarn & Partner AG*, 2001). The applied one dimensional sediment transport model suffered from numerical instabilities due to the frequent hydraulic drops in this relatively steep river reach.

Since humans impact the Rhone River system through flow regulation and gravel extraction, it is of great importance to understand and to quantify the sediment dynamics in the natural Pfynwald River reach, not only with respect to the ongoing river restoration project of the third Rhone River correction, but also to contribute to the scientific understanding of fluvial processes in gravel-bed braided rivers in general.

1.2 Objectives

The goal of this Master Thesis is to model sediment transport in the braided Pfynwald section of the Rhone River by means of the software system BASEMENT. Both the one dimensional as well as the two dimensional sediment transport model of BASEMENT are applied to the investigated river reach. A special focus is set to the response of the riverbed of the Rhone to massive sediment inputs through debris flows from the Illgraben. The underlying hypothesis is that understanding the interactions of flow regime, sediment supply and channel morphology is fundamental for quantifying the sediment dynamics in steep gravel-bed rivers. Within the described framework the following five objectives are addressed in this thesis:

1. Computation of a sediment balance for the Pfynwald river reach in order to estimate the mean annual sediment supply by the Illgraben and to quantify the observed mean annual sediment transport rate through the study reach

2. Reproduction of the observed mean annual sediment transport rate by means of a one dimensional numerical sediment transport model

3. Identification of sensitive model parameters with respect to the model output

4. Analysis of the sensitivity of the Pfynwald river reach to variable boundary conditions

5. Investigation of spatial patterns of sedimentation and erosion at the confluence of the Rhone River and the Illgraben with a two dimensional sediment transport model

Chapter 2

Study site

2.1 Geographical setting

The Pfynwald reach of the Rhone River is situated in the central part of the Valais (see figure 2.1). The village of Susten is located at the upstream end of the investigated section. The downstream boundary is represented by the city of Sierre. The length of the river reach adds up to approximately 8 km.

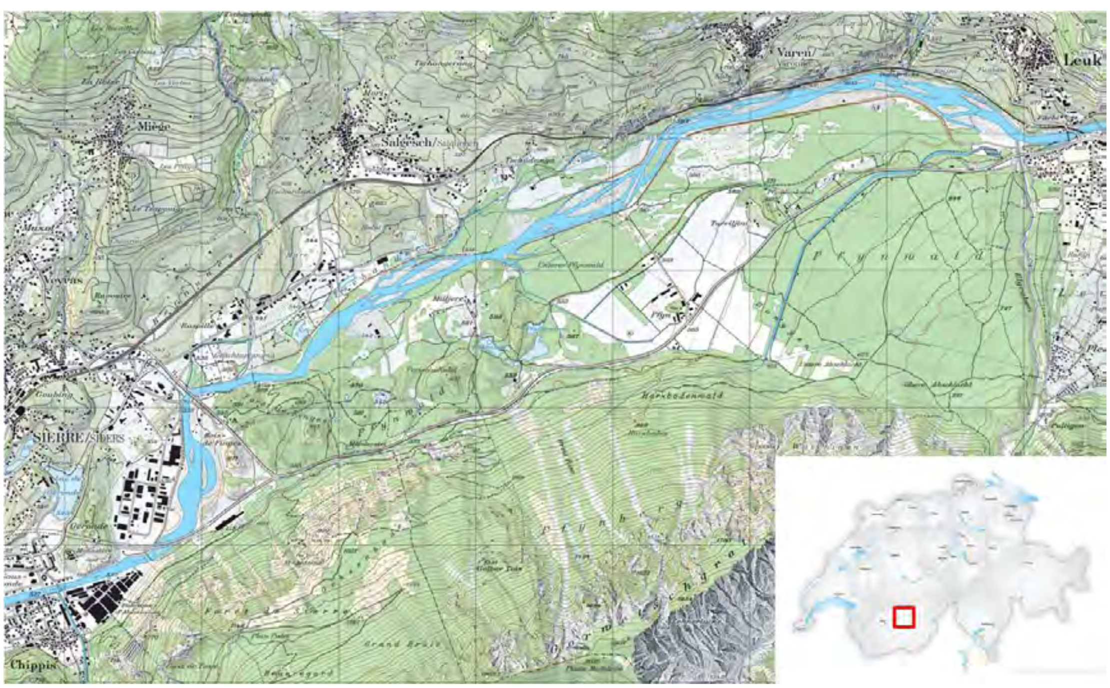

Figure 2.1: *Overview of the Pfynwald reach of the Rhone River. The study site is marked with a red rectangle on the map representing Switzerland.*

2.2 Rhone River

The Rhone is one of the major rivers in Europe, draining large areas of the north-western Alps and the Jura mountains. The river rises as the effluent of the Rhone Glacier in the central Swiss Alps. On its 812 km long way to the Mediterranean Sea it first drains the Valais and several tributary valleys before entering Lake Geneva. On its further route the Rhone runs through south-eastern France and enters the Mediterranean Sea close to the city of Arles.

2.2.1 Hydrology

The hydrological regime of the Rhone cannot be allocated to one specific regime type. In fact it is a combination of glacial, nival and pluvial regime with low flows in wintertime and high flows during summertime. The initiation of the large reservoir power stations Grande Dixcence (1956), Mauvoisin (1957), Mattmark (1967) and Emosson (1974) in the catchment area of the Rhone River caused a significant change of the streamflow regime. The mentioned reservoirs retain the large melt water discharge in spring and summer and release it during low flow periods in winter. Consequently natural floods are reduced and discharge during low flow season is increased.

Particularly in the Pfynwald section of the Rhone River the flow regime is significantly influenced by a weir situated at the village of Susten. Since the year 1911, when the barrage was brought into service, up to 65 m^3/s of water are extracted and delivered to a power plant at Chippis through a separate channel. Before autumn 2008 the riverbed underneath the weir used to stay dry, if discharge at Susten went below the maximum extraction volume of 65 m^3/s. In the course of the renewal of the power plants concession, the operating company is bounded to guarantee a residual discharge of 3,25 m^3/s in the Pfynwald reach of the Rhone River from that time on.

There is no gauging station located directly on the river reach between Susten and Sierre. Discharge measurements are taken either in Brig, located 30 km upstream, or in Sion that lies 25 km downstream of Susten. Streamflow data at the top end of the Pfynwald reach is therefore reconstructed from the hydrometric gauging stations in Brig and Sion. The correlation between the size of the catchment and the measured discharge was used to set up a relationship that allows computing discharge in the Pfynwald reach.

$$Q_{Pfynwald} = Q_{Brig} + a \cdot (Q_{Sion} - Q_{Brig}) - 60\, m^3/s$$

with a = 0.6

The factor a was calculated based on the differences between catchment sizes at Brig

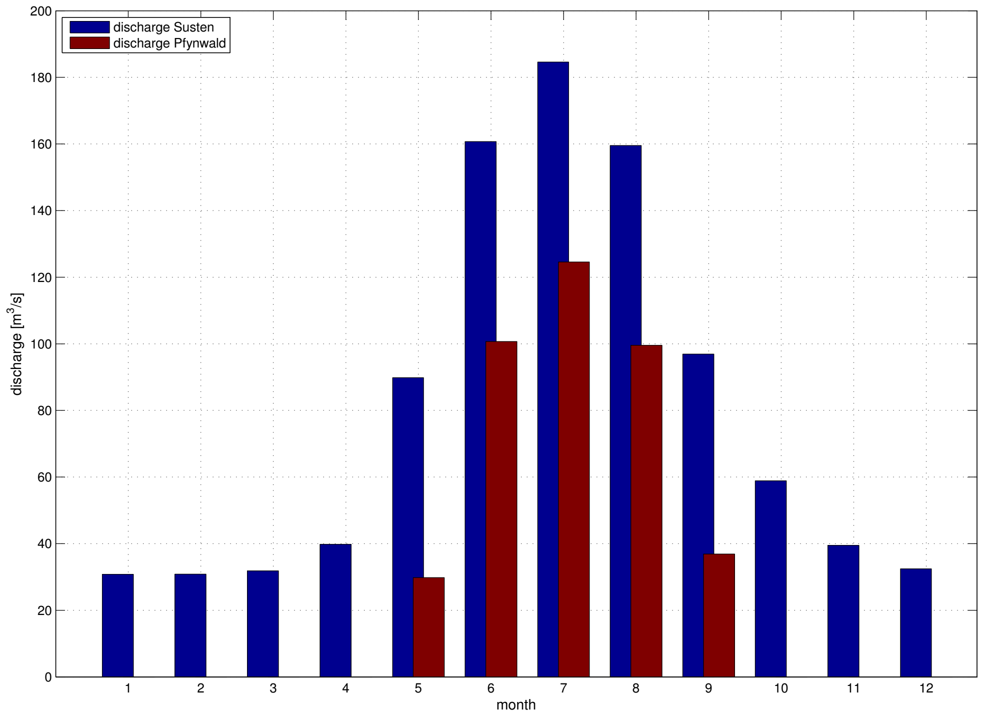

Figure 2.2: *Reconstructed mean monthly discharge in the Pfynwald reach of the Rhone River based on observed streamflow at measuring gauges at Brig and Sion.*

(913 km^3), Susten (2400 km^3) and Sion (3373 km^3). The underlying assumption states that discharge increases with growing catchment size. Additionally the water extraction at the weir at Susten has to be considered, since this significantly changes streamflow conditions downstream of the weir. The determined discharge, based on the observations at Brig and Visp, was therefore reduced by a constant extraction volume of 60 m^3/s. Figure 2.2 shows the mean monthly discharge for the period of 1974 to 2008. One can see that there is no discharge during low flow periods due to the water extraction at the weir in Susten.

The flood frequency analysis for the Pfynwald reach is also based on the gauging stations at Brig and Sion. The expected discharges are interpolated from the flood peaks available at the measuring gauges (*Bundesamt für Umwelt BAFU*, 2010). It is assumed that flood peaks are linearly dependent on catchment size (see figure 2.3).

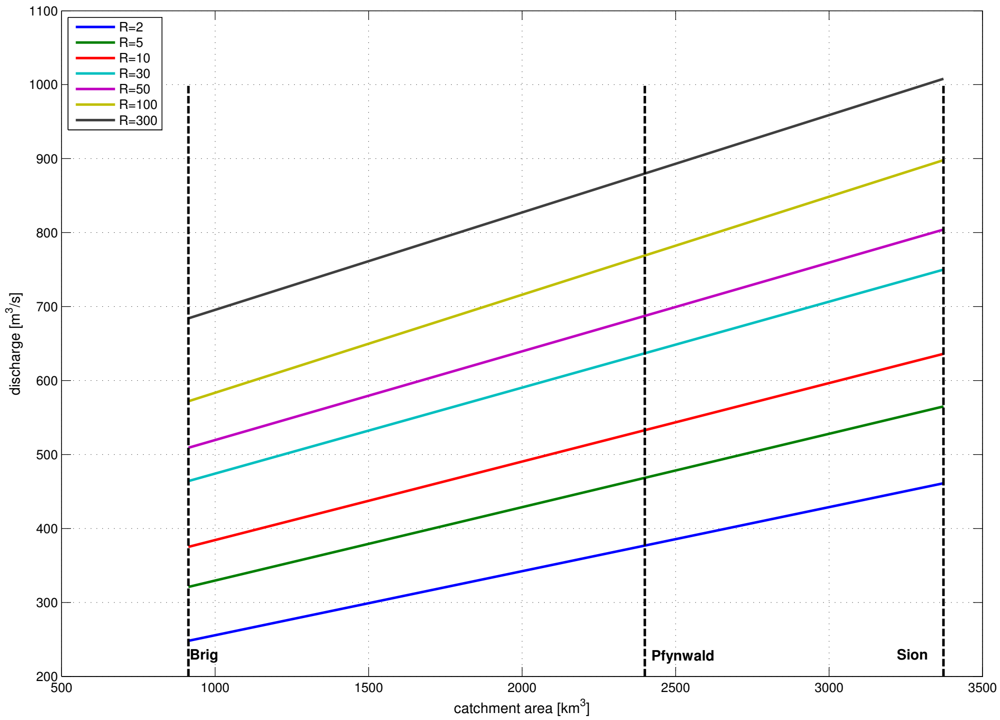

Figure 2.3: *Interpolation of floods with return periods of 2, 5, 10, 20, 50, 100 and 300 years in the Pfynwald reach based on the flood frequency analysis at the measuring gauges Brig and Sion.*

Table 2.1: *Expected flood peaks in the Pfynwald reach*

return period	discharge	
	Susten	Pfynwald
2	376	316
5	467	407
10	532	532
30	636	636
50	686	686
100	757	757
300	878	878

The resulting flood peaks for the Pfynwald reach of the Rhone River are summarized in table 2.1. In case of extreme floods (August 1987, September 1993, October 2000) the weir at Susten is not anymore in use (*Hunziker, Zarn & Partner AG*, 2001). Thus discharge is flowing completely through the Pfynwald reach and the extraction volume has not to be considered. The critical discharge at which the water extraction is stopped is not known. For this study it is assumed to correspond to a discharge with a return period of 10 years.

2.2.2 Morphology

The morphology of the Pfynwald reach is controlled to a large extent by the sediment input from the Illgraben. The confluence of the Illgraben and the Rhone goes along with a bend in the longitudinal profile and a change of the channel morphology from an alternating bar to a braided structure (see figure 2.4). The channel gradient changes from $< 0.15\,\%$ upstream to $> 2\,\%$ downstream of the Illgraben confluence (*Schlunegger et al.*, 2009). As a result of the massive and permanent sediment input from the Illgraben, the Pfynwald river section has never been channelized. Therefore the Rhone between Susten and Sierre has kept several elements, which are typical for a natural gravel-bed river. The river flows in several anastomosing branches, the channel bed consists of several vegetated islands, a large floodplain and floodplain forests.

The Pfynwald reach is morphologically very dynamic. The fluvial topography is reshaped completely during channel-forming discharges, which occur in periodic intervals. Thereby the river shapes its geometry (channel width, slope) in such a way that the corresponding optimum with respect to the sediment transport capacity is reached in the long-term. This optimum allows an equilibrium between sediment input and output and the sediment transport capacity.

Generally the bed-forming discharge has a return period of 2 to 5 years. According to *Jäggi* (1988) the bed-forming discharge in the Pfynwald reach exhibits a return period of 10 years due to the water extraction at the weir in Susten.

Figure 2.4: *Braided morphology in the uppermost part of the Pfynwald river reach.*

2.2.3 Topography

The longitudinal profile of the Rhone River in the Pfynwald area is characterized by a dramatic decrease of the channel bed slope from 2.2 % at the confluence of the Illgraben to a gradient of 0.3 % at Sierre (*Hunziker, Zarn & Partner AG*, 2001). Since 1995 aerial pictures of the Pfynwald reach are taken annually. These pictures are analyzed by the local engineering company KBM SA and further used to generate a digital terrain model (DEM) of the study area. Additionally cross sections and annual sediment volume balances are computed from the topographic data (*KBM SA*, 1995-2007). The Pfynwald river reach is represented by 79 cross sections, located in constant gaps of about 100 m.

Figure 2.5 shows the evolution of the longitudinal profile of the channel bed in the Pfynwald reach between 1995 and 2007. At the top end of the reach significant channel bed erosion was observed. Compared to the profile of 1995 the channel bed lowered up to 1.5 m until the year 2007. In the last relatively flat 2.5 km of the river section, there is a clear trend to aggradation. In-between the channel bed remains around the level of 1995.

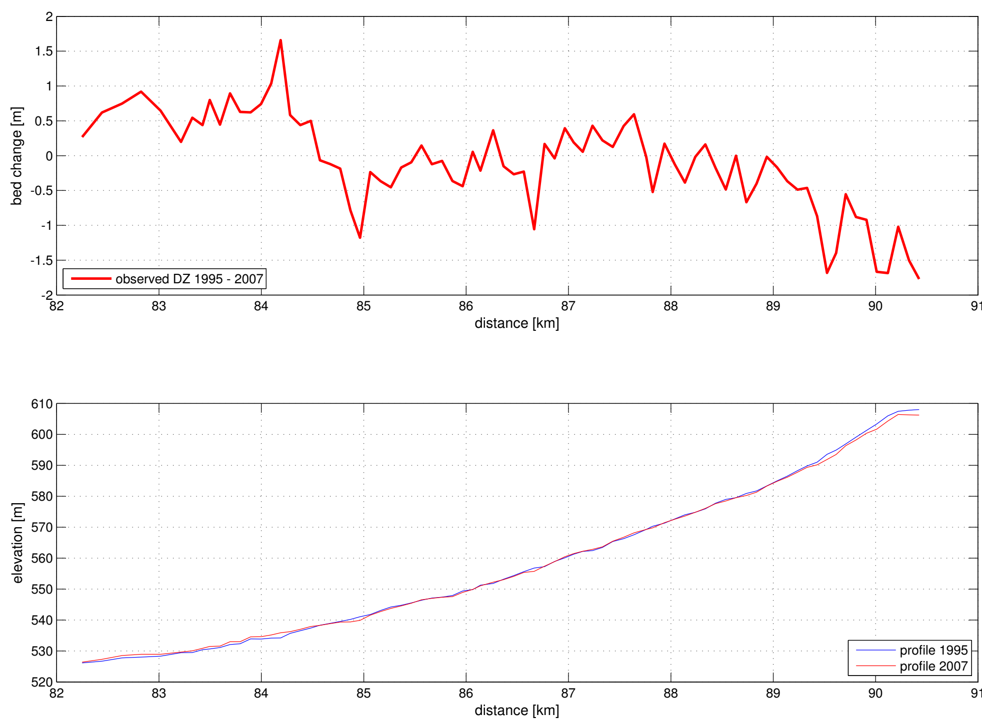

Figure 2.5: *Observed channel bed changes (top) and evolution of the longitudinal profile (bottom) in the period of 1995 to 2007.*

2.2.4 Sediment grain size distribution

The particle-size distribution of the bed sediment was analyzed by the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) at ETH Zurich in August 1987 as well as by the study group 'Rottenbewirtschaftung Pfyn' in November 2000 (*Jäggi*, 1988 and *Hunziker, Zarn & Partner AG*, 2001). This data is completed with observations that have been accomplished in January 2010 in the framework of the present study. In all of the above mentioned studies the grain size distribution was determined based on line surveys.

The grain size distribution of the river bed is displayed in figure 2.6. The mean diameter d_m as well as the d_{90} (90 % proportion by mass of the grain sizes that are smaller than the given diameter) are plotted along the flow direction. The mean diameter is an important measure for the sediment transport computation, while the d_{90} describes a characteristic dimension for the channel bed roughness. Generally both diameters decrease with increasing distance from the confluence of the Illgraben. The main reason for this is the so-called sorting of grains due to particle size dependent initiation of motion. Finer particles are mobilized faster and more often than the larger fractions of the gravel-bed, so that larger grains generally remain closer to the place where they were deposited (confluence of Illgraben).

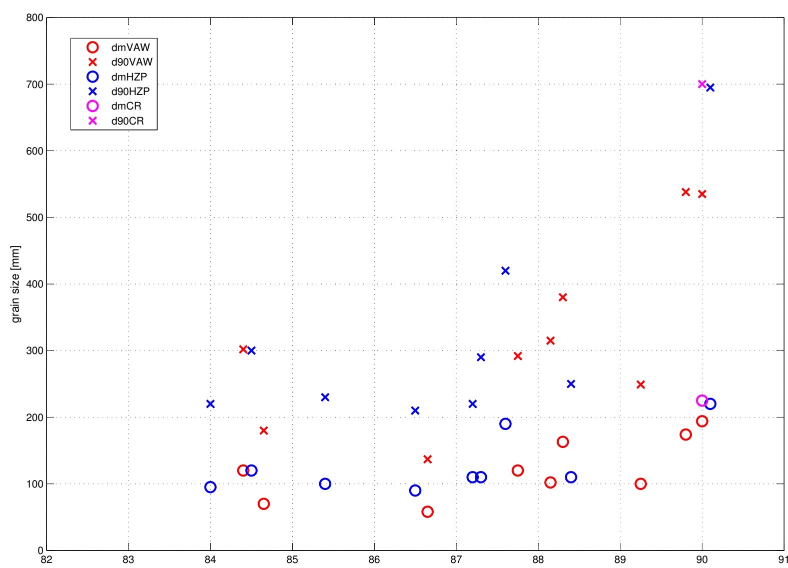

Figure 2.6: *Observed characteristic grain sizes d_m and d_{90} of the channel bed in the Pfynwald reach of the Rhone River.*

2.2.5 Gravel extraction

Three gravel pits are located in the Rhone river reach between Susten and Sierre. They extract a considerable amount of sediment from the river bed. Additional gravel extraction takes place at exact defined locations in the channel bed. The definition of the gravel-extraction volumes and locations is conducted according to a flood protection concept that is managed by the canton of Valais (*KBM SA*, 1995-2007). Sediment volume and extraction locations are determined annually based on the channel bed state at the end of the respective past year. A summary of annual sediment extraction volumes distributed among the extraction sites is given in table 2.2. On average, a total volume of 137'611 m^3/a of gravel is extracted annually from the channel bed of the Rhone River in the Pfynwald reach.

Table 2.2: *Gravel extraction volumes in the Pfynwald river section for the period of 1996 to 2007. Leuk, Salgesch and Sierre are permanent gravel pits. In areas A to D selective extractions were done according to the flood protection concept of the Canton Valais. Volumes are given in m^3 including porosity. (modified after KBM SA, 1995-2007 and Hunziker, Zarn & Partner AG, 2008).*

Year	Area A km 89.3 - 90.1 CS 4 - 12	Leuk km 88.6 - 89.3 CS 13 - 19	Area B km 87.9 - 88.4 CS 21 - 26	Area C km 86.8 - 87.9 CS 27 - 37	Area D km 85.9 - 86.4 CS 41 - 46	Salgesch km 84.3 - 85.7 CS 48 - 62	Sierre km 82.6 - 83.2 CS 2F - 8F	Total
1996		27'478				~67'057	68'084	162'619
1997	17'704	10'154	24'034	13'446	16'238	63'812	61'870	207'258
1998	9'617	18'661			8'252	47'310	46'982	130'822
1999	12'542	9'766			3'427	26'732	42'819	95'286
2000	16'404				6'847	~25'000	43'472	91'723
2001	52'356	13'928				~25'000	~44'069	135'353
2002	42'240			1'740		~11'818	~51'366	107'164
2003	9'024		33'602	5'995		~32'470	54'499	135'590
2004	23'050					17'650	82'004	122'704
2005	3'703	12'576	5'000		585	~40'000	89'000	150'864
2006	~28'500					~30'000	90'040	148'540
2007	33'463		21'367			~30'000	78'583	163'413
Total	248'603	92'563	84'003	21'181	35'349	416'849	752'788	1'651'336

2.3 Illgraben

2.3.1 General description

The Illgraben catchment is one of the most active torrents in the Alps. Every year several thousand tons of sediment are delivered to the Rhone River by debris flows (*Hürlimann et al.*, 2003). Since the last Ice Age a more than 100 m-thick fan of gravel covering an area of 6.6 km^2 has formed in the Rhone Valley. The Rhone River is therefore deflected to the north side of the valley. The Illgraben merges the Rhone River at their left bank roughly 500 m meters downstream of the weir at Susten. The catchment area of the torrent is about 10 km^2. Geologically the Illgraben catchment lies in Triassic schists and dolobreccias. The matrix of the debris flow material is silt, clay and quartzites, which are prone to erosion during heavy rainfall events (e.g. summer thunderstorms). Average erosion rates are as high as 7 cm per year (*Hürlimann et al.*, 2003 and *McArdell et al.*, 2007).

2.3.2 Sediment grain size distribution

The constitution of the debris flows is highly variable, ranging from relatively liquid mudflows to water-saturated debris flows. The latter are able to transport very large boulders ($>$ 2 m). The composition of the solid fraction of the debris flows is also diverse. Generally the finer fractions (silt and sand) account for a quite substantial proportion.

Jäggi (1988) estimates the fraction of the fines that is transported away by the Rhone River in suspension to be in the range of 50 % to 70 %. Line surveys carried out within the scope of this study on the deposit of a debris flow that happened on August 9th 2009 result in a mean particle diameter of 10 cm and a d_{90} of 30 cm. The grain size distribution of this particular debris flow is shown in figure 2.7. Compared to Jäggi's findings, the fraction of silt and sand ($<$ 2 mm) seems to be very small (ca. 10 %). A possible explanation for the deviation may be that a line survey is not an appropriate method to deal with such fine material or that it was transported further downstream.

Figure 2.8 gives a visual impression of the debris flow material. It shows the material deposit in the channel bed of the Rhone River at the confluence. The picture was taken right after the debris flow event on August 9th 2009. The impact of the debris flow sediment input to the channel bed of the Rhone River is illustrated in figure 2.9. As soon as the debris flow delivered material reaches the channel bed of the Rhone it is exposed to the current of the river. The occurrence of debris flows in the Illgraben does not always coincidence with high flows in the Rhone. Therefore the sediment supply is not immediately carried away by the current. If the discharge is not high enough, just the smaller fractions of the sediment are mobilized and transported downstream. Larger

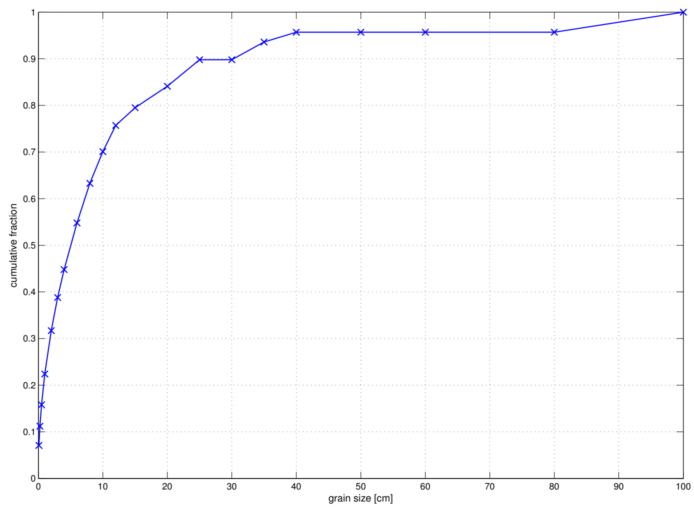

Figure 2.7: *Grain size distribution of one particular debris flow that occurred on 09.08.2009. The corresponding d_m is 10 cm and the d_{90} 30 cm.*

particles remain in the channel bed. The sorting of grain sizes leads to the development of a very strong armored layer in the area of the confluence of the Illgraben and the Rhone. This layer protects the channel bed against erosion. A relatively large flood is needed to break up the armored layer. Figure 2.9 gives a very nice example of an armored layer.

2.3.3 Observation

Historical data on the debris-flow activity in the Illbach exist from the beginning of the 20th century (*GEO7*, 2001). In the year 2000 the first automatic monitoring systems, including video cameras, ultrasonic devices, a radar device, geophones, and rain gauges, were installed at the Illgraben to quantify the characteristics of debris flows (*Hürlimann et al.*, 2003). Since then the volumes of debris flows can be estimated using the hydrographs as obtained by the radar device. In addition to the existing gauging systems, a force plate was installed in the Illgraben in 2003. Its instrumentation measures the normal and shear forces and fluid pressures, so in combination with the geophones not only the volume of debris flows but also the solid portion can be computed (*McArdell et al.*, 2007).

The tables A.2 and A.1 in the appendix give an overview of observed debris flows in the Illgraben since 1932. Until the year 2000 the observation is very poor and incomplete. With the installation of an automatic monitoring system in 2000, debris flow events have been recorded consistently.

Figure 2.8: *Visual impression of the debris flow material. The picture was taken after the debris flow event on 09.08.2009 right at the confluence of the Illgraben and the Rhone River.*

Figure 2.9: *Confluence of the Illgraben and the Rhone River. Parts of the massive deposit of the debris flow on 09.08.2009 are not transported downstream by the Rhone yet.*

Chapter 3

Numerical sediment transport model

3.1 Introduction

The numerical sediment transport model system applied in this study is called BASEMENT (*Faeh et al.*, 2006-2008). The development of this software started in the year 2002 and is still maintained by the applied numerics division at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW). The name BASEMENT stands for BASic EnvironMENT for simulation of environmental flow and natural hazard simulation. The software consists of the numerical solution algorithms, included in different modules. Pre- and post-processing has to be done with independent products. So far BASEMENT consists of two subsystems, a one-dimensional tool called BASEchain and a two-dimensional module named BASEplane. Both are able to simulate flow behavior and sediment transport under steady and unsteady conditions in a channel. In the scope of this work the currently available version 1.7 of the numerical tools BASEchain and BASEplane was applied.

The simulation tools are further partitioned into three different parts (*Faeh et al.*, 2006-2008):

- the mathematical-physical modules consisting of the governing flow equations
- the computational grid representing the discrete form of the topography
- the numerical modules with their methods for solving the equations

Figure 3.1 gives a graphical overview of the different modules and their components.

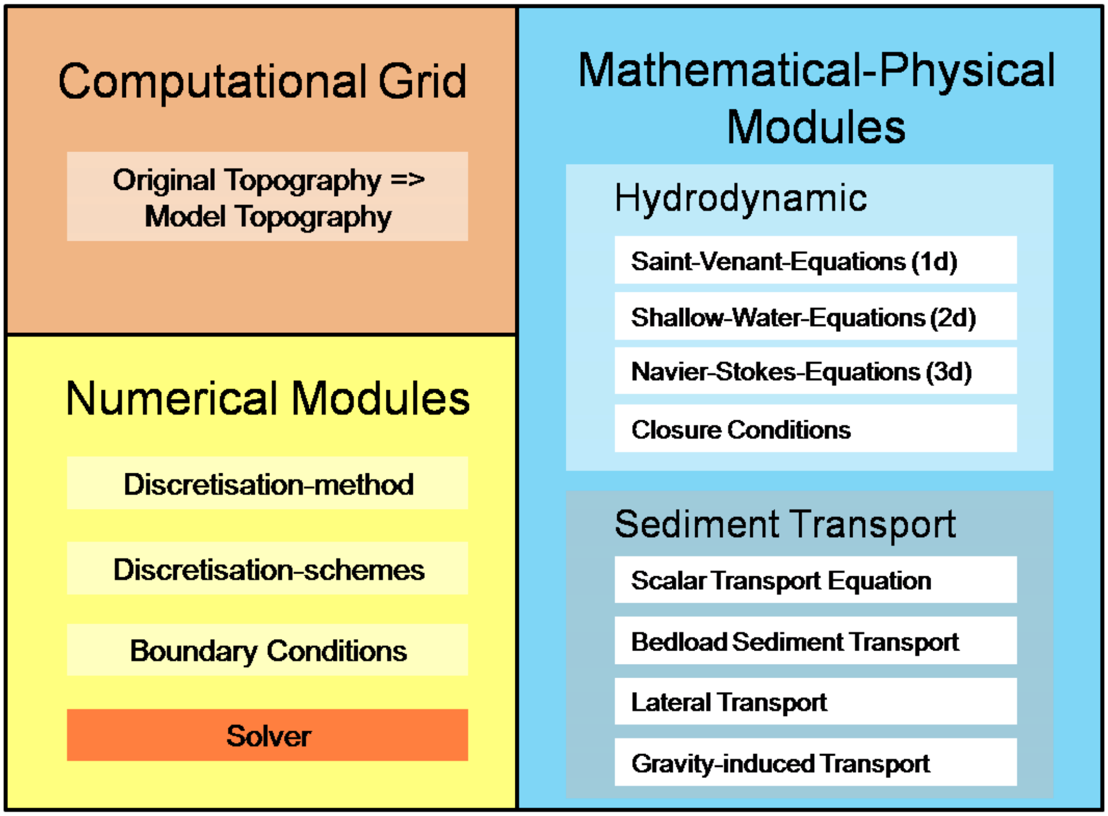

Figure 3.1: *Modules of BASEMENT and their components (modified after Faeh et al. (2006-2008))*

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3.1.1 Mathematical-physical modules

The hydraulic computation of the flow characteristics is based on physical models, such as the conservation of mass and momentum. These models allow resolving processes covering a large spectrum of temporal and spatial scales. Concerning real problems, the complex physical models need to be simplified due to a lack of data to set up the boundary and the initial conditions. In addition, the computational efficiency to solve the complete system of equations suffers from the increasing spatial and temporal resolution that is required to account for small scale processes. For that reason the full set of equations is simplified by less complex mathematical models.

In case of a three dimensional problem, the Navier-Stokes equations are used to describe the flow and pressure distribution. The equations need to be solved numerically, because analytical solutions exist just for a few very simple problems.

The two dimensional flow can be described by means of the 2-dimensional shallow water equations. This set of equations is a simplification of the Navier-Stokes equations, assuming a static pressure distribution and neglecting the vertical flow components.

Turbulence effects cannot be resolved anymore, so that they need to be parameterized by an appropriate relationship to a resolved variable.

For a one dimensional problem the 1D Saint-Venant equations are used. They allow computing the mean velocity in flow direction and the water level.

Contrary to the hydraulics, sediment transport is treated in a simpler manner. Instead of calculating the movement of every single particle, empirical relations developed by river engineers from flume and river studies, are used to determine sediment transport and riverbed changes. These formulas are conceptual rather than physically-based.

3.1.2 Computational grid

The basis for the computation of flow is the riverbed topography. Usually the topography is given in the form of a digital elevation model (DEM) or as a sequence of river cross sections. To solve the governing equations a special internal computational grid is required. Therefore the real world topography needs to be transformed into an appropriate representation. This step is very important since the computational grid has a great impact on the accuracy of the results and the computational time. There are two types of computational grids: structured and unstructured. A structured grid is a regular raster that consists of quadrilaterals. The simple data structure allows the use of efficient algorithms. The mesh generation is relatively easy and timesaving. But the structure itself is not flexible and cumbersome for the representation of difficult topography. BASEMENT is built on unstructured grids. This type of grid is highly flexible, especially for the automatic mesh generation in complex geometries. The grids resolution can easily be adjusted locally to account for local topographic conditions. Unstructured grids consist of triangles and quadrilaterals. The data structure is therefore more complicated.

Generally a mesh is build up by cells, so-called control volumes. The definition of the mesh is based on three different objects:

- nodes: mass free points in relation to a coordinate system.
- edges: defined by two nodes. Edges define the place of information flux between two elements in Finite Volume Methods.
- elements: defined by several nodes. Elements define the place of the physical variable.

The above explained data structure is appropriate for one and two dimensional computations.

3.1.3 Numerical modules

BASEMENT uses the Finite volume (FV) method to discretize the system of equations. This method is based on the integration of the equations over a volume that is defined by nodes of grids on the mesh. The equations are therefore discretized in their integral form and not in the commonly used differential form. The FV method is locally and globally conservative, because of the integration over a volume. To solve the initial value problem (IVP) three different algorithms are implemented in BASEMENT: exact Riemann solver, HLL and HLLC approximate Riemann solver. For further details about the numerical kernel of the model refer to the manual of BASEMENT (*Faeh et al.*, 2006-2008).

3.2 Goals

3.2.1 1d-model BASEchain

The one dimensional tool BASEchain was used to investigate the bed load transport capacity as well as the evolution of the riverbed in the Pfynwald reach of the Rhone River. The one dimensional model is not capable of simulating changes of single river branches or gravel banks, but it is a very useful tool to study changes of the mean elevation of the riverbed. Additionally a one dimensional numerical sediment transport model is suitable to investigate the influence of variable boundary conditions on the evolution of the long profile and the sediment transport capacity of a river reach.

BASEchain is applied to the whole 8 km long Pfynwald section, starting at the weir at Susten and ending after the gravel pit at Sierre (figure 3.2).

3.2.2 2d-model BASEplane

A two dimensional sediment transport model is able to study spatially riverbed changes. In contrast to a 1d model, a two dimensional model can simulate the behavior of single river channels and gravel banks. In this study BASEplane is employed to get a more sophisticated image of river bed changes and sediment transport capacity, in particular with respect to spatial patterns. Due to the long computational time, BASEplane is only applied to the uppermost 2 km of the Pfynwald reach (figure 3.2). Morphologically this is the most interesting part of the domain, as the confluence of the Illgraben and the Rhone is situated in this section. In the present study sediment transport simulations were limited to the computation of bed load transport. The computation of suspension load is not addressed in this thesis, because suspension load has limited impact on the bed forming processes in the Pfynwald reach.

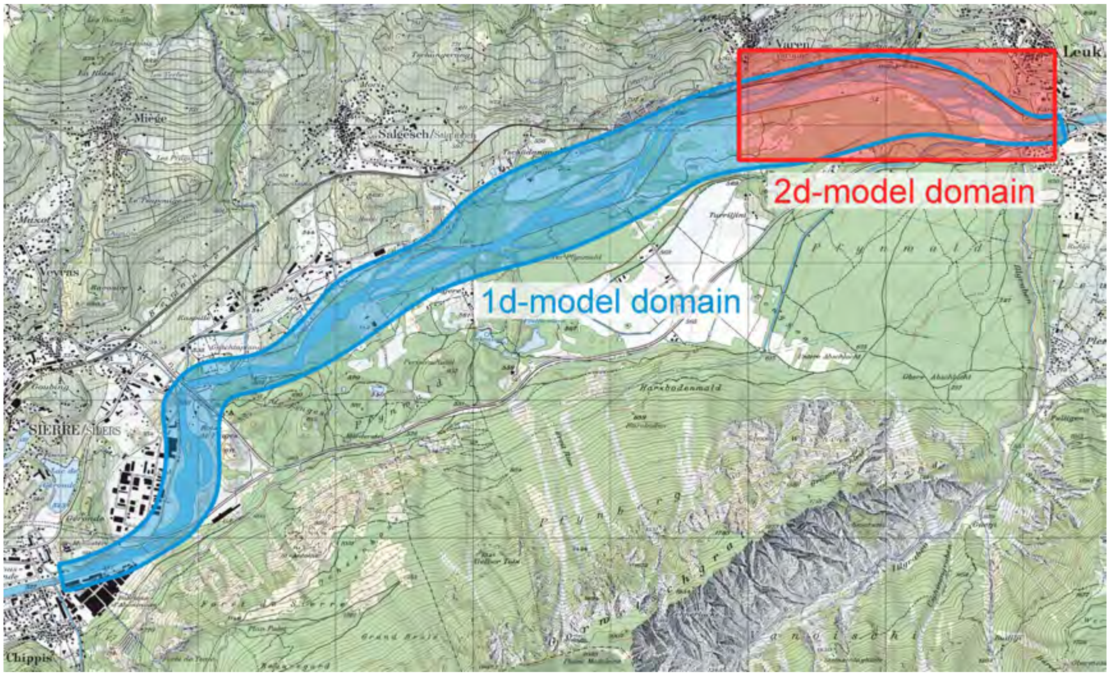

Figure 3.2: *Overview of the different project domains. The one dimensional project covers the whole Pfynwald section from Susten to Sierre. BASEplane is only applied to the uppermost 2 km of the reach.*

3.3 Preprocessing

Preprocessing is a very important step in the simulation procedure in order to guarantee successful and efficient simulation runs. The preprocessing includes the definition of the project, the set up of different simulation scenarios, the preparation of the input data, the choice of the computational approach and the definition of boundary and initial conditions.

In this study two different projects were defined: project BASEchain (1D), consisting of the one dimensional simulations and project BASEplane (2D), covering the two dimensional computations. In the following these two projects are treated separately.

3.3.1 Project BASEchain (1D)

Input data

Topography

River cross sections were used as topographic raw data. In the Pfynwald section a total of 79 cross sections exist, separated in constant gaps of approximately 100 m. The geometry data was provided by the engineering company KBM (*KBM SA*, 1995-2007).

In order to use the cross sections for a numerical simulation, the geometric data needs to be transformed into a specific topography file format, saved as a textfile (txt). This file contains the topographic description of the cross sections and all the relevant information for the computations that is related to the riverbed. In this study, the topographic file type 'floris' was used. The pure topographic information is given by a sequence of points, for which the distance from the left border is known. The file further specifies the definition of the main channel, the channel bed bottom, the floodplain, the bed friction and the soil type. A detailed description of the definition of the topography file is given in the manual of BASEMENT (*Faeh et al.*, 2006-2008).

Hydrological data

The hydrological data is the most important boundary condition of the model. Hydrographs, steady-state or continuous, or water levels provide the necessary information. The hydrological data is needed as a sequence of water level [m] or discharge [m^3/s] in times [s]. The file needs to be saved as a textfile (txt).

Hydrographs can either be implemented in the model as an inflow boundary condition or an external source or sink. The inflow boundary condition is used to simulate discharge from upstream that enters the study reach. Additional discharge coming from a tributary is described with a source. Sinks are implemented e.g. in case of water abstraction by a hydroelectric power plant.

Regarding this study, a continuous hydrograph was used for the inflow boundary condition at the weir at Susten. Smaller tributaries (e.g. Illbach, Dala) that drain into the Rhone in the Pfynwald reach are negligible, so that they are not considered as additional sources.

Sediment data

Sedimentological data is needed to characterize the riverbed surface as well as the subsurface, which can be eroded by the current. The granulometric size distribution of the river bed is crucial in terms of sediment transport calculations. Sedimentological properties of the riverbed are directly written into the command file of a particular simulation. The present study uses the sedimentological data that is specified in detail in chapter

2.2.4. The observed grain size distribution needs to be discretized into classes in order to use it for the simulation. The resolution of the material composition is determined by the number of chosen grain classes. Each grain class is defined by its mean diameter. The number of grain classes strongly affects the computational effort of the simulation; the more grain classes are taken into account, the more computing power is needed. Both the number of grain classes and the classification of the grain diameters are very important with respect to the computation of sediment transport, so that both serve as a calibration parameter.

In case of a sediment transport computation the boundary condition at the top end of the model domain has to be known. Additional sediment supply or extraction can be implemented by means of an external source, respectively sink. In this thesis the sediment supply, delivered by debris flows from the Illgraben, is introduced as an external source at the corresponding cross section. Gravel extraction at the different gravel pits is simulated with external sinks. Time, volume and location of the extractions are known (see chapter 2.2.5), so that sediment extraction hydrographs were defined for every single cross section. The weir at the top end of the Pfynwald section is equipped with underflow hydraulic gates, so that the carried sediment from upstream can pass the weir. As a consequence there is sediment supply to the Pfynwald reach from upstream. It is implemented by means of a sediment inflow boundary condition.

Command file

Before one can execute a simulation with BASEMENT a command file has to be set up. This file contains all the information in order to run the simulation. It is built up by several blocks. The four main blocks are called 'GEOMETRY', 'HYDRAULICS', 'MORPHOLOGY' and 'OUTPUT'. The 'GEOMETRY' block specifies the name and the type of the geometry file as well as the arrangement of the cross sections, ordered from upstream to downstream. In the 'HYDRAULICS' block, the boundary and initial conditions, the friction, possible external sources and some characteristic parameters of the simulation (e.g. numerical scheme, run time, CFL-number, calibration parameters) are defined. All the information about the sediment transport computation is stored in the 'MORPHOLOGY' block. This is namely the grain size distribution of the bed material, the chosen sediment transport formula and sediment transport calibration parameters. Finally the 'OUTPUT' block allows you to specify the desired outputs.

3.3.2 Project BASEplane (2D)

Input data

Topography

The two dimensional simulation of the hydraulics and the sediment transport of a river requires a grid that describes the three dimensional topography of the river bed. This is the most important difference to the input data that is needed for a one dimensional simulation. The mesh file consists of interconnected node and element data that contain the topographic information. A grid can either be interpolated from river cross sections, defining the channel geometry, or generated with the aid of a digital elevation model (DEM). The latter is the easier approach and therefore used in this thesis. Still, there is the need of a so-called preprocessor to generate an appropriate mesh file. It is recommended by the developers of BASEMENT to use SMS (Surface Water Modeling System) (*Scientific Software Group*, 2009) as a preprocessor. For this study the currently available version SMS 10.0 was used.

For the mesh generation a 2 m Digital Terrain Model DTM-AV was used as raw data. This data is produced by Swisstopo (*Bundesamt für Landestopographie Swisstopo*, 2005b). It represents the topography of the Earth's surface without vegetation and buildings. The model is based on high precision laser scanning (LIDAR) from airplanes, and the accuracy is +/- 0.5 m. To reduce the amount of data, the spatial resolution of the DEM was decreased to 4 m. The accuracy is still good enough for the purpose of simulations of sediment transport.

The use of an orthophoto or a detailed map is very helpful in the process of mesh generation. The geometrically corrected picture or the map can be imported into SMS and then used as a background image. This study used an orthophoto taken from Swisstopo in summer 2005 (*Bundesamt für Landestopographie Swisstopo*, 2005a).

An automatic triangulation of the data points would be the easiest way to generate a mesh, but this will end up with some unfavorable element shapes and configurations (e.g. unnatural flattening of the terrain). Therefore the mesh is rather generated using a conceptual model as a basis for the triangulation. This conceptual model is built up with the aid of the aerial photo. The boundaries of the model domain are defined as significant terrain features, and consequently the structure of the model domain terrain is predefined. Besides, the spatial resolution can be modulated locally, by assigning the number of nodes along a significant terrain feature or boundary. The use of a conceptual model to triangulate the data points results in a mesh that allows for variability in the spatial resolution and that contains edges that follow along the centerlines, shoulders, and bathymetry intersections. The generated mesh still needs to be checked and locally adjusted. Moreover one has to define the material type of the elements to account for spatial differences in the composition of the riverbed and the channel bed roughness (e.g. channel bed, floodplain, embankments). Not to forget is the conversion of quadratic elements (six node triangles and eight node quadrilaterals) to linear elements (three node triangles and four node quadrilaterals) in order to use the grid for a simulation with BASEMENT. Finally the mesh has to be saved as a 2dm file.

The mesh of the two dimensional model domain is shown in figure 3.3. It can easily be seen that the spatial resolution is variable. High resolution dominates within the channel bed, while it decreases in the floodplain with increasing distance from the riverbed. By using a coarse grid in areas of lower interest, the computational effort can be reduced.

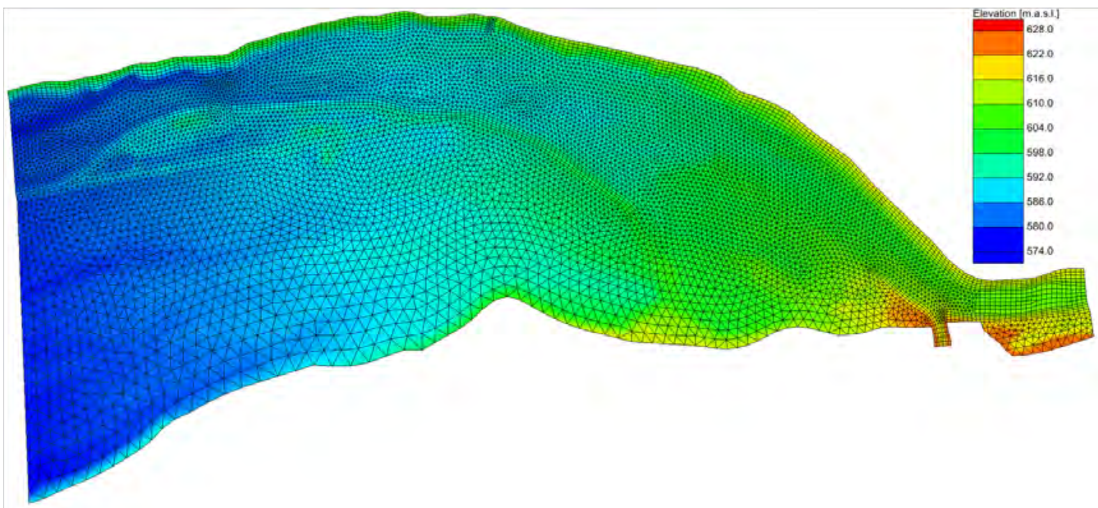

Figure 3.3: *Mesh of the study area for the 2d modeling.*

Hydrological data

The definition of the hydrological input data and the definition of boundary conditions is analogue to the procedure for one dimensional simulations.

Sediment data

The same granulometric data is used here as for computations with BASEchain. Also the definition of the boundary conditions is similar. Though, there is one important difference. Sources or sinks are not assigned to cross sections, but to single elements or nodes of the mesh.

Command file

The command file for a two dimensional simulation with BASEplane has the same structure as the 1d command file. There are some discrepancies in the definition of the geometry, the boundary conditions and the channel bed for sediment transport computations.

Chapter 4

Model calibration

4.1 Project BASEchain (1D)

Generally the model needs to be calibrated in a two step procedure. First, one has to calibrate the hydraulic part of the model, meaning that only the water flow through the study reach is simulated. Observed flood marks are usually taken as a reference value. The simulated water levels need then to be fitted to the observed flood marks, by changing the roughness coefficient of the channel bed. Due to the use of quite sophisticated physical models for the hydraulic computations, on the one hand the need for a hydraulic calibration is limited and on the other hand the number of calibration parameters is inherently small. Since it is very complicated to measure the roughness of a riverbed, it is obvious that the roughness coefficient is the most sensitive and important calibration parameter in hydraulic simulations.

Unfortunately there is no flood mark observation data available for the Pfynwald river reach. For that reason the hydraulic part of BASEchain was not calibrated. That is of no consequence, concerning the sediment transport simulation, since the calibration potential of the sediment transport computation is much larger than the hydraulics. The formulas for sediment transport are primarily based on empirics, so that a model calibration is essential.

There is very good data available for the calibration of BASEchain concerning sediment transport in the Pfynwald reach. The model was calibrated on the basis of topographic data for the period of 12 years from October 1995 to October 2007 that was surveyed annually by the engineering company KBM (see chapter 2.2.5). The goal was to fit the simulated riverbed changes to the observed changes. In addition, the simulated bed load transport is compared to the one that was reconstructed on the basis of observations in the Pfynwald reach and sediment transport simulations in the adjacent river sections.

4.1.1 Input data

The topographic data from October 1995 was used as the starting position for the calibration of the model. The channel bed geometry observed in 2007 was then applied as a reference to evaluate to models performance.

The granulometric composition of the riverbed was described by means of particle size distributions that were measured by *Hunziker, Zarn & Partner AG* (2001) and *Jäggi* (1988). To characterize the grain size distribution of the debris flow material, the data that was surveyed in the scope of this study was used.

The inflow-hydrograph used for the calibration was computed according to the method described in chapter 2.2.1. During low flows generally no sediment is transported in the Rhone, so that low discharges were omitted in the hydrograph. Normally the initiation of sediment transport coincidences with the breakup of the armored layer. The corresponding stress to the riverbed, expressed as a discharge, is called Q_D. According to *Hunziker, Zarn & Partner AG* (2001) and *Jäggi* (1988) sediment transport is initiated at a discharge that exceeds 150 to 200 m^3/s. To remain considerably below this critical streamflow a discharge of 100 m^3/s was chosen as a threshold for the hydrograph. Due to the shortening of the effective duration of the hydrograph, computational time can be saved.

The sediment supply at the upper boundary is assumed to be linearly dependent on discharge. The annual supply was estimated by *Hunziker, Zarn & Partner AG* (2008), using a sediment transport model. The sediment yield at the weir at Susten adds up to about 15'000 m^3 per year. The sediment volume delivered by the Illgraben was determined based on a balance of the sediment volumes in the Pfynwald reach with respect to bed load transport (table 4.1). Thereby the gravel pit extraction volumes, the inflow at the upper boundary, the sediment discharge at the lower boundary, the sediment volumes resulting from riverbed erosion or aggradation and the sediment supply by the Illgraben have to sum up to zero. According to *Hunziker, Zarn & Partner AG* (2008) the sediment outflow at the downstream end of the river section constitutes to an annual volume of 30'000 m^3. The sediment volumes from erosion and aggradation were computed on the basis of the changes of the riverbed elevation. The erosion volume is introduced as a supply, because sediment that is taken up from the channel bed contributes to bed load transport. Aggradation reduces bed load transport, so that deposition volumes are declared as extractions. The sediment balance results in a sediment supply by the Illgraben of roughly 140'000 m^3 per year in the period for 1995 to 2007. The sediment is brought into the model domain as an annual average at the river cross section 4 at km 90.14. It is not possible to correctly distribute the sediment volume among the observed debris flows, because the observed time series in the period before the year 2000 is not complete (see table A.2).

Table 4.1: *Sediment balance in the Pfynwald reach for the period of 1996 to 2007 regarding bed load transport. Volumes are given in m^3/a including porosity.*

	supply		extraction/discharge	
	total 1995-2007	annual	total 1995-2007	annual
upper boundary	180'000	15'000		
lower boundary			-360'000	-30'000
gravel extraction			-1'651'336	-137'611
bed erosion	309'842	25'820		
aggradation			-178'345	-14'862
subtotal	361'649	30'137	-2'325'308	-193'776
Illgraben	1'699'839	141'653		

The gravel pits were implemented to the model as external sinks, distributed along the reach according to table 2.2. The extraction volumes were simulated as constant annual extraction rates. Because all of the above mentioned sediment volumes include porosity, they need to be transformed into pure sediment volumes in order to satisfy the requirements of BASEMENT. A constant porosity of 0.37 was applied to convert the volumes.

The initial condition was defined using an initial state stored in a separate file. This file describes the exact initial situation of the hydraulic conditions in the channel. It was obtained by means of a hydraulic simulation with a steady-state hydrograph of $100\,\mathrm{m}^3/\mathrm{s}$. The hydraulic simulation was started with the initial condition 'dry' and it was run as long as a steady state was reached.

4.1.2 Calibration parameters

The models performance was improved by calibrating three different parameters:

- Upwind
- Active layer height
- Sediment composition

Upwind

The parameter 'upwind' determines how the bed load flux at the cell interface between two cross sections is calculated. The calculation of bed load transport takes place in the cross sections, since all the data, which is needed to compute the flux is available there. The parameter 'upwind' defines which data is used to interpolate the bed load flux in the cell interface. A value between 0 and 1 can be assigned to the parameter. If upwind is set to 1, only the upstream cross section is considered, in case of a 0 the value of the downstream section is assigned to the flux. 'upwind' is a very important calibration parameter with respect to the stability of the simulation.

Active layer height

The active layer height defines the uppermost layer of the riverbed in which the important processes of sediment transport take place. By enlarging this height, sediment transport rates generally increase, because more bed material is exposed to the flow and the applied shear stress. The active layer height is constant in the whole model domain; it cannot be adjusted for specific cross sections.

Sediment composition

The grain size distribution of the riverbed material was measured by means of line surveys or sieving analysis. To use this data for the numerical simulation it needs to be discretized as mentioned earlier (chapter 3.3.1). Based on the observed particle size distribution, one has to define the desired grain classes with their corresponding mean diameters. The easiest approach to characterize the channel bed material is to use one single mean diameter. However, a great disadvantage of single grain simulations is that bed material sorting effects cannot be captured, so that the model is not able to simulate bed armoring. In case of the Pfynwald reach it is very important to account for the forming and destroying of the armored layer. For a single grain simulation BASEMENT provides two methods to artificially introduce a protection layer. Either a critical shear stress (τ_{cr}) of the protection layer or the d_{90} grain diameter of the bed armoring layer can be defined. In case of the critical shear stress, erosion of the river bed starts if the stress is exceeded. Using the d_{90} grain diameter to characterize the armored layer, first the model needs to compute the dimensionless critical shear stress of the bed (θ_{cr}). If the stress induced by the flow exceeds the dimensionless critical shear stress of the riverbed, erosion of the channel bed begins. If the armored layer is eroded once, it cannot be built up again. In this study the first approach using a critical shear stress was applied to account for a protection layer. The employed critical shear stress was computed on the basis of the d_{90} according to figure 4.1 using the following formula:

$$\tau_{cr} = \theta_{cr,armor} \cdot (s-1)\, d_m = \theta_{cr} \left(\frac{d_{90}}{d_m}\right)^{2/3} \cdot (s-1)\, d_m$$

with d_{90} as the specified d_{90} grain diameter of the substrate, d_m is the mean diameter of the riverbed material, θ_{cr} corresponds to the critical shear stress of the substrate (here $\theta_{cr} = 0.05$) and s denotes the relative density of the gravel ($\rho_s/\rho_w = 1.65$).

To consider bed material sorting effects it is advisable to perform multiple grain size simulations. In this thesis the effect of the use of multiple grain sizes was studied in the course of the model calibration. Additionally to the single grain size runs, simulations with two different numbers of grain classes were performed, using either 5 or 10 grain classes to specify the substrate. Depending on the number of used grain classes, different approaches for the computation of sediment transport were used. In case of a single grain simulation the sediment transport formula of Meyer-Peter Müller (MPM) was applied. For multiple grain class simulations the revised form of the MPM formula after Hunziker (MPMH) was applied.

Single grain simulation

In case of a single grain simulation one mean particle diameter was used to characterize the riverbed as well as all the material that is supplied to or extracted from the Pfynwald river reach. The mean grain size is the parameter that needs to be adjusted in order to improve the models performance. According to the observations of the granulometric composition of *Hunziker, Zarn & Partner AG* (2001) and *Jäggi* (1988) the mean particle diameter of the riverbed in the Pfynwald reach adds up to about 100 mm. Hence a first simulation was run using this value. Subsequently the mean grain size was adjusted to achieve a better fit of the model results.

Multiple grain size simulation

In multiple grain size simulations the method of fractional sediment transport is applied. It provides a detailed insight into sorting and separation effects in riverbeds with a broad sediment grain size distribution. Multiple grain size simulations also allow for accounting for spatial variability of the riverbeds grain size distribution. According to figure 2.6 the mean particle diameter decreases along the Pfynwald reach. To represent this variability, the river reach was subdivided into six different reaches with similar characteristics of the gravel bed. Figure 4.1 shows the observed characteristic grain sizes d_m and d_{90} as well as those that were used to characterize the composition of the channel bed in the simulation runs.

The goal of the multiple grain size calibration runs was to investigate the sensitivity of the model output to the number of employed grain classes as well as to the composition of the debris flow material from Illgraben.

The grain size distribution was discretized using both, 5 or 10 grain classes. With

5 grain classes the smallest considered mean grain size measures 25 mm and the largest 600 mm. In the case of 10 grain classes the mean particle diameter ranges from 5 mm to 650 mm.

The grain size distribution of the debris flow material was chosen according to the data that is described in detail in chapter 2.3.2 ($d_m = 100$ mm and $d_{90} = 300$ mm). But large uncertainties exist with respect to the composition of the debris flows substrate, since the constitution of the debris flow material is highly variable. For that reason different model runs were performed using a substrate with a mean particle diameter ranging between 70 and 120 mm.

The riverbed material was not used as a calibration parameter. Thus, the constitution of the substrate of the riverbed in the six different subreaches was chosen according to the observations (figure 4.1) and no further changes were done.

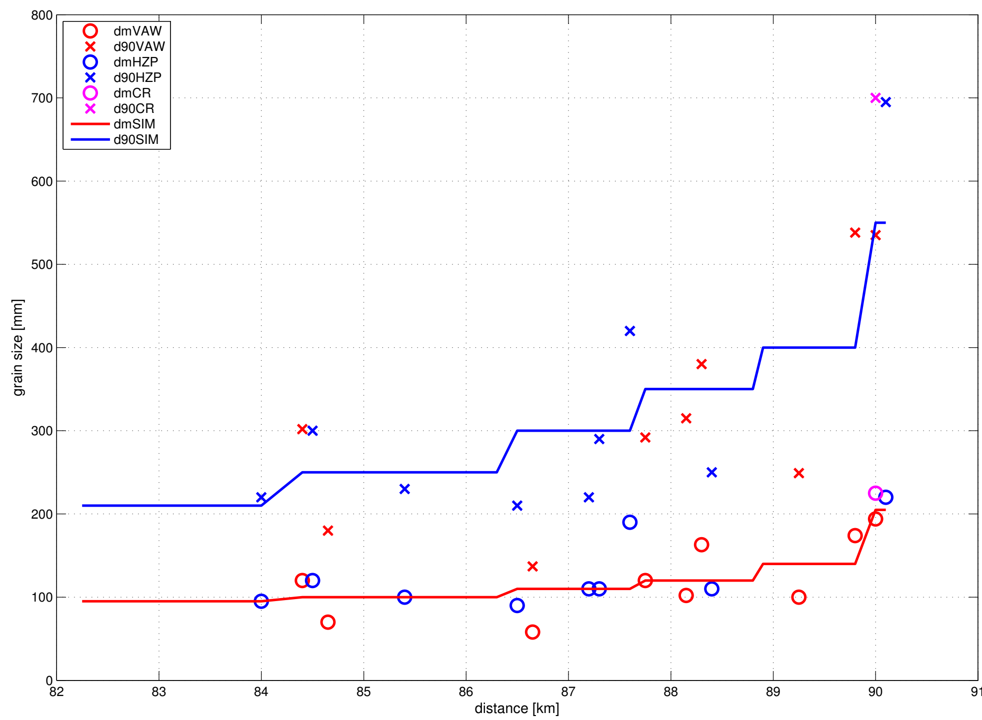

Figure 4.1: *Observed and simulated characteristic grain sizes d_m and d_{90} in the Pfynwald reach.*

4.1.3 Calibration results

Before starting the calibration of the sediment transport model, a closer look at the results of a hydraulic simulation only was taken in order to check if the hydraulic model is working properly. Figure 4.2 shows the water surface elevation, the energy line and the talweg of a pure hydraulic simulation using a steady-state hydrograph of $300\,\mathrm{m}^3/\mathrm{s}$. The result looks reasonable. Numerical problems that one may expect due to the frequent change of the flow regime causing e.g. a rise of the energy line cannot be observed.

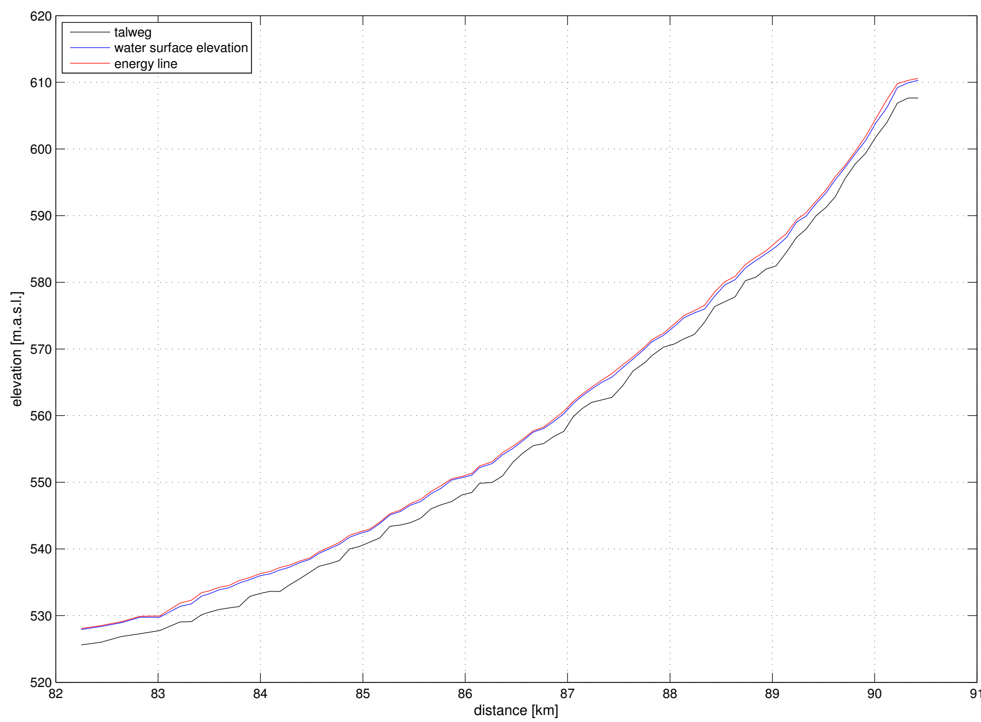

Figure 4.2: *Results of the hydraulic simulation using a steady-state hydrograph of 300* m^3/s*. Illustrated is the talweg (black), the water surface elevation (blue) and the total energy line (red).*

The temporal variation of the riverbed is usually demonstrated by means of a plot of the longitudinal profile of the mean elevation of the riverbed for two or more dates. Since changes in the vertical direction are comparably small with respect to the longitudinal extent of a river section, shifts in the riverbed elevation cannot always be clearly identified. For that reason this study uses a different approach, explained in detail by *Bezzola* (2009), to evaluate the simulation results. The temporal variation of the riverbed is illustrated using a diagram that shows the absolute differences of the mean bed elevation at every cross section for two different dates. With the aid of this plot a so-called transport diagram is computed. On the basis of the mean bed elevation for two different times, the volumes of erosion and deposition at every cross section are calculated. Adding the computed volumes along the considered river section yields the bed load transport in the form of a transport diagram. Sediment that enters the river e.g. through tributaries or gravel that is extracted at gravel pits needs to be added to the transport diagram additionally. For that purpose the extraction volumes as well as the sediment supply have to be known. It is very important that all the sediment volumes are declared consistently with respect to porosity. Particularly in the case of sediment volumes originating from numerical sediment transport computations one has to make sure how porosity is considered. While the volumes of erosion or deposition, gravel extraction and sediment supply already account for porosity, sediment volumes stemming from sediment transport simulations generally estimate pure sediment mass. In this thesis the sediment quantity is always given as a volume including porosity.

The transport diagram is an excellent tool to get an idea of the sediment budget and the general transport behavior of a river. In case the sediment inflow or outflow of the considered river section is known accurately enough, the transport diagram even allows determining sediment transport quantitatively.

A decreasing curve in the transport diagram corresponds to aggradation or sediment extractions in the riverbed. Conversely erosion provokes a rising curve. Locally restricted sediment supply (e.g. tributary) or extraction (e.g. gravel pit) causes an abrupt increase, respectively a sudden decrease of bed load transport.

Upwind

The effect of different values of the upwind calibration parameter is shown in figure 4.3. The green curve illustrates a simulation run with an upwind factor of 1; the magenta curve corresponds to a value of 0.6, the red line to 0.5 and the blue curve to 0.4. The simulations were run with a substrate that is discretized by means of five grain classes. The differences between the simulations are impressive. The graph demonstrates explicitly how important this calibration parameter is in order to avoid numerical instabilities. The most stable simulation runs are achieved with an upwind factor of 0.5. This means that both the data from the upstream and the downstream cross sections are equally used to interpolate the bed load flux in the cell interface.

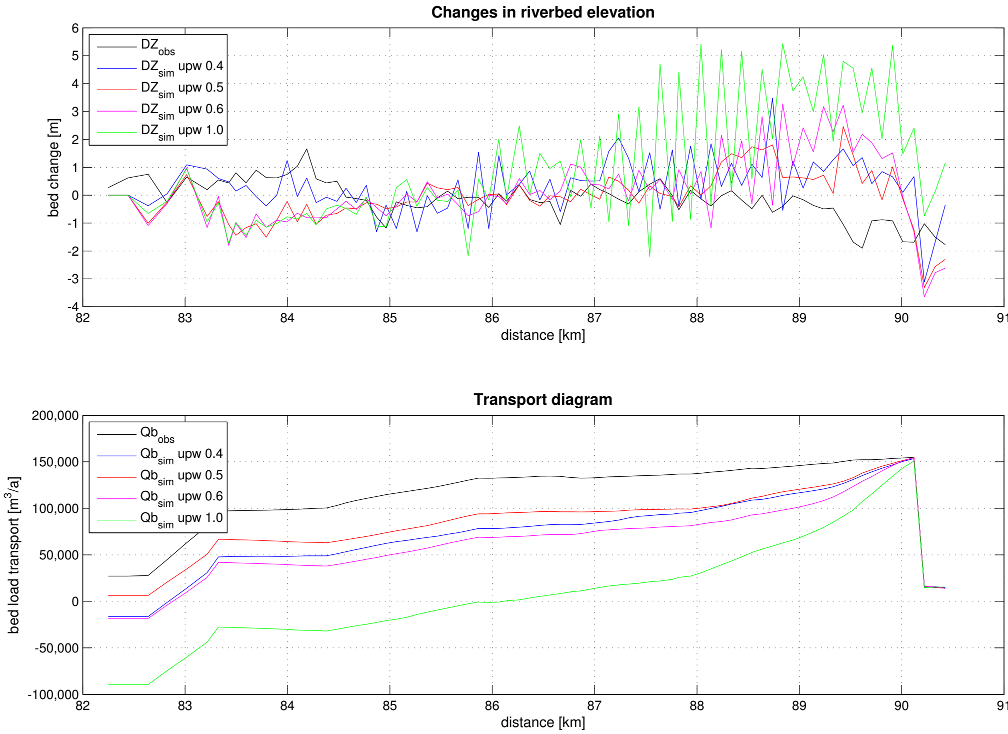

Figure 4.3: *Simulation results using different values for the calibration parameter upwind: Observed riverbed elevation changes (black), upwind of 1.0 (green), upwind of 0.6 (magenta), upwind of 0.5 (red), upwind of 0.4 (blue). An increase of bed load transport in the transport diagram corresponds either to erosion of the channel bed or a sediment supply; gravel extractions or aggradation result in a drop of bed load transport.*

Active layer height

The results of three simulation runs using different heights for the active layer are displayed in figure 4.4. The values of 5 cm, 20 cm and 50 cm were assigned to the active layer height. 10 grain classes were used to represent the gravel bed. Although the differences between the results of the three simulation runs are not very large, some significant features need to be highlighted. At the beginning of the reach there is more bed load transport with a larger active layer height (20 cm and 50 cm). The transport rate then decreases in the central part of the reach due to aggradation. Instead the simulation with an active layer height of 5 cm yields higher transport rates in this river section. Compared to the curves corresponding to the simulations using a height of 20 cm respectively 50 cm, the computation with a small active layer height results in a relatively smooth curve, particularly the sharp peaks at km 83, 83.5, 85 and 86 are damped significantly.

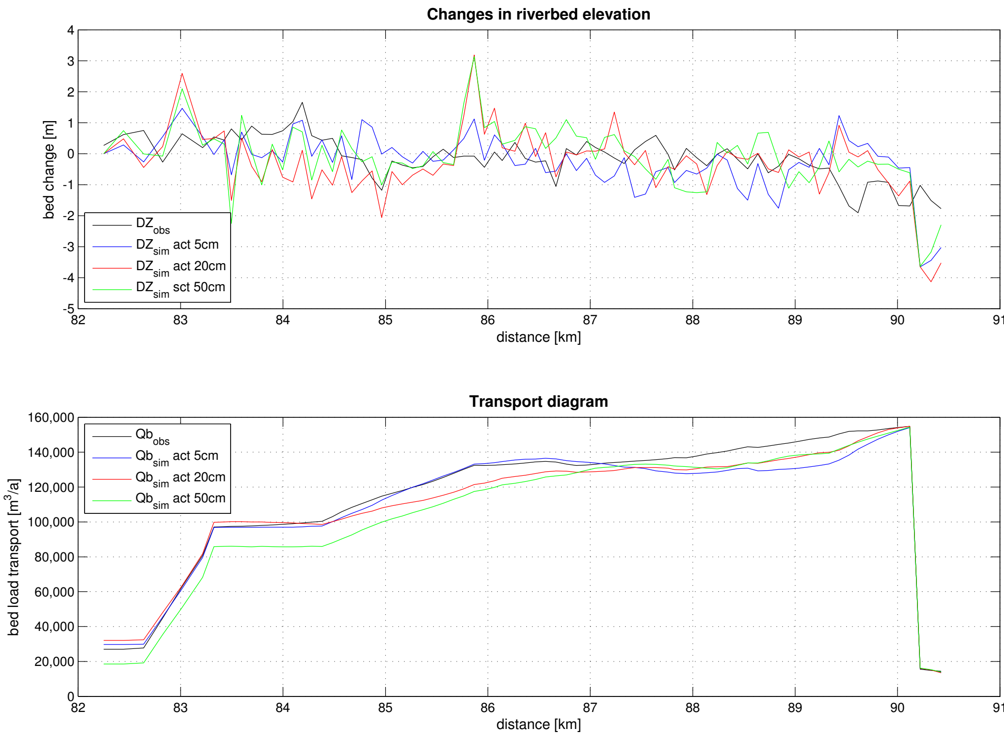

Figure 4.4: *Simulation results using different active layer heights: Observed riverbed elevation changes (black), active layer height of 5 cm (blue), active layer height of 20 cm (red), active layer height of 50 cm (green).*

Sediment composition

Single grain simulation

Several simulation runs were performed using different mean particle diameters. Furthermore it was distinguished between computations considering an armored layer using a critical shear stress and simulations that did not account for a protection layer at all. The visual results of six different model runs are illustrated in figure 4.5. The color indicates the mean grain size used for the simulation. Solid lines represent computations without any consideration of an armored layer, while dashed lines show the results of simulations using a critical shear stress. The black curve indicates the observed changes in riverbed elevation in the calibration period. The upper graph presents observed and simulated changes in the riverbed elevation. The transport diagram is also shown.

None of the simulation runs was able to capture satisfactorily the observed changes in riverbed elevation. Independent of the mean grain size and the consideration of an armored layer, significant deviations to the observations result. In the first few cross sections just at the beginning of the Pfynwald river section, the model consistently

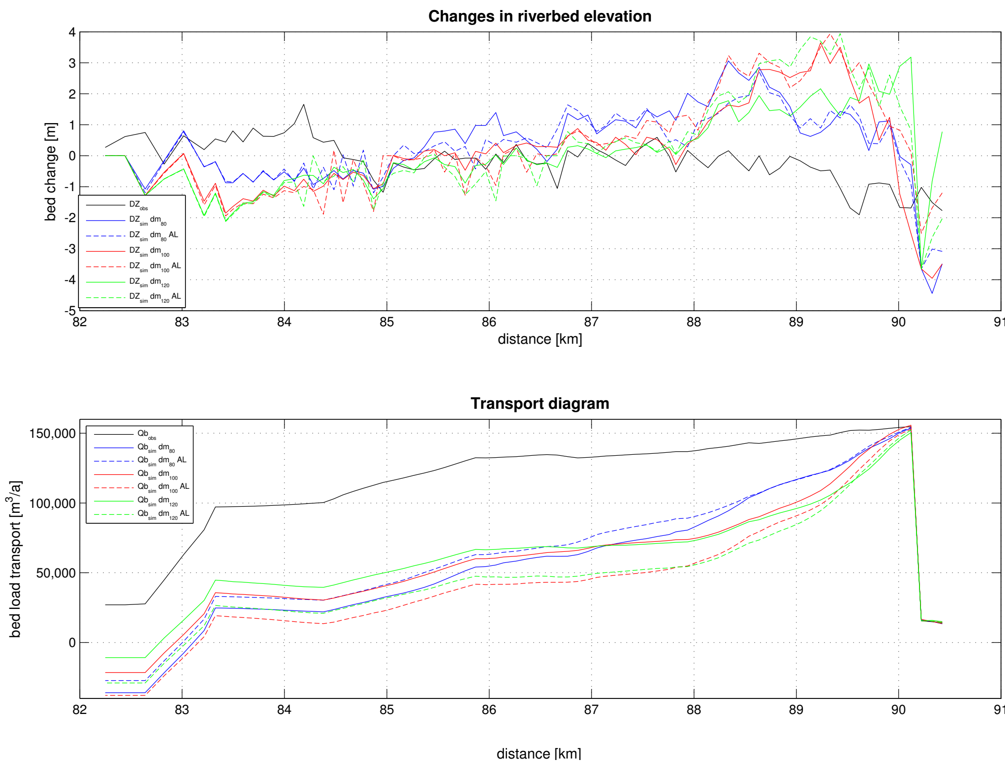

Figure 4.5: *Calibration results of single grain simulations. The upper graph illustrates observed and simulated changes in the riverbed elevation. The bottom graph shows the transport diagram of bed load transport. The color indicates the mean grain diameter, the dashed lines represent simulations with consideration of a critical shear stress. The black curve displays the observations.*

simulates too much erosion. In the following 2-3 kilometers massive aggradation is computed. The extent of the deposition is dependent on the mean particle diameter. With decreasing mean grain size the delivered sediment by the Illgraben is transported further downstream, so that the extent of the aggradation spreads over a lager domain.

In the lower zone (km 83 - 85) in all of the six simulations significant erosion of the riverbed can be observed. This is mainly the result of the absent sediment, which is deposited in the upper part of the river section. Due to the sediment deficit, the transport capacity exceeds the actual transported sediment mass, so that the river erodes the missing sediment from the channel bed. The extensive gravel extraction at the gravel pit located around km 83 intensifies erosion additionally. Naturally there is a trend to aggradation in the lower section of the Pfynwald reach as a consequence of the continuous decrease of the channel bed slope. The gravel pit intends to counteract this trend. However, the model is not able to simulate the trend to aggradation in the lower part, so that the riverbed is eroded artificially in the area of the gravel pit. The magnitude of the channel bed erosion decreases with smaller mean particle diameter, because more sediment is transported to the lower areas of the Pfynwald reach.

The transport diagram reflects the riverbed changes quite well. The massive aggradation at the beginning of the reach causes a dramatic drop of bed load transport. Roughly two-thirds of the supplied sediment by the Illgraben is deposited within the first two kilometers after the confluence with the Illgraben. In reality bed load transport remains at a very high rate, so that most of the debris flow material is transported further downstream. On average, the computations of bed load transport result in a deficit of about 60'000 to 70'000 m^3/a in the Pfynwald reach. In the lowest section of the reach the model computes even a negative bed load transport rate, which seems to be quite strange, just as the fact that the simulation with a mean grain diameter of 80 mm (blue curve) yields the largest sediment transport deficit. One actually would expect the opposite, meaning that coarser gravel would result in a decrease of transport capacity. These effects remain unexplained.

The use of a critical shear stress affects the simulation results only marginally. In general, the use of a critical shear stress amplifies the magnitude of the aggradation. The effect is more pronounced, the larger the considered mean particle diameter is.

Multiple grain size simulation

In the following the results of a couple of simulations using either different numbers of grain classes or variable compositions of the debris flow material are presented.

Figure 4.6 shows the effect of using different **multiple grain classes**. The results of a single grain simulation (blue) and two multigrain simulations (5 grain classes: red, 10 grain classes: green) are illustrated. Again all of the simulations show massive erosion at the beginning of the reach. Most probably this is caused by effects triggered by the definition of the upper boundary condition. The main differences occur in the river section that follows after the confluence of the Illgraben. In principle, the magnitude of the aggradation increases with decreasing number of grain classes. While in case of the 10 grain class simulation the riverbed elevation does not show a significant change in this area, the single grain simulation results in very large deposition of up to 3 meters. If one also considers the huge channel width in this area (100 to 250 m) the deposited sediment volume is substantial. Nearly all of the supplied sediment by the Illgraben is deposited in this river section. Beside the vertical shift, all of the three curves show a similar progression in the first two kilometers. This indicates a consistent model behavior, meaning that simulated channel change is caused by the different model set ups and not by randomness or numerical instabilities.

The simulation using 10 grain class generally fits the observations best. No aggradation at all is computed in the confluence area. This means that the computed transport capacity is sufficient enough to carry away the debris flow material that enters the Rhone River. However, the transported sediment then causes some problems in the lower sections of the Pfynwald reach. In the central part of the reach as well as at the end anomalous aggradation is computed in the 10 grain class simulation run. Both the simulations with a single grain and the one with five grain classes yield a smoother and more continuous curve.

A significant difference to the observed riverbed change can be observed in the area between km 83 and 85. The model consistently simulates a trend to erosion independently of the employed number of grain classes.

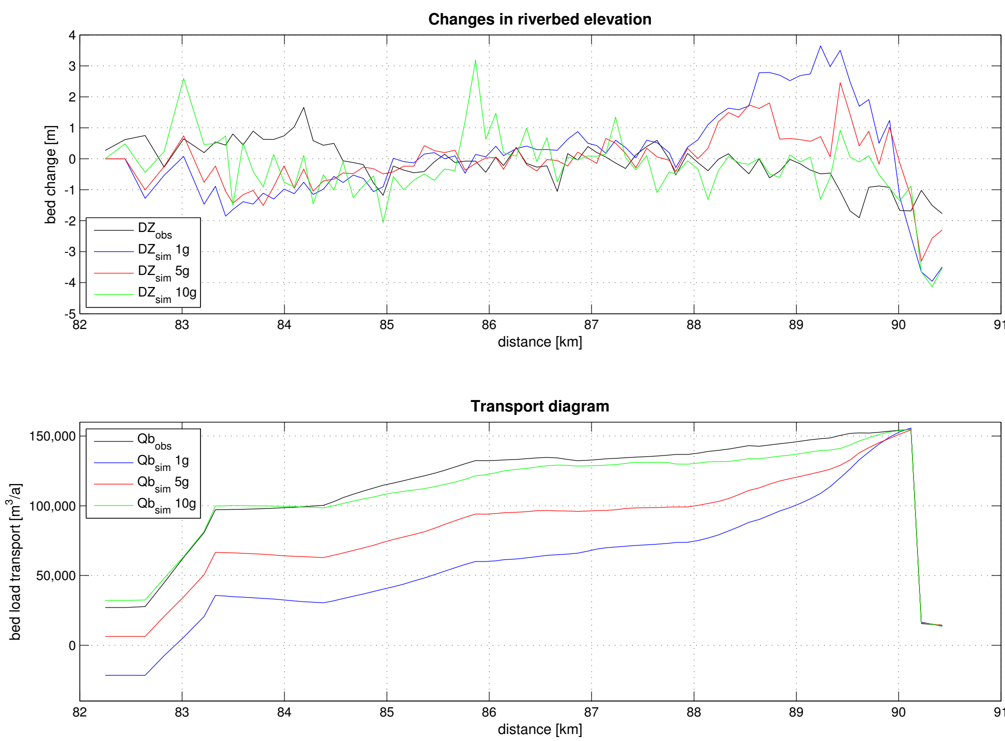

Figure 4.6: *Simulation results using different numbers of grain classes: Observed riverbed elevation changes (black), Single grain simulation (blue), Simulation with 5 grain classes (red), Simulation using 10 grain classes (green).*

The model sensitivity to the **composition of the substrate of the debris flows** from the Illgraben is illustrated in figure 4.7. To see if there is a different behavior for varying numbers of grain classes, a set of three simulations was performed for grain mixtures represented by 5 respectively 10 grain classes. The colors indicate the different material compositions. The red curve corresponds to the simulation with the observed grain size distribution ($d_m = 100$ mm), the simulation runs with a finer substrate ($d_m = 80$ mm) as well as a coarser material ($d_m = 120$ mm) are indicated with a blue respectively a green curve. Solid lines correspond to the 5 grain class simulations; the simulation results using 10 grain classes are plotted with dashed lines. For the sake of readability the riverbed elevation changes for the two different numbers of grain classes are illustrated in two separate plots.

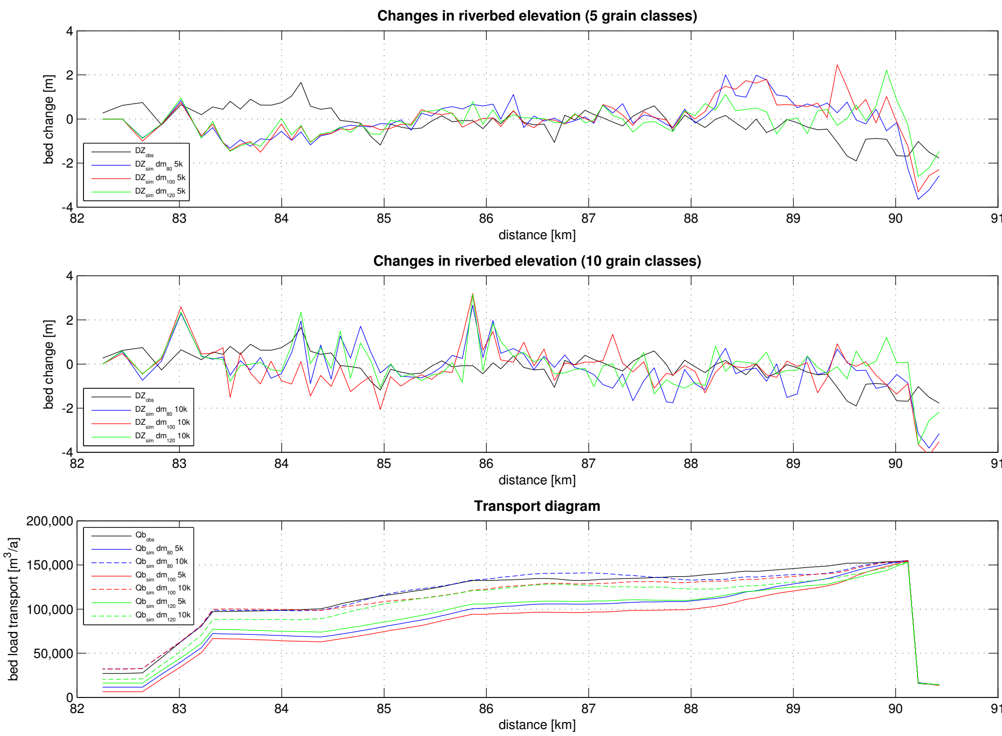

Figure 4.7: *Simulation results using different compositions of the debris flow material: Observed riverbed elevation changes (black), finer substrate with a d_m of 80 mm (blue), observed grain size distribution with a d_m of 100 mm (red), coarser material with a d_m of 120 mm (green). In the transport diagram solid lines correspond to simulations with 5 grain classes; the results of 10 grain classes are illustrated with dashed lines.*

The main differences corresponding to a varying debris flow material are limited to the area of the confluence of the Illgraben. The results differ not only with respect to the composition of the substrate but also with regard to the number of applied grain classes. The effect of different grain mixtures increases in case of fewer grain classes. The results of the 10 grain class simulations show only minor differences in the range of the confluence. There seems to be somewhat more deposition using a substrate with a mean diameter of 120 mm. There is much more variability in the results of the 5 grain class simulations. All of the three simulations result in aggradation in the river section after the confluence of the Illgraben. However, the spatial extent of the deposition is dependent on the composition of the debris flow material. Generally the sediment supply by Illgraben is transported further downstream, the finer the material is. It seems that the simulation run with a mean diameter of 120 mm yields the least deposition. Effectively that is not true, because one has to consider the riverbed width. Just at the location of the largest simulated aggradation, the channel bed exhibits its maximum width of 250 m. The channel bed width then decreases rapidly to 100 to 150 m.

A further discrepancy between the simulations using different numbers of grain classes can be observed in the lower section of the Pfynwald reach. In case of the 5 grain class simulation the differences between the results become smaller with increasing distance to the confluence of the Illgraben. The lowest part of the Pfynwald reach is not anymore affected by the choice of the substrate composition, so that the simulation results are nearly identical. By contrast the varying composition of the debris flow material has an effect on the whole Pfynwald river reach in the 10 grain class model.

4.1.4 Best fit

On the basis of the insights gained in the course of the calibration of the model, the parameters of the model were adjusted in such a way that the simulation result fits best the observations in the calibration period. The results were evaluated visually by means of the generated output plots of the change of the riverbed elevation and the transport diagram. The result of the model configuration that fits the observations best is illustrated in figure 4.8. The sediment was discretized using 10 grain classes. A substrate with a mean diameter of 90 mm was assigned to the debris flow material. The upwind parameter was set to 0.5 and an active layer height of 5 cm was chosen.

The model is able to simulate the observed processes more or less satisfactorily. Apart from the large deviations in the first few cross sections, which are likely due to boundary effects the simulated riverbed elevation changes are in the range of the observed ones. The model captures the trend to erosion in the uppermost two kilometers of the reach. In the central part (km 85 to 89) the model reproduces correctly the observed trend to a stagnant riverbed, except for the section between km 87 and 88, where the model computes slight erosion. The observed aggradation in the lowest section is underestimated. Though, an overall trend to deposition in this final section can be noticed in the simulated change of the riverbed elevation.

According to the transport diagram bed load transport is simulated correctly by the model. The computed bed load transport rate corresponds reasonably well to the observations. If one also accounts for the likely errors in the observations, the simulated bed load lies definitely within the range of uncertainty.

The temporal evolution of the mean riverbed elevation at six different cross sections is

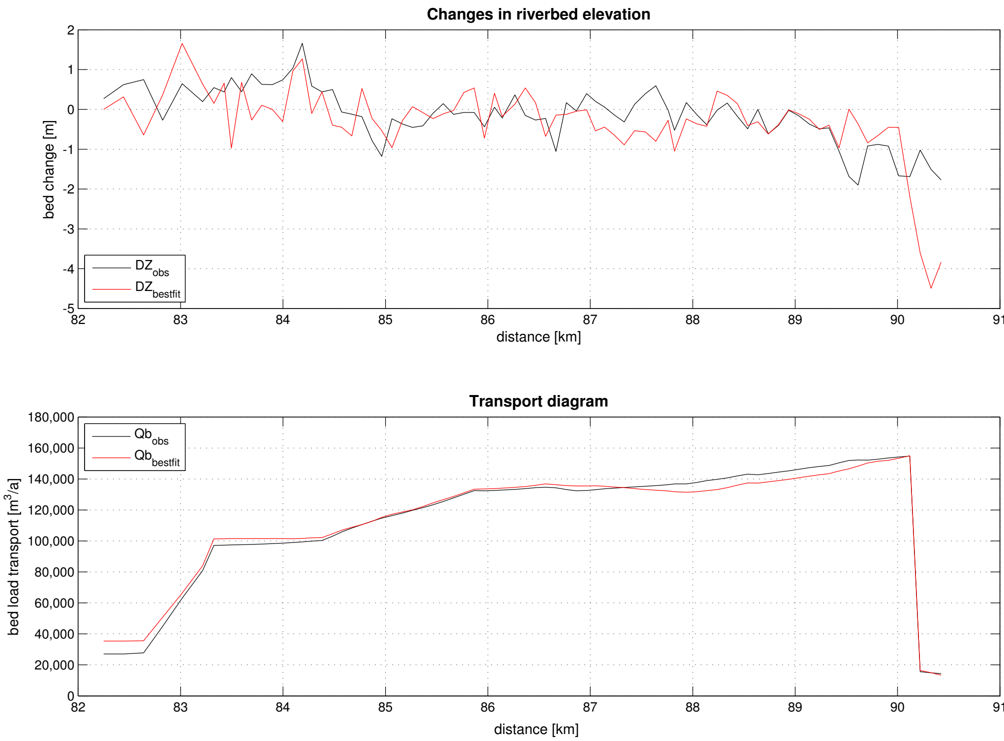

Figure 4.8: *Simulation results of the model configuration that fits the observations best. Multi-grain simulation with 10 grain classes; debris flow material with a mean particle diameter of 90 mm; upwind parameter = 0.5; active layer height = 5 cm.*

shown in figure 4.9. The observations are presented in black, while the simulated riverbed elevation is illustrated with a red color. With the aid of these plots, one can evaluate the performance of the model in capturing the observed progression of the riverbed. Generally there is quite a large discrepancy between the two curves, independently of the considered cross section. The best match results at cross section 4F, which is located just at the end of the Pfynwald reach. In cross sections 30, 46 and 63 the model even computes the evolution of the channel bed elevation in a converse manner. Concerning the cross section at the confluence of the Illgraben (CS 4), the model is able to capture the long-term trend to a subsidence of the riverbed, but it does not reproduce the massive aggradation in the years 1998 and 1999.

Looking just at the observed progression of the riverbed, a pulsation of the channel bed elevation can be identified. The large aggradation at cross section 4 in the year 1998 propagates downstream and shows up in the graph corresponding to cross section 16 in the year 2001. The magnitude of the absolute riverbed change has decreased from 2.5 m at cross section 4 to 1.5 m at cross section 16. With increasing distance to the confluence of the Illgraben it becomes more difficult to allocate a particular detail to its initial feature at cross section 4, because the different pulses are damped and they may also interfere with each other. However, a pulsation of the riverbed can also be observed further downstream as the plots of the cross sections 46 and 63 illustrate very well.

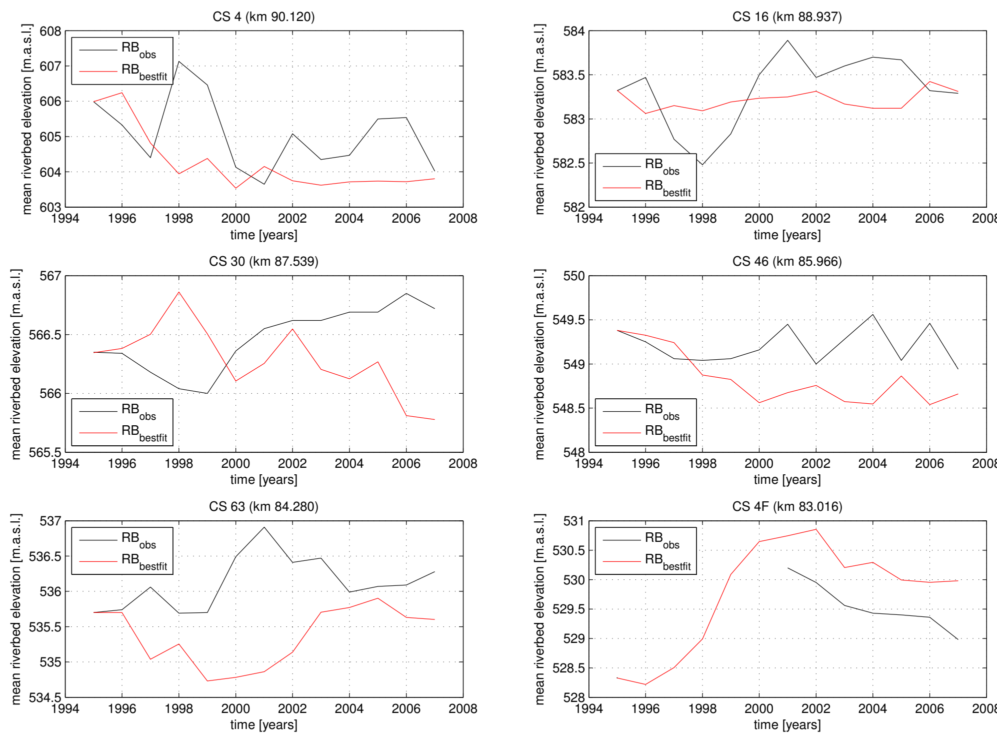

Figure 4.9: Temporal evolution of the riverbed elevation in the period 1995 to 2007 at six different cross sections. Black illustrates the observations; the results of the best fit simulation is shown in red.

4.2 Project BASEplane (2D)

Contrary to BASEchain, a calibration of the hydraulics was performed in case of the two dimensional model BASEplane. The calibration method is based on an orthorectified aerial photograph and a digital elevation model produced at approximately the same time. The orthorectified SWISSIMAGE was taken on August 5th 2005, and the digital elevation model dated either in March or May 2005. Both data records are provided by Swisstopo. Regrettably the exact date of the flight for the DEM is not available. We consider these data to be suitable for the calibration because in between the date of the DEM and the SWISSIMAGE the topography of the riverbed was not affected by major changes. The goal of the calibration process was to determine the values of the roughness coefficients of the riverbed, so that the simulated wet area fits best the area that is inundated by water on the SWISSIMAGE.

4.2.1 Input data

As already mentioned in chapter 3.1.2 the 2005 digital elevation model was used as a basis to generate the mesh, on which the two dimensional simulations were done. The inflow boundary condition was defined as a steady-state hydrograph of $60\,\mathrm{m}^3/\mathrm{s}$, since this discharge was observed in the Pfynwald reach at the time the SWISSIMAGE was taken. For the outflow boundary condition the option 'zero gradient' was used. In this case a zero gradient is assumed at the outflow cross section. The calibration runs were all started with the initial state 'dry' and they were run until a steady state solution was reached. Depending on the employed friction factor, the simulation time needed to establish a steady state varied between one and two hours.

4.2.2 Calibration parameters

The roughness coefficient of the riverbed was the only parameter that was considered in the calibration process. The model domain was subdivided into three areas of similar channel bed roughness and two additional areas representing embankments and the floodplain (figure 4.10). A first guess for the roughness coefficient was obtained using the formula according to the friction concept of Strickler:

$$k_{st} = \frac{21}{\sqrt[6]{d_{90}}}$$

In order to find out the value for the roughness coefficient that yields the best fit, several simulation runs were performed, varying the Strickler friction factor from 1 to $40\,\mathrm{m}^{1/3}/\mathrm{s}$. While the roughness coefficient was changed in one area, in the rest of the

Figure 4.10: *Subdivision of the 2D model domain into five different areas (brown: bed1, red: bed2, blue: bed3, yellow: embankments, green: floodplain).*

domain it was kept constant. This ends up in a total of 120 calibration runs (3 different areas x 40 different friction factors).

The parameters for sediment transport computations could not be calibrated due to a lack of appropriate data. The calibration requires at least one pair of digital elevation models covering the same area on two different dates. For this thesis just one DEM was available. This data was used as initial topographic boundary condition for the simulations. A second digital elevation model that could have been used as reference topography is mandatory in order to evaluate the performance of the sediment transport and erosion/deposition computations and to adjust the model parameters.

4.2.3 Calibration results

To validate the performance of the model, an objective accuracy measure called sensitivity and specificity was applied. This validation scheme is normally used for the evaluation of mathematical models in natural hazard analysis (*Begueria*, 2006). Usually a continuous response variable expressing the degree of hazard is given. One then has to set a classification threshold to divide the variable into two classes. These two classes separate the cases predicted as safe and those as unsafe. Together with the frequency distributions of observed cases with the dangerous characteristics and without it, the so-called confusion matrix can be built. Instead of using standard accuracy statistics, the confusion matrix (or contingency table) is used to compute an alternative set of statistics that does not depend on prevalence (different proportion of positive and negative cases). This set of statistics is called sensitivity and specificity. The sensitivity of a model describes the proportion of the positive cases correctly predicted. The specificity is defined as the proportion of the negative cases correctly predicted.

At first glance, the transfer of the sensitivity/specificity accuracy statistic to the evaluation of a hydrodynamic model is not trivial. In fact the application of this method to the present study was not straightforward. Originally a classification threshold for the continuous response variable has to be defined in order to separate the models predictions into positive and negative cases. In case of a hydrodynamic model an actual response variable does not exist. However, one can declare the roughness coefficient to be the virtual continuous response variable. The performance of the model is then evaluated by means of the nodes of the mesh. The number of nodes in the model domain defines the size of the sample. A simulation run with one particular roughness coefficient (classification threshold) assigns a binary number, 0 or 1 corresponding to dry or wet, to every node. The confusion matrix is built by means of the comparison of the simulated and the observed wet areas (see table 4.2). A confusion matrix has to be computed for every simulation run, which results in this case in a total of 40 confusion matrices for each characteristic riverbed section. Subsequently the model's sensitivity and specificity can be determined with the aid of the confusion matrix.

Table 4.2: *Confusion matrix (or contingency table). a: true positives, b: false positive (error type I), c: false negatives (error type II), d: true negatives.*

	observed	
predicted	dry	wet
dry'	a	b
wet'	c	d

In order to obtain the optimal roughness coefficients a ROC (receiver-operation characteristics) plot was generated. In natural hazard analysis this plot shows accuracy statistics over a range of thresholds. The area under the ROC curve is used as a global accuracy statistic for a model (*Begueria*, 2006). In the present study not an actual threshold was used, but simulations were run over a range of friction factors. Hence, the different accuracy values obtained by means of the confusion matrix were plotted against the whole range of applied friction factors. As an example, the ROC plot for bed 2 is shown in figure 4.11. The ROC plots of the other bed sections can be found in the appendix B.

On the x-coordinate specificity is plotted, the y-coordinate represents the sensitivity of the model. For every simulation run a different pair of sensitivity and specificity is plotted. The values of sensitivity and specificity indicate the ability of the model to correctly predict wet and dry nodes. A sensitivity of 1 denotes that all positive observations (wet node) have been simulated correctly. On the other hand a specificity of 1 means that the model captures correctly all the negative observations (dry nodes). In case of a perfect model, both sensitivity and specificity have to be 1. In the ROC

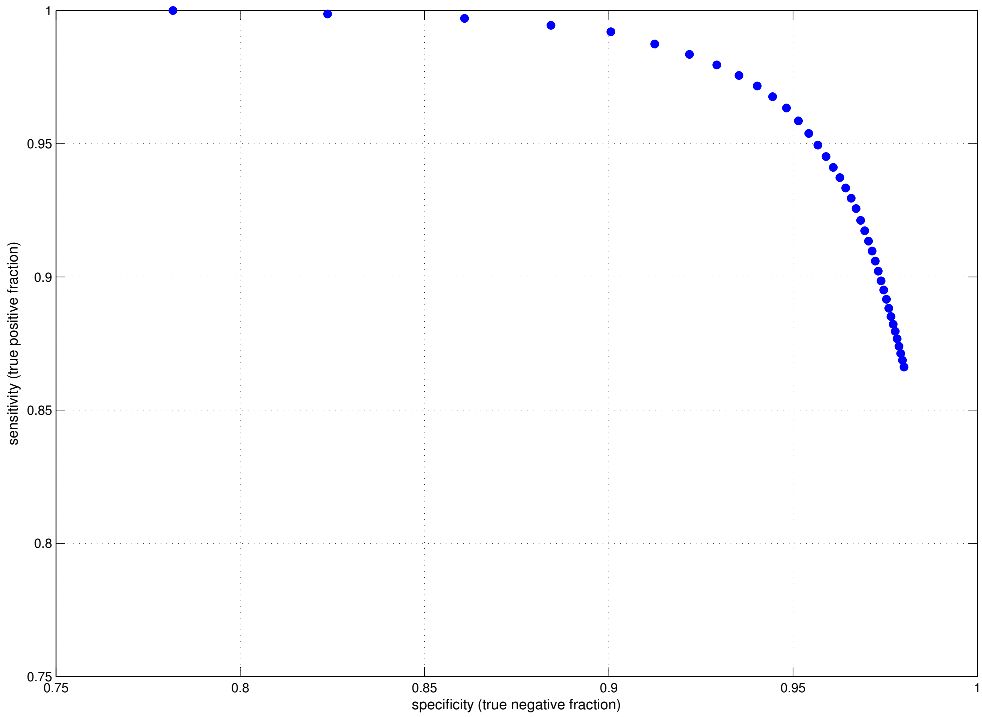

Figure 4.11: *Receiver-operation characteristics (ROC) plot at the example of bed 2.*

plot the sensitivity/specificity pair of a perfect model would be situated in the upper right corner. Consequently a model performs well, the closer the corresponding pair of sensitivity and specificity lies to the upper right corner in a ROC plot.

To determine the roughness coefficient for which the model performs best, an accuracy statistic T = sensitivity + specificity is defined. Plotting this statistic as a function of the roughness coefficient allows us to objectively define the best value for the friction factor (figure 4.12). The best model performance is achieved at the maximum value of T. The values for the optimal as well as the computed Strickler roughness coefficients are summarized in table 4.3.

Table 4.3: *Calibrated and computed roughness coefficients.*

	bed 1	bed 2	bed 3
calibrated roughness coefficient	$33\,m^{1/3}/s$	$11\,m^{1/3}/s$	$12\,m^{1/3}/s$
roughness coefficient according to d_{90}	$35\,m^{1/3}/s$	$23\,m^{1/3}/s$	$25\,m^{1/3}/s$

Using the Strickler formula to compute the friction factor on the basis of the characteristic grain diameter d_{90}, results in larger values. A large Strickler roughness coefficient corresponds to a smooth channel bed. This means that the Strickler formula underestimates the roughness of the riverbed. The empirical formula according to Strickler just takes into account the friction that is induced by the grains of the gravel bed. However the total roughness of a channel bed consists not only of the grain friction, bedforms also play a very important role, especially in case of a braided river. Bedforms such as riffles, dunes, antidunes and gravel banks cause additional friction losses. In case of the Pfynwald reach the bedform fraction seems to be very high, decreasing the roughness coefficient of the channel bed for more than 10 Strickler units.

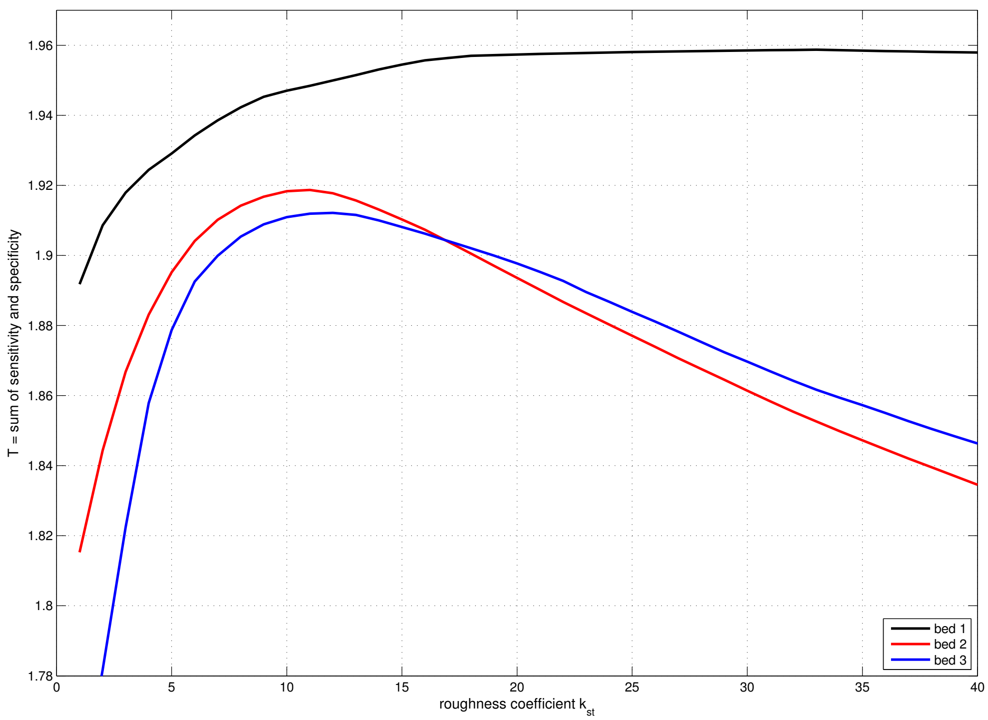

Figure 4.12: *Accuracy statistic T = sensitivity + specificity.*

Finally the best fit of the model for the whole domain is achieved by combining the respective optimal friction factors of the three different riverbed sections. The visual result is illustrated in figure 4.13. The graph shows the simulated water depth; in the background the orthorectified SWISSIMAGE from August 2005 is visible. This combination allows a visual compromise of simulated wet areas and observed ones. At this point is has to be mentioned again, that the DEM and the SWISSIMAGE are not taken exactly at the same date, so that minor changes are ascribed to this circumstance.

The application of the sensitivity/specificity accuracy measure highlights the excellent performance of the model. The models sensitivity adds up to 0.93 and the specificity is 0.99, resulting in a T-value of 1.92. A T-value of 1.9 and more is outstanding, since a perfect model would end up with a T-value of 2.0. In other words, the model is able to predict correctly 93% of the wet nodes and 99% of nodes that are observed to be dry.

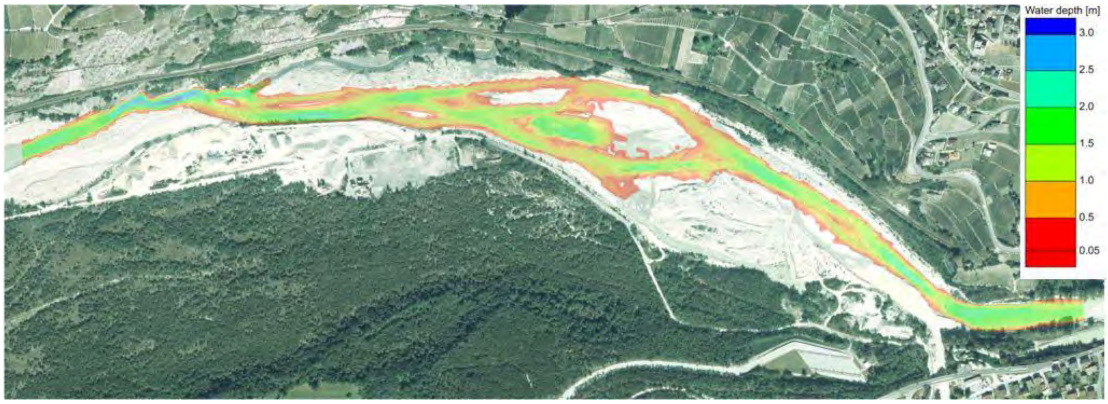

Figure 4.13: *Visual result of the best fit of the 2D model. The graph illustrates the simulated water depth. In the back the orthorectified SWISSIMAGE from August 2005 is displayed.*

Chapter 5

Scenario analysis

5.1 Project BASEchain (1D)

This section presents the results of four scenarios addressing two different issues. First the sensitivity of the Pfynwald river reach with respect to sediment extraction was studied, second the impact of a variable sediment supply from the Illgraben was investigated. For the scenario analysis the 10 grain class model with the best calibrated parameter set and the adjusted sediment composition according to section 4.1.4 was used. The investigations are restricted to the same 12 year-period that was used for the calibration of the model. The topography observed in autumn 1995 was applied as the initial riverbed. Discharge was simulated with the observed hydrograph that was used for the calibration of the model. An overview of the performed simulations in the different scenarios is given in table 5.1.

Table 5.1: *Overview of the investigated scenarios using the one dimensional model BASEchain.*

scenario	sediment supply		gravel extraction	hydrograph
	weir Susten	Illgraben		
no gravel extraction	15'000 m^3/a	140'000 m^3/a	no extraction	continuous hydrograph of 1995 - 2007
low supply by Illgraben (50 %)	15'000 m^3/a	70'000 m^3/a	extraction according to table 2.2	continuous hydrograph of 1995 - 2007
high supply by Illgraben (150 %)	15'000 m^3/a	200'000 m^3/a	extraction according to table 2.2	continuous hydrograph of 1995 - 2007
very high supply by Illgraben (200 %)	15'000 m^3/a	280'000 m^3/a	extraction according to table 2.2	continuous hydrograph of 1995 - 2007

5.1.1 Sensitivity to sediment extraction

Just one scenario was considered with respect to the sensitivity of the Pfynwald reach to sediment extraction. Thereby a simulation was performed without any gravel extraction along the reach. The result is presented in figure 5.1. Besides the outcome corresponding to the scenario (red), the graph shows the results of the calibrated best fit (blue) and the observations for the period of 1995 to 2007 (black). Stopping gravel extraction has some implications on the evolution of the riverbed. Right at the confluence of the Illgraben the trend to erosion of the channel bed ceased. Instead the riverbed between km 87 and 89 experiences degradations of up to 1.5 m due to erosion. In the lowest section of the Pfynwald reach significant aggradation with a magnitude between 1 and 3.5 m develops.

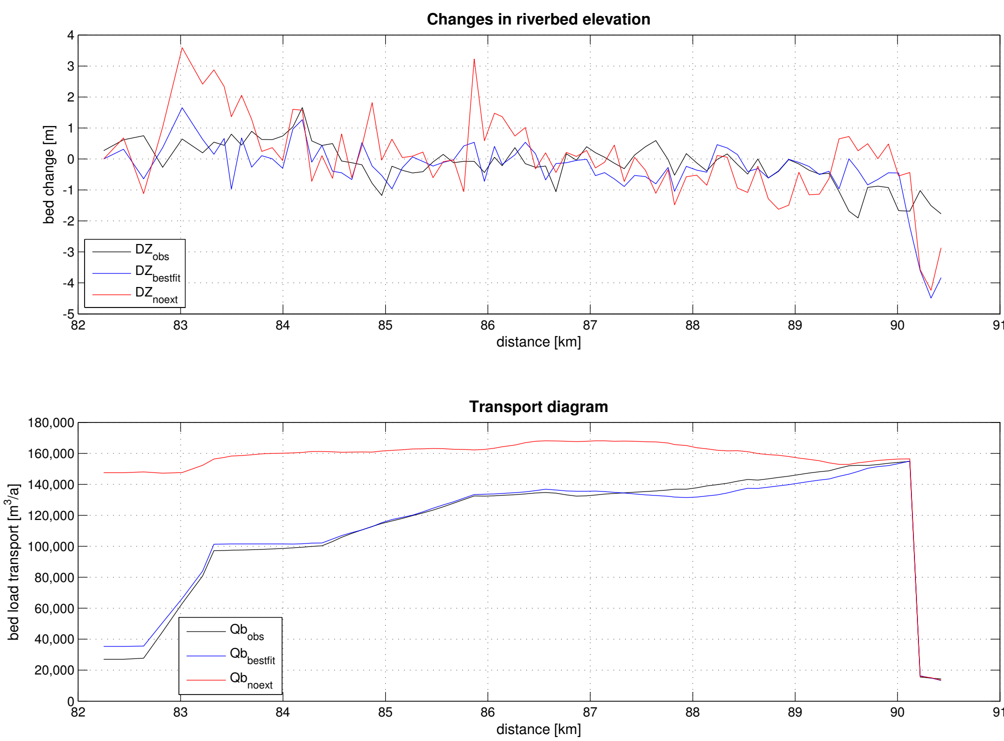

Figure 5.1: *Result of the scenario with no gravel extraction. The black curve corresponds to the observations in the period of 1995 to 2007; the blue color indicates the results of the best fit; the results of the scenario without gravel extraction are shown in red.*

In the scenario run with no gravel extraction bed load transport remains at a very high rate for the entire Pfynwald section. This implies that nearly all of the delivered sediment by the Illgraben (140'000m^3/a) is transported through the reach and leaves the study area at Sierre. The increase of bed load transport in the upper section due to erosion of the riverbed is compensated by massive aggradation in the lowest 2 km of the reach. At the lower end of the Pfynwald reach a difference in bed load transport of roughly 120'000m^3/a results between the scenario with no extraction and the observations. This corresponds approximately to the annual mean sediment volume that is extracted at the gravel pits (see table 4.1).

The overall good impression of the simulation results is compromised by some very sharp peaks between km 84 and 86. These unnatural features are presumably induced by numerical instabilities or inconsistencies in the model.

5.1.2 Sensitivity to sediment supply by the Illgraben

The sensitivity of the Pfynwald reach to a variable sediment supply by the Illgraben was investigated by means of three different simulation runs. Thereby the delivered sediment by the Illgraben was assumed to amount to 70'000 m^3/a, 200'000 m^3/a respectively 280'000 m^3/a corresponding to 50 %, 150 % and 200 % of the actually observed mean annual supply between 1995 and 2007. The simulated changes of the riverbed elevation and the bed load transport rate are presented in figure 5.2. Besides the three scenario runs, the results of the calibrated best fit with a supply of 140'000 m^3/a as well as the observations are plotted. In general no significant differences can be observed between the different simulations, which implies that either the Pfynwald reach or even more likely the model is not very sensitive to the supplied sediment. Not even a doubling of the delivered debris flow material causes aggradation in the Pfynwald reach. The most significant response is for a reduced supply of 70'000 m^3/a. Around km 89 the model computes relatively large erosion of the channel bed.

The transport diagram points out that the sediment outflow at the downstream boundary of the Pfynwald reach is directly proportional to the delivered sediment volume by the Illgraben.

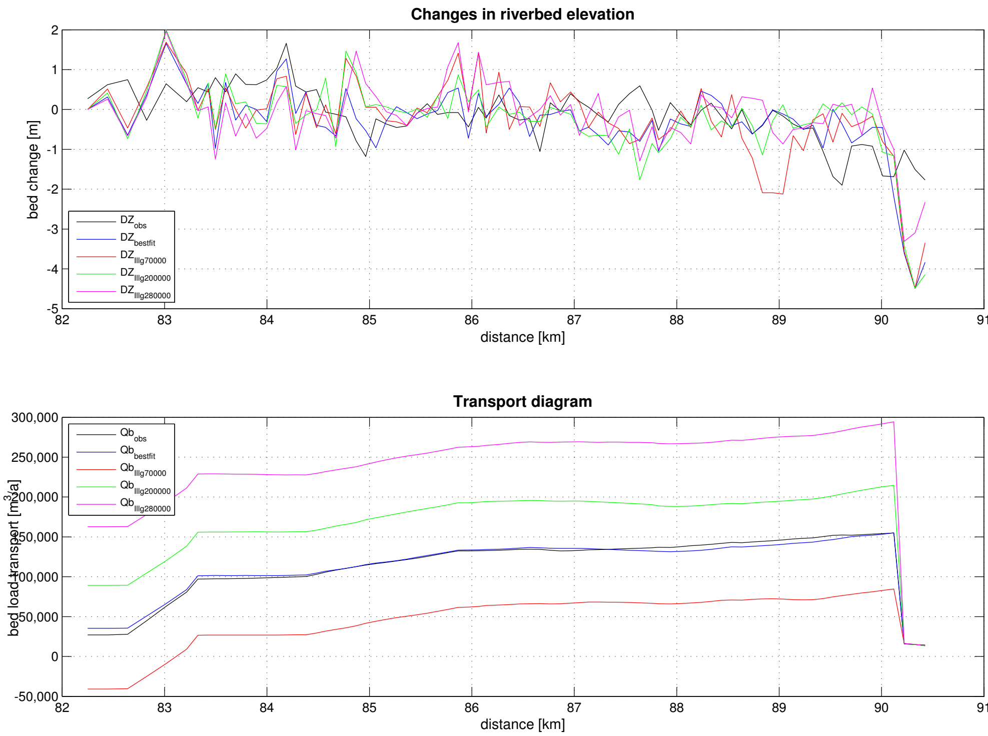

Figure 5.2: *Result of the scenario modeling different supplies by the Illgraben. Three different delivered sediment volumes are shown: 70'000 m^3/a (red), 200'000 m^3/a (green) and 280'000 m^3/a (magenta). Additionally the observations (black) and the best fit (blue) are plotted.*

5.2 Project BASEplane (2D)

Two different scenarios were run with the hydraulically calibrated two dimensional sediment transport model BASEplane. The sediment was discretized with the same 10 grain classes used for the simulations with the one dimensional model BASEchain. Thus, sediment transport is computed fractionally. Consequently the model is able to account for sorting effects. Both simulations were performed using a mobile riverbed in order to investigate the spatial changes of the channel bed elevation. Discharge was modeled with a steady-state hydrograph. In a first setting a sediment inflow at the upper boundary at the weir at Susten was simulated. The second scenario addresses the sediment supply by the Illgraben. The results of the simulations are described in the following sections. An overview of the performed simulations in the two different scenarios is given in table 5.2.

Table 5.2: *Overview of the investigated scenarios using the two dimensional model BASEplane.*

scenario	sediment supply		gravel extraction	hydrograph
	weir Susten	Illgraben		
sediment boundary condition	0,1 m^3/s	no input	no extraction	steady-state hydrograph of 400 m^3/s
debris flow event	no input	25'000 m^3/h	no extraction	steady-state hydrograph of 400 m^3/s

5.2.1 Simulation of the sediment inflow at the upper boundary condition

In case of a flood in the Rhone, bed load passes the weir at Susten and enters the Pfynwald reach. This section is dedicated to the simulation of this scenario. Thereby the delivered sediment from upstream is inserted into the model domain as upper boundary condition. A steady-state sediment flux of 0.1 m^3/s was taken to represent the bed load inflow. The simulation was run for one hour, so that a total of 360 m^3 of sediment entered the model domain. The constitution of the supplied material was modeled with a mean particle diameter of 60 mm. Discharge was simulated by means of a steady-state flow rate of 400 m^3/s. The definition of the initial condition was done with the aid of an old hydraulic simulation.

Figure 5.3 shows the simulated changes of the riverbed. Erosion is indicated with blue colors; aggradation is shown with yellow to brown colors. The magnitude of the channel bed changes ranges from erosion in the order of 1 m to deposition up to 2 m. Two main sections of riverbed changes can be identified. On the one hand the area right at the confluence of the Illgraben is affected by major erosion of the channel bed. Thereafter a section of alternating erosion and aggradation follows. On the other hand there are significant riverbed changes in the lowest part of the study area. The observed pattern of erosion and deposition reminds one strongly of an alternating bar morphology. Right at the beginning of the model domain the model computes locally large aggradation, which is adjacent to a node with significant erosion. This phenomenon is certainly related to the definition of the sediment inflow boundary condition. Surprisingly no riverbed changes are simulated in the central part of the study area.

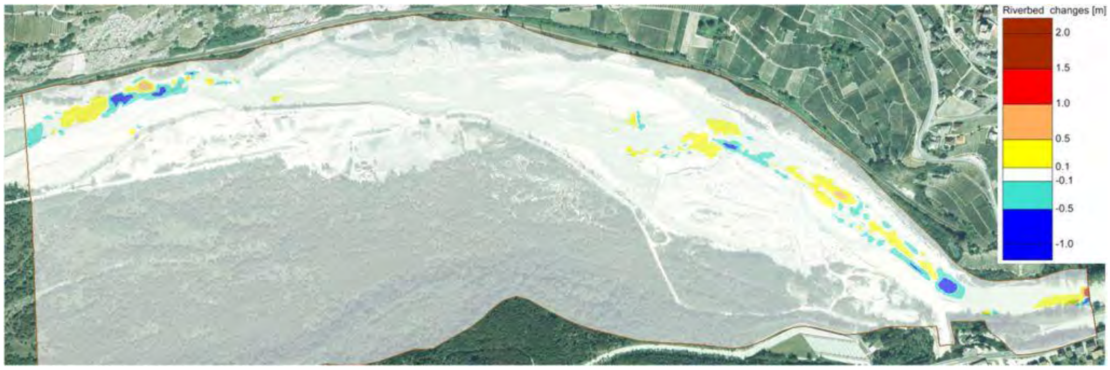

Figure 5.3: *Simulated riverbed changes with a sediment flux at the upper boundary after a simulation time of one hour. Erosion is highlighted with blue colors. The yellow to brown colors correspond to aggradation.*

5.2.2 Simulation of a debris flow event

The sediment supply by the Illgraben was simulated in this scenario using the example of a medium-sized debris flow with a sediment volume of 25'000 m^3. For the discharge again a steady-state flow rate of 400 m^3/s was applied. An old hydraulic simulation was used to define the initial condition. The simulation was run for two hours, whereas the supply of sediment was limited to the first hour. The debris flow cannot be modeled as a flowing viscous mixture of sediment and water, like it is observed in nature. The sediment is inserted into the channel by means of an external source. The substrate is then brought into the model domain via the nodes of the defined source area. The composition of the debris flow material was defined according to the observed grain size distribution of one particular event (see section 2.3.2).

The visual representation of the simulated spatial riverbed changes is shown in figure 5.4. Striking is the massive sediment deposit that has developed in the area of the confluence of the Rhone River and the Illgraben. The extent of the deposition corresponds very well to the area of the external source, at which the sediment is introduced to the model. According to figure 5.5 the accumulated sediment acts like a dam, so that the water is retained behind the confluence. The figure shows the simulated water depth as well as the vectors of the flow velocity. The flux-vectors indicate that the water flows around the massive sediment plug (16 m high), whereby it is accelerated. As a result some erosion of the floodplain along and after the deposit can be observed. It is most pronounced in the areas where the largest flow velocities are observed. The section behind the deposit is not much affected by the supplied sediment. The pattern of erosion and aggradation corresponds quite well to the outcome of the simulation described in section 5.2.1.

In reality the material of a medium-sized debris flow spreads in the confluence area of the Rhone with the Illgraben. While the fine fractions of the substrate are transported downstream immediately, larger grains are deposited in the riverbed and they form a sediment plug that normally does not fill up the channel bed completely. At higher discharges the sediment plug is eroded gradually. In case of a very high, bed-forming discharge the applied shear stress is large enough to even remove the remaining plug and the material is transported downstream.

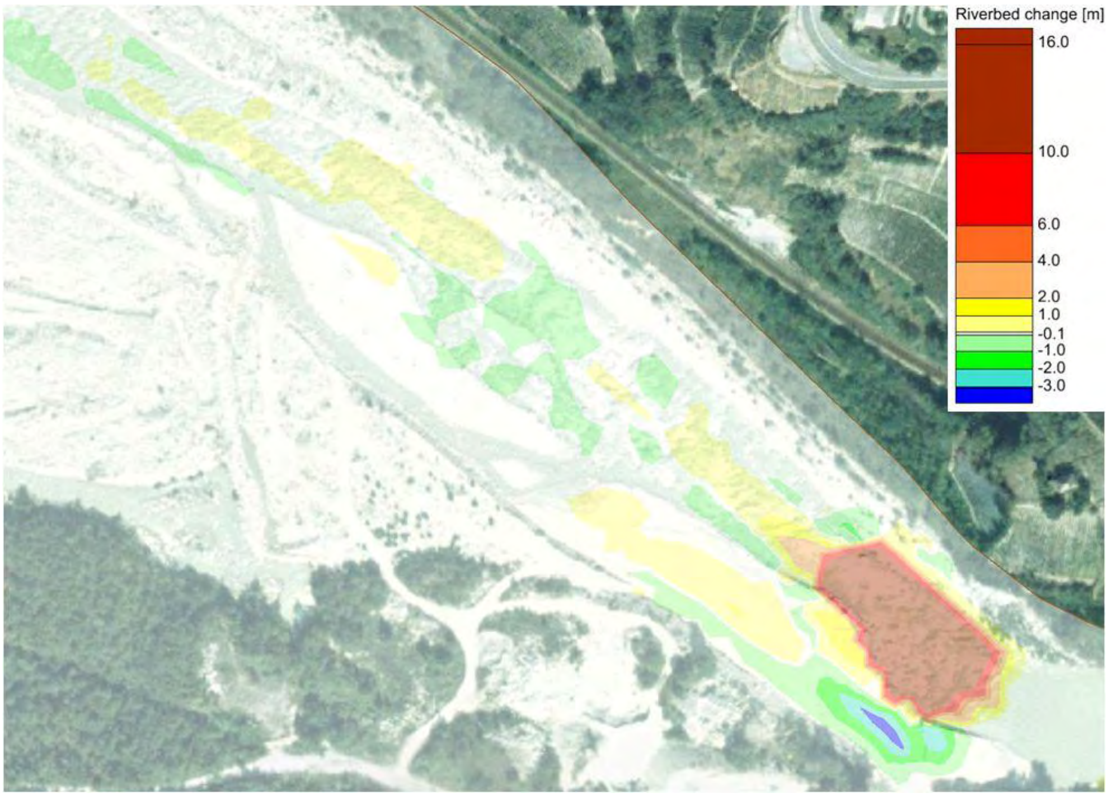

Figure 5.4: *Computed riverbed changes for the scenario describing a debris flow simulation after a simulation time of two hours. Erosion is highlighted with blue colors. The yellow to brown colors correspond to aggradation.*

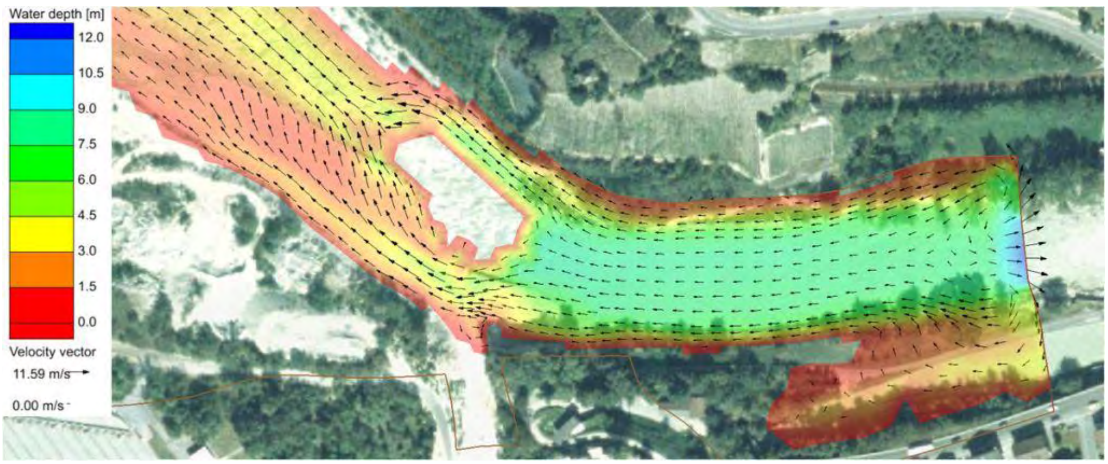

Figure 5.5: *Simulated water depth and velocity vectors for the scenario describing a debris flow simulation. The figure represents the situation after a simulation time of two hours. The colors illustrate the water depth; the vectors correspond to the simulated flow velocity.*

Chapter 6

Discussion

Right from the start it was clear that the application of a numerical model to the Pfynwald reach is a very challenging task. The braided morphology of the Rhone, the steepness and the large variability in the width of the riverbed, the frequent hydraulic drops and the massive sediment input through the debris flows in the Illgraben are some of the exceptional characteristics of this river reach, which complicate the successful use of numerical models. This fact has been approved explicitly by the investigations of *Hunziker, Zarn & Partner AG* (2001). Although the development of computer programs as well as the scientific research in the field of sediment transport was advanced since then, morphodynamic modeling of such systems remains a challenging task. For this thesis the software system BASEMENT was used. According to the developers one main focus of this system is the stability of the numerical models. Further it was designed explicitly for the simulation of alpine rivers and sediment transport. However, the application of BASEMENT in the present study to the alpine Pfynwald river reach reveals several problems. In the next sections these difficulties are discussed in detail.

6.1 Project BASEchain (1D)

6.1.1 Model calibration

On the contrary to the study of *Hunziker, Zarn & Partner AG* (2001) the frequent hydraulic drops did fortunately not create numerical instabilities in the present hydraulic computations. Generally the one dimensional model BASEchain performed well in case of pure hydraulic simulations (see also figure 4.2). A proper calibration of the hydraulic model was not conducted due to the lack of data that would have been needed for it. Additionally the improvement of the sediment transport computations is negligible compared to the effect of a calibration of the sediment transport parameters. Therefore in this study I focused on the identification of important calibration parameters related to sediment transport. The sensitivity of different model parameters to the output was the main focus (see chapter 4.1). Obviously the goal was to identify the most sensitive parameters in order to adjust as many parameters as necessary to obtain the best fit. In principle the sensitivity analysis of the model parameters was thought to provide the best parameter configuration for the subsequent scenario analysis. Shortly after the start of the calibration of BASEchain serious problems appeared, so that the calibration process was delayed. The model suffered from several bugs. At the beginning BASEchain was not able at all to run a simulation without crashing due to numerical instabilities. The developers of BASEMENT at VAW were then contacted in order to remove bugs in the model code. After solving a couple of bugs in the code the simulation results significantly improved. Especially the occurrence of numerical instabilities could be reduced tremendously. Finally, the calibration and the adjustment of BASEchain to the study reach became a very time consuming component of this thesis and eclipsed the actual planned scenario analysis.

In the scope of the calibration of the model, the most important parameters could be identified. Clearly the most crucial of all the calibration parameters is the upwind parameter, which determines the interpolation of bed load flux to the cell interface. An inappropriate value provokes numerical instabilities leading to unfeasible simulation results. For that reason it is advisable to find out the most suitable value for the upwind parameter before calibrating the rest of the parameters. A less important calibration parameter is the active layer height. It does have significant effects regarding the bed load transport rate and the occurrence of numerical instabilities. In this study the reduction of the active layer height generally attenuated the occurrence and the magnitude of numerical instabilities. Thus, the parameter can be used to reduce or even avoid numerical instabilities on a small scale. Concerning bed load transport, the expected increase of bed load transport using a larger active layer height was only partially confirmed. The modeling results are too inconsistent in order to make a general statement about the relationship between the active layer height and the computed sediment transport rate.

Sediment transport models should be calibrated on long periods in order to avoid effects of short- to medium-term process variability. In the present study the model is calibrated on the basis of a period that spans 12 years. This length corresponds to a medium temporal scale. Consequently the model may be inappropriate for the simulation of short-term processes like for example the change in the riverbed during an individual flood event.

Number of grain classes

The number of grain classes that discretize the sediment grain size distribution is a very important calibration parameter. It determines if fractional sediment transport can be applied and thus sorting effects can be modeled. The calibration results show that a single grain simulation is not able to simulate satisfactorily sediment transport in the Pfynwald reach. In general too little sediment transport is computed, which leads to the development of large aggradation. An increase in the number of grain classes produces an increase in the bed load transport capacity in the Pfynwald river reach. To explain this behavior one needs to take into account the unique setting in this river reach. Sediment transport usually takes place when the shear stress applied by the flow exceeds the bed shear stress of the riverbed, so that the armored layer is broken up. This happens only at very high, so-called bed forming discharges. In this case a sediment transport simulation is not very sensitive to the applied number of grain classes, because the induced stress by the flow is large enough to mobilize the whole spectrum of grain sizes. Sorting effects are negligible, so that fractional sediment transport is not required explicitly. In this case a single grain simulation would be sufficient.

In the Pfynwald reach sediment transport takes place not only at the breakup of the armored layer, but also in case of a debris flow in the Illgraben. These debris flows occur even during low flows in the Rhone River, when the flow is just able to transport the fine fractions of the supplied debris flow material. Therefore fractional sediment transport is very important in order to be able to simulate correctly the ongoing processes. To compute the mean grain size of a grain class, the average of the particle sizes in the corresponding class, weighted by mass, is taken. A coarse resolution of the debris flow substrate cannot reproduce adequately the fine sediment fractions, because in case of only a few grain classes the range of grain sizes in one particular grain class is large, so that fine sediment fractions are averaged out. The larger the mean diameter of the smallest grain class is, the less likely the flow is able to transport this grain fraction during low flows. In other words, the more grain classes one takes into account, the better the whole spectrum of different grain sizes of a substrate can be represented and the more grain classes are transported by the flow even during low flows.

At this point the modification of the applied hydrograph should be mentioned. The negligence of discharges below $100\,\mathrm{m}^3/\mathrm{s}$ has certainly an implication to the computation of sediment transport in the Pfynwald reach. As already mentioned above, not the break-up of the armored layer is crucial in terms of sediment transport but the occurrence of debris flows. A model with a clipped hydrograph cannot account for the ongoing processes during a debris flow that enters the Rhone at a discharge below the considered minimum streamflow.

In the model the sediment supply by the Illgraben is simulated as constant inflow, independently of the observed discharge in the Rhone River. In order to simulate satisfactorily sediment transport in the Pfynwald reach it is indispensable to employ fractional sediment transport. Moreover it is important to use a sufficient amount of grain classes to discretize the sediment. But it does not make sense to consider more grain classes than needed for the sake of the computational efficiency. Besides, the chance to encounter numerical instabilities increases with a larger number of considered grain classes as it was observed in the calibration process. In the present study the use of 10 grain classes seems to be adequate in order to obtain satisfying results and to avoid major numerical instabilities.

Apart from the insufficient modeling of sediment transport due to the missing computation of sorting effects, the single grain simulation exposes an inconsistency relating to the calculation of sediment relocation. The problem is manifested best at the example of the fact that bed load transport drops to negative values approaching the lower end of the river section. In nature this can definitely not happen, because it implies that the model extracts or deposits sediment that is actually not available. Consequently the model does not allow for mass conservation.

To locate the error in the model code for the computation of sediment relocation, a simulation run was performed modeling just the sediment extraction. Thereby a fixed riverbed was applied in order to not disturb the evolution of the riverbed by sedimentation and erosion processes. Sediment relocation was then tested based on the comparison of the simulated erosion caused by the sediment extraction and the corresponding bed load transport. If sediment relocation is computed correctly the simulated erosion has to compensate the extraction volumes. Because there is no additional sediment input, neither a supply by the Illgraben nor an input at the upper boundary the resulting bed load transport is zero. Figure 6.1 illustrates the result of a simulation run to test BASEchains algorithm to compute sediment relocation. The transport diagram supports explicitly the above denoted concerns regarding the computation of sediment relocation, since the simulated erosion does not correspond to the actual extracted sediment volume. The blue curve highlights bed load transport considering the eroded sediment volume. The red line does not account for erosion. Thus, the difference between the two curves corresponds to the simulated eroded sediment volume. As a consequence of this, BASEchain consistently computes too little erosion at the location of external sinks. The mass balance error in the computed eroded sediment volume is indicated by the green curve. On average, the mass balance error adds up to -75 %, which implies that 75 % of the extracted sediment volume is not converted into channel bed erosion.

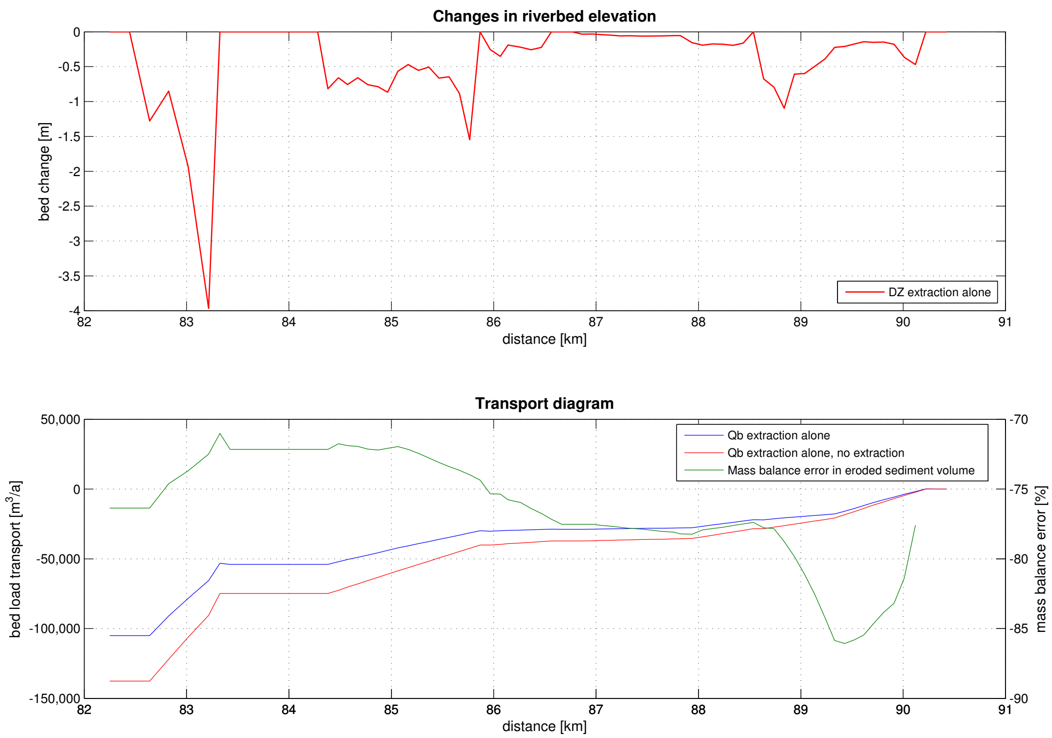

Figure 6.1: *Results of the sediment relocation test. Illustrated are the modeled riverbed changes of a simulation that accounts just for sediment extraction. The transport diagram shows bed load transport including (blue) respectively neglecting (red) the eroded sediment volume as well as the mass balance error in the computed eroded sediment volume.*

Composition of the debris flow material

The effect of a variable constitution of the material supplied by the Illgraben verifies the significance of the use of fractional sediment transport. There is a strong dependency between the impact of different material compositions and the employed number of grain classes. Again the explanation for this behavior is most likely in the way how sediment transport is computed. The multigrain simulation using 10 grain classes is more robust against a variable grain mixture, because the change of the sediment composition is distributed among the different grain size fractions. In the end the change of the proportion of every single grain class is marginal. Hence, the transport per fraction is affected just slightly. But in the case of only a few grain classes, the change of every single grain class increases, which finally affects bed load transport to a greater extent. The effect of a change in the substrate composition is most pronounced in single grain simulations because the model is highly sensitive to the applied mean particle size of the sediment (see figure 4.5).

In case of the 5 grain class simulations the riverbed elevation changes at the confluence of the Illgraben do not affect the lowest part of the Pfynwald reach. Generally fluvial systems are coupled in lateral as well as longitudinal direction, so that a local change of the channel bed elevation can have major impacts on the whole river section. This finding implies the surprising fact that there is no significant longitudinal coupling of the channel bed in the 5 grain class model. In relation to that the results of the 10 grain class simulations appear to be more realistic, since the entire Rhone River reach is affected by changes of the debris flow substrate. A longitudinal coupling seems to exist, because different changes in the riverbed elevation at the beginning of the considered river section provoke different responses at the lower end of the Pfynwald reach.

Best fit

After a very extensive and cumbersome calibration of the one dimensional model BASEchain, finally a model configuration was found, which was able to simulate reasonably well the observed riverbed changes and the mean annual bed load transport rate. Generally speaking the magnitude of the deviations from the observations lies in a tolerable range. Just like all the calibration runs, the best fit simulation shows major erosion at the beginning of the reach. This is most likely an effect of the definition of the upper boundary condition. The definition of the boundary condition might also affect the simulation results at the lower end of the Pfynwald reach between km 82 and 84 where aggradation was simulated.

To evaluate the development of the riverbed elevation in the Pfynwald reach one has to consider that the supply of the debris flow material in the model is simulated as a steady-state external source throughout the year. In reality the sediment, which is supplied by the Illgraben, is delivered intermittently to the channel bed of the Rhone River in only a few very large sediment inputs. In the majority of cases the discharge in the Rhone is not able to carry away the delivered sediment all at once, so that a gravel plug is formed in the confluence area. The deposited material remains in the channel bed of the Rhone until a flood removes and carries it further downstream where it is deposited again. This results in an intermittent transport of the debris flow inputs through the Pfynwald reach. The wave-like propagation of the aggradation leads to a permanent pulsation of the riverbed, whose intensity is damped with increasing distance to the Illgraben confluence. This is highlighted very nicely in the plot of the temporal evolution of the riverbed elevation (figure 4.9). *Jäggi* (1988) describes this behavior in detail in his extensive study about the Pfynwald reach. He also tried to estimate the magnitude of the pulsation of the riverbed.

A sediment transport model, which uses a simplified continuous sediment supply of the debris flow material is certainly not able to simulate this short- to medium-term pulsation of the riverbed as the plot of the temporal evolution of the channel bed clearly indicates. For that reason the local discrepancy between the simulated and the observed riverbed elevation change between km 87 and 88 might be explained with the inability of the model to capture the pulsation of the riverbed. Though, the figure of the temporal channel bed change also shows that the model can capture the long-term trend of the riverbeds development. Therefore the use of a continuous sediment supply seems to be adequate in order to simulate the evolution of the longitudinal profile in the Pfynwald river reach on a longer temporal scale. This is obvious, since the adjustment of the riverbed on longer time scales is not affected by short-term processes, but more importantly by characteristic mean boundary conditions and fluxes.

6.1.2 Scenario analysis

One specific goal of this thesis was to study the sensitivity of the Pfynwald reach to variable boundary conditions. Originally it was planned to define several scenarios, which were characterized by different boundary conditions. Due to the laborious calibration of BASEchain, just a few of these simulation runs could be performed. The main focus was set to the effect of a change of sediment extraction and the influence of a variable sediment supply by the Illgraben.

Sensitivity to sediment extraction

The results of the simulation without gravel extraction demonstrate that the Rhone River is on the average able to transport the delivered sediment by the Illgraben through the Pfynwald river reach. In the long run, aggradation only occurs in the lowest part of the Pfynwald reach that is characterized by a small channel bed gradient. As a consequence not all of the currently existing gravel pits are required in order to prevent the Pfynwald reach from significant deposition caused by the large sediment inputs by the Illgraben. However, the large volume of sediment that is carried out of the Pfynwald section certainly has a major impact to the adjacent river section downstream of Sierre. Since the slope of the longitudinal profile further decreases, the consequence is most likely associated with large aggradation in this river section as this is already indicated by the massive aggradation computed for the flat end of the Pfynwald reach. In order to avoid negative impacts to the downstream river sections, it is therefore necessary to continue to extract sediment in the Pfynwald reach. The extraction volume should be determined by the transport capacity of the downstream river section.

The gravel extraction in the Pfynwald reach is an issue that is very much disputed.

Environmental organizations would like to stop the gravel extraction in order to establish a natural fluvial system that is completely unaffected by human interventions. As a result an expertise was commissioned by the Canton Valais (*Jäggi*, 1988; *Bezzola*, 1989) to investigate the feasibility of a restoration of the natural river dynamics. The study concludes that gravel extraction is required in order to guarantee sufficient flood protection for the surrounding areas.

In the scope of the sediment transport study of *Hunziker, Zarn & Partner AG* (2001) the sensitivity of the Pfynwald reach to gravel extraction was also addressed. They ran a scenario without any extraction. The sediment supply by the Illgraben was assumed to be 100'000 m^3/a. A volume of 22'000 $^3/a$ was applied to the sediment inflow at the upper boundary. The simulation was run for a period of 26 years. The results and findings are comparable to those obtained in the present thesis. In the uppermost 2 km of the reach the model computes significant erosion, while in the lower section a trend to relatively large aggradation results. Regarding bed load transport a similar output was obtained as well, concluding that the sediment discharge at the lower end of the reach corresponds to the volume that is supplied by the debris flows. Analog to the simulations in this thesis the Rhone is able to transport the supplied volume of the debris flows through the Pfynwald reach. One needs to keep in mind that the model used by Hunziker was calibrated on the basis of just four years.

With regard to sediment extraction, the way in which it is applied in the model as well as in reality needs to be emphasized. In the Pfynwald reach gravel is extracted mainly at three different gravel pits. The extraction is restricted to the low flow period during winter, because in this time the riverbed can be accessed safely by heavy machinery. In case of the model sediment extraction is modeled with spatially distributed sinks, which allows representing the location of the extraction quite accurately. But the timing of the extraction is not well represented, since the low flow periods are not modeled. Gravel extraction is simulated only for high discharges ($Q > 100\,m^3/s$) with a constant extraction rate. In the model the processes of gravel extraction and sediment transport interfere with each other as opposed to reality. This may have some implications to the evolution of the riverbed, since the complex feedback mechanism behind sediment transport and channel bed changes might be disturbed by simultaneous gravel extraction in the model.

Sensitivity to sediment supply by the Illgraben

According to the results of the simulation runs with variable sediment supply by the Illgraben, the Pfynwald reach is not sensitive to the volume of the material input. This result is very surprising, because it is contrary to what one would actually expect based on the physical understanding of sediment transport in a river. In the same way *Hunziker, Zarn & Partner AG* (2001) tested the sensitivity of the Pfynwald reach to sediment supply with the aid of a numerical sediment transport model. Their results are contradictory to the finding in this thesis. They conclude that an increase of the sediment input by the Illgraben causes major aggradation in the Pfynwald reach. By contrast a decreased supply results in significant erosion. For that reason the result in this thesis is doubtful and we cannot make the statement that the Pfynwald reach is effectively non-sensitive to the volume of the supplied sediment. One rather concludes that the applied sediment transport model is not sensitive to the sediment input and it may not be suitable to investigate this particular attribute of the river reach.

A possible explanation for the lack of response to a variable sediment supply by the Illgraben may be the continuous implementation of the debris flow input. The use of episodic inputs, as it would be in reality may generate more aggradation in the channel bed close to the confluence.

6.1.3 Limitations of the model

The troubles that have emerged during the calibration of BASEchain as well as the difficulties that have been experienced in a previous study (*Hunziker, Zarn & Partner AG*, 2001) raise the concern if a one dimensional model is actually appropriate to simulate sediment transport in the Pfynwald river reach. As a result of the braided morphology, the Rhone River has a two dimensional character in the area of the Pfynwald. Very often the water is flowing in different river branches, which are not always parallel to the main direction of the riverbed. In addition, the flow frequently changes from subcritical to supercritical flow due to the irregular and partly quite steep channel bed. For that reason the assumptions behind a one dimensional model may not be valid anymore for parts or even the complete study area, so that the simplifications in the mathematical model can lead to inconsistencies and errors in the simulation results. In consideration of the difficulties which BASEchain encountered and the two dimensional character of the Pfynwald reach, it is legitimate to ask if a two dimensional sediment transport model should be more applicable to the Pfynwald river reach. 2d models are able not only to simulate lateral flow but also to provide spatial changes of the riverbed. However, a huge drawback of two dimensional simulations is certainly the much longer computation time. It is often not feasible to apply a two dimensional model for the analysis of the evolution of the longitudinal profile or for the study of the sediment balance in a river section.

Particularly in the very unique Pfynwald river reach, one may also doubt the applicability of the concepts that are incorporated in the numerical sediment transport models in general. The scope of application of the sediment transport formulas is limited. The most widely-used formulas are practically all deduced from measurements in laboratory experiments and they are based on the concept of complete mobility, meaning that all fractions of the sediment substrate are in motion. In order to account for sorting effects, correction functions were deduced for fractional sediment transport in numerical models (*Hunziker*, 1995). The prevailing circumstances in the Pfynwald section are certainly at the limits of the operative range of the sediment transport formulas. Mainly the relatively large fraction of huge grain sizes ($> 0.5\,\text{m}$) is a problem in terms of the computation of incipient motion and resulting sediment transport.

In this context it has to be mentioned that BASEchain does not provide a sediment transport formula specifically developed for the special conditions in braided rivers. Such formulas were developed for example by *Zarn* (1997) and *Marti* (2006). They account for gravel banks and separate channels in a braided river by means of a mean water level width and depth and a correction factor for slope.

A further limitation of the model concerns abrasion of sediment particles, meaning that the decrease of the characteristic mean particle diameter of the riverbed substrate along a river by the processes of e.g. splitting is not considered in the model.

Finally a remark about the definition of the initial conditions is given. BASEchain allows for the definition of the hydraulic initial conditions, but it does not provide the definition of an initial condition concerning the composition of the riverbed. Therefore one cannot start a simulation with an already existing armored layer. The model has to compute it first, so that the beginning of a simulation run is always affected by the sorting processes leading to the formation of an armored layer.

6.2 Project BASEplane (2D)

6.2.1 Model calibration

The two dimensional project used a different approach to calibrate the model. The main work consisted of the calibration of the hydraulic model. Since the roughness coefficient is the only parameter that is worth to calibrate, the calibration process is relatively simple. There is no interaction of different parameters or any feedback mechanism that need to be taken into account. The critical point in the calibration process is the evaluation of the calibration results. A small change of the roughness coefficient produces just a minor difference in the model output. Therefore it is rather difficult to identify the optimal value of the friction factor at first sight. Besides, a qualitative judgment of an output plot is always affected by the personal subjective impression. In order to guarantee an objective evaluation of the models performance sensitivity/specificity accuracy measures were applied (*Begueria*, 2006). Although this method was actually designed for the evaluation of mathematical models in natural hazard analysis, it has been proven in this study that it is also suitable to quantitatively estimate the performance of a two dimensional hydrodynamic model. A great advantage of the sensitivity/specificity approach is the robustness with respect to unequal sample sizes. The number of dry and wet nodes in the model domain is usually not equal and it strongly depends on the definition and the characteristics of the model domain (e.g. floodplain, embankments, channel width) as well as on the simulated discharge (e.g. low flows, floods). In order to guarantee a consistent evaluation of the model results e.g. over the range of different discharges it is very important to have an accuracy measure that is able to deal with the presence of prevalence.

The successful calibration of a two dimensional hydrodynamic model makes high demands on the availability of compatible data. The calibration requires pairs of aerial photos and digital elevation models that were recorded at the same time. If one relies on the data from Swisstopo it is only by chance that an aerial image matches the available digital elevation model. Unfortunately the publicly available aerial photos and the digital elevation model data are not recorded on the same flights at Swisstopo, so that there is always a temporal gap between the two datasets. The data availability tremendously increases if a river section is permanently monitored e.g. in the scope of a research project. A good example is the RECORD project at the Thur River (*RECORD*, 2010).

The calibration of the two dimensional hydrodynamic model in this study was based just on one pair of an aerial picture and a digital elevation model for the Pfynwald reach. That is sufficient data simply for one calibration scenario, for a discharge of $60\,\mathrm{m}^3/\mathrm{s}$ which was measured at the time the aerial picture was taken. This flow rate corresponds approximately to the mean hourly discharge that was observed in the period of 1974 to 2008. Preferably a hydrodynamic model should be calibrated for a range of different flow rates, because the total roughness of a riverbed is not constant. Depending on discharge, the friction that is induced to the flow by the riverbed is changing. Most pronounced is the flow rate dependent roughness in the case of bedform induced friction. While during low flows gravel banks remain dry and do not affect streamflow, they can add significantly to total roughness if they are inundated in case of high flows.

Concerning riverbed roughness it is also worth to look at the values of the calibrated roughness coefficient. In particular the comparison of the initial values obtained by means of the characteristic grain size d_{90} and the calibrated values is very interesting and shows that a significant fraction of the total roughness of a braided riverbed consists of roughness induced by bedforms.

Finally the excellent performance of the hydrodynamic part of BASEplane should be mentioned. Using the calibrated parameter set, the model simulates very well the hydraulics of the Pfynwald reach. The good performance of BASEplane in the Pfynwald reach allows for the conclusion that the model is certainly qualified for the hydraulic simulation of alpine rivers, even if they exhibit a very complex topography.

6.2.2 Scenario analysis

The main focus of the simulations with the two dimensional model BASEplane was to test the ability of the model to simulate sediment transport in the Pfynwald reach using a mobile riverbed as well as the investigation of spatial patterns of sedimentation and erosion at the confluence of the Rhone River and the Illgraben. The results of the first simulation runs showed a rather strange pattern of erosion and deposition at a couple of nodes. When erosion was initiated at a particular node the sediment loss at this point progressed continuously, which finally led to relatively deep holes in the riverbed. The eroded substrate was usually deposited at the adjacent nodes causing small sediment piles. This effect was pointed out to the developers of BASEMENT, who subsequently implemented gravitative sediment transport into the model. Therewith the formation of holes and piles was prevented, because the material slips off automatically if a critical angle of repose is exceeded. The implementation of gravitative transport procured the expected improvements, so that BASEplane was applied to model two different scenarios. However, the significance of the results is debatable, since the model was not calibrated with respect to sediment transport.

Simulation of the sediment inflow at the upper boundary condition

It is interesting to assess just qualitatively the simulated riverbed changes due to a lack of data, which could be used as a reference for a quantitative evaluation. For the most part, the computed spatial pattern of erosion and deposition seems to be appropriate. The large erosion at the confluence of the Illgraben can be explained with the steep gradient of the channel bed. A discharge of $400\,\mathrm{m}^3/\mathrm{s}$ induces a shear stress high enough to even break up the strong armored layer in this area.

The results in the central part of the reach are quite peculiar, since the model computes no changes at all. This implies that the transport capacity in this river section lies in-between the minimum (Q_0) and the maximum transport capacity (Q_D) according to *Bezzola* (2009), meaning that discharge is high enough to transport the supply from upstream through this section, but the shear stress is too small to break up the armored layer.

The inconsistency concerning the deposition right at the beginning of the river reach is most likely generated by the disturbance of the hydraulics due to the definition of the boundary condition. A way to bypass this problem might be an artificial extension of the study reach by means of a channel that is placed just upstream of the actual model domain. The goal of this channel would be to absorb the effects caused by the definition of the boundary condition. The sediment inflow needs then to be introduced to the model domain with the aid of an external source. This has the disadvantage that the supplied sediment does not have any momentum. In order to transport the sediment the flow first needs to initiate particle motion.

Simulation of a debris flow event

Apparently the model is not able to simulate satisfactorily a massive point sediment supply in the form of a debris flow. This may have several reasons. Certainly the way how the sediment is brought into the channel bed has a large impact to the outcome. BASEplane allows introducing additional sediment to the study area by the declaration of an external source. The pure gravel enters the channel bed at the specified nodes of the source area. As already mentioned above, the material does not have any momentum, so that first the sediment particles need to be set in motion by the flow in order to be transported downstream. In reality a debris flow delivers not only sediment to the riverbed but also water and suspended load. In addition, the supplied water and sediment mixture enters the channel with a particular momentum. For that reason a debris flow spreads its material in the confluence area with the Rhone. Thus, the supply of sediment is not bound to a specific location (cross section or nodes) as it is in the model. Moreover the current in the channel bed of the Rhone is better able to transport the sediment away, if the delivered material is already in motion, since the required shear stress to take up the particles from the riverbed is different from the one it needs to keep them in motion.

If the sediment has accumulated to a level above the water surface, all of the delivered sediment contributes to the formation of the sediment plug, since the material is not exposed to the flow-induced shear stress anymore. Not even gravitative transport is able to reduce the growth process by a collapse of the slopes, because gravitative transport only affects areas that are inundated.

Obviously, the supply of large sediment masses by means of an external source seems to be not appropriate. In order to be able to simulate the point influx of a debris flow a new approach needs to be developed. A possible solution may be the design of a numerical model that is able to simulate debris flows.

Chapter 7

Conclusion and outlook

7.1 Conclusion

The present thesis aimed at modeling sediment transport in the braided Pfynwald river reach of the Rhone by means of the numerical sediment transport model system BASEMENT. The one dimensional model BASEchain as well as the two dimensional tool BASEplane were applied in order to study the sensitivity of the riverbed and the bed load transport rate in the Pfynwald river reach to variable boundary conditions.

The main conclusion of this thesis states that the application of a numerical model to relatively steep alpine rivers with a braided morphology is a very difficult task and that current numerical models are not yet fully adequate to simulate satisfactorily sediment transport and erosion and deposition in such very dynamic river reaches. Apart from this general conclusion, the main findings of this thesis with respect to the addressed objectives are:

- The mean annual sediment supply by the Illgraben is roughly 140'000 m^3/a for the period of 1995 to 2007.
- The observed mean annual sediment transport rate in the Pfynwald reach decreases from 150'000 m^3/a at the confluence with the Illgraben to 30'000 m^3/a at Sierre.
- The one dimensional model BASEchain is able to reproduce the observed mean annual bed load transport rate in the Pfynwald reach.
- The upwind parameter and the number of grain classes were identified as very sensitive model parameters regarding the sediment transport computation with the 1d-model BASEchain. Concerning BASEplane the roughness coefficient ascertained to be a crucial parameter in terms of hydraulic simulations. The sediment transport parameters were not addressed in this thesis.

- The sensitivity of the Pfynwald reach to variable boundary conditions was investigated on the example of the two aspects 'gravel extraction' and 'sediment supply by the Illgraben'. The abandonment of gravel extraction would just marginally impact the evolution of the longitudinal profile in the Pfynwald reach, because the Rhone River is able to transport most of the delivered debris flow material through the reach. However, sediment extraction in the Pfynwald reach should be continued in order to prevent the downstream river section from major aggradation.

- Concerning a variable sediment supply by the Illgraben no conclusion can be made due to doubtful simulation results.

- The two dimensional model BASEplane is not appropriate to simulate the channel bed changes caused by a single debris flow event unless a new approach for the simulation of point influxes of massive sediment volumes is developed (e.g. a numerical model that is able to simulate debris flows).

Besides, the following results were obtained:

- In general, BASEMENT does an excellent job with respect to hydraulic simulations.

- The 1d-model BASEchain is not able to simulate short-term processes (e.g. pulsation of the riverbed, single flood events). As a consequence it does not capture sufficiently the temporal evolution of the riverbed.

- Thanks to the present work several bugs in the model code of BASEchain were identified and could be eliminated by the developers.

Although the application of the numerical sediment transport model system BASEMENT produced finally some satisfying results, they need to be viewed critically. In particular, the good results of BASEchain concerning the best fit and the sensitivity to gravel extraction need to be regarded with suspicion. Their significance is doubtful, because of the existing model inconsistencies concerning the computation of sediment relocation. This is further supported by the missing sensitivity of the model to the sediment supply by the Illgraben. This are both issues that need to be addressed in the future.

7.2 Outlook

The Pfynwald river reach is a very interesting place to study sediment dynamics in rivers. Besides the huge variety of scientific questions that can be addressed in this study area, it is also worth to focus on some practical issues concerning river engineering. Thereby numerical models provide a useful tool to study sediment transport on relatively large temporal and spatial scales, particularly with respect to changing boundary conditions. With the continuous increase of computational power, numerical sediment transport models on the one hand become an even more powerful tool and on the other hand they can be applied to larger spatial and temporal scales. Though, their application is usually limited to rivers with a relative simple topography as not only this thesis has shown. In order to apply these models in topographically complex terrain they certainly need to be improved. Concerning the numerical model BASEMENT the following suggestions for improvement should be considered:

- Eliminating the bug at the computation of sediment relocation in the one dimensional model BASEchain
- Implementation of a sediment transport formula that is suitable for the unique settings of a braided river (e.g. *Zarn* (1997), *Marti* (2006)).
- Implementation of abrasion of sediment grains along a river reach
- Provide an option for an initial condition for the composition of the riverbed in order to account for an already existing armored layer
- Develop a new approach to simulate the point influx of massive sediment volumes like a debris flow

In order to potentially improve the simulation results, the following propositions should be tested in future sediment transport modeling in the Pfynwald reach:

- Distribute the sediment supply by the Illgraben to single events in order to may be able to simulate the pulsation of the riverbed.
- Introduce gravel extraction as intermittent sources in order not to disturb the complex feedback mechanisms of sediment transport and channel bed change.
- Choose a smaller discharge as a threshold for the simulation hydrograph in order to account for processes during a debris flow that enters the Rhone at low flows.

Numerical models require a set of input data for the definition of the boundary conditions as well as the initial conditions. Additionally a time series of topographic data

- digital elevation models and river cross sections - is necessary for the calibration of the model. The application of numerical models relies on the availability of data with sufficient accuracy and for sufficiently long periods. The topographic surveys of the Pfynwald reach, the supervision of gravel extraction in the Rhone River as well as the monitoring of the debris flows in the Illgraben need therefore to be maintained or even expanded. Particularly the need for frequently recorded digital elevation models is highlighted in order to calibrate the sediment transport computations of a two dimensional model.

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Appendix

A Observation of debris flows in the Illgraben

Table A.1: *Sediment volumes of observed debris flow events in the Illgraben in the period of 2000 to 2005 (modified after Teysseire & Candolfi and WSL, 2005).*

Date	Volume [m^3]	Comments
03.06.2000	10'000	
28.06.2000	90'000	
24.07.2000	20'000	
06.06.2001	32000	
09.06.2001	7'500	
15.06.2001	10'500	
28.06.2001	36'000	
07.07.2001	45'000	
21.07.2002	$<$ 5'000	
31.07.2002	20'000	
10.08.2002	71'000	
29.06.2003	no data	
19.05.2003	90'000	
08.06.2003	$<$ 5'000	
12.08.2004	34'000	
24.08.2004	36'000	
26.10.2004	$<$ 5'000	
28.05.2005	140'000	water and sediment
03.06.2005	48'000	water and sediment
13.06.2005	25'000	water and sediment
04.07.2005	25'000	water and sediment
18.07.2005	19'000	water and sediment
02.08.2005	6'800	water and sediment
18.08.2005	3'000	water and sediment

Table A.2: *Sediment volumes of observed debris flow events in the Illgraben in the period of 1932 to 1999 (modified after Rhyner et al., 2005).*

Date	Volume [m^3]	Comments
29.06.1932	75'000 - 250'000	
04.09.1944	25'000 - 75'000	
25.07.1945	$<$ 25'000	
08.08.1945	25'000 - 75'000	
19.08.1945	$<$ 25'000	
28.07.1948	75'000 - 250'000	
24.06.1953	25'000 - 75'000	
06.06.1961	$>$ 250'000	
09.06.1961	no data	
11.07.1961	no data	
19.07.1961	no data	
01.06.1962	no data	
02.06.1962	no data	
08.06.1963	no data	
18.06.1963	no data	
28.06.1963	no data	
12.08.1963	no data	
20.05.1964	no data	
30.05.1964	no data	
02.06.1964	no data	
14.06.1964	no data	
17.06.1964	no data	
04.05.1965	no data	
07.06.1965	no data	
08.06.1965	no data	
18.06.1965	no data	
04.07.1965	no data	
25.07.1965	no data	
31.07.1982	$<$ 25'000	
06.06.1985	$<$ 25'000	
06.07.1986	25'000 - 75'000	date doubtful
07.06.1987	$<$ 25'000	
29.08.1988	$<$ 25'000	
16.08.1989	25'000 - 75'000	date doubtful
13.08.1990	$<$ 25'000	
12.07.1991	75'000 - 250'000	
03.10.1995	75'000 - 250'000	date doubtful
21.08.1997	25'000 - 75'000	date doubtful
30.10.1998	$<$ 25'000	
16.08.1999	75'000 - 250'000	

B ROC plots and accuracy statistic T

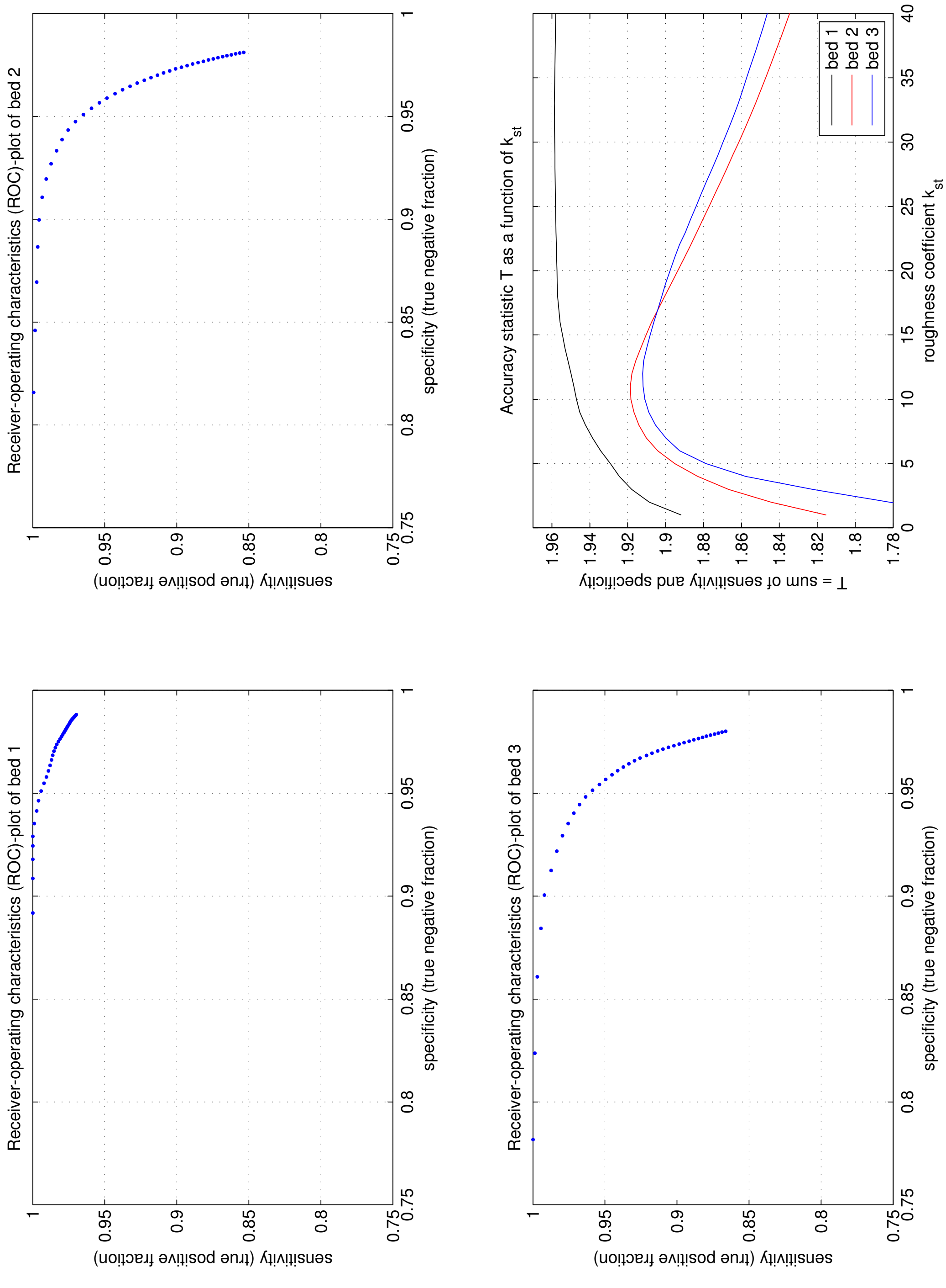

Figure B.1: *Receiver-operation characteristics (ROC) plot and accuracy statistic T for the different subreaches.*