

## 2 Flood Forecasting for the River Inn

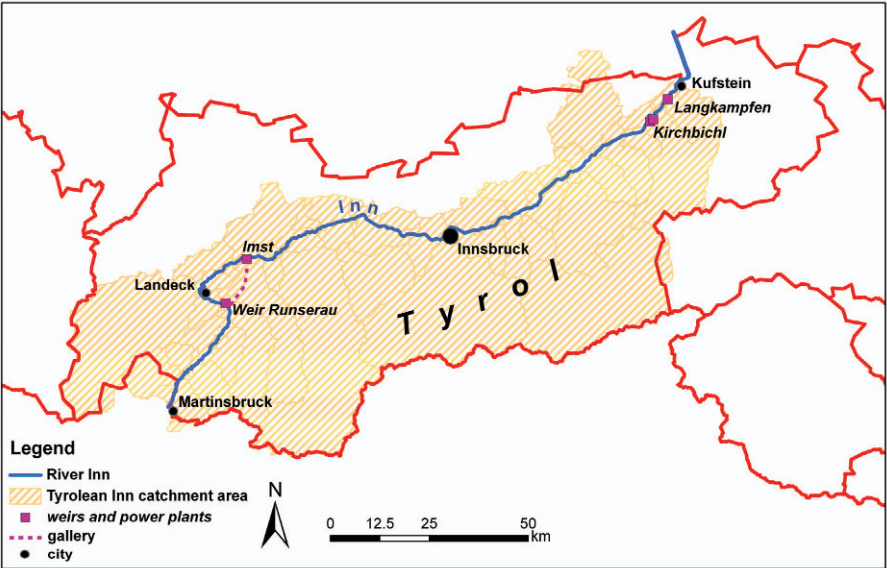
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### 2.1 Introduction

#### 2.1.1 The River Inn in Tyrol

The river Inn as the main river in Tyrol moulds the settlement and economic area in Northern Tyrol in a considerable way. 66 % of the area drains into the Inn, whereas the remaining 34% drain into the Lech, the Grossache and the Drau in East Tyrol. The Inn flows through Tyrol for about 200km, from the Swiss border at Martinsbruck to Kufstein, where it leaves Tyrol and flows into Bavaria/Germany (Fig. 2.1).

The 100-year flood ( $HQ_{100}$ ) discharge is  $512\text{m}^3/\text{s}$  in Martinsbruck and increases to  $1,370\text{m}^3/\text{s}$  at Innsbruck and rises further to  $2,250\text{m}^3/\text{s}$  at Oberaudorf after crossing the border at Kufstein (Table 2.2). Until now the highest level of discharge in the river Inn at Innsbruck ( $1,511\text{m}^3/\text{s}$ ) was measured on August 23, 2005 (Fig. 2.2). It was determined for this particular flood event in Innsbruck that it took 20 hours from the first response of the gauge until the peak discharge was reached (Gattermayr 2005).



**Fig. 2.1** Map of Northern Tyrol showing the river Inn, the catchment area in Tyrol and run-of-river/diversion power plants

**Table 2.1** Characteristic discharges for selected gauges on the Inn

	MQ	HQ <sub>1</sub>	HQ <sub>100</sub>
Gauge Martinsbruck	-	275[m <sup>3</sup> /s]	512[m <sup>3</sup> /s]
Gauge Innsbruck	165[m <sup>3</sup> /s]	641[m <sup>3</sup> /s]	1,449[m <sup>3</sup> /s]
Gauge Oberaudorf	307[m <sup>3</sup> /s]	1,220[m <sup>3</sup> /s]	2,250[m <sup>3</sup> /s]

MQ (mean water discharge), HQ<sub>1</sub> and HQ<sub>100</sub> (flood discharges with a statistical recurrence interval of 1 and 100 years respectively) for selected gauges, determined from a statistical series covering at least 30 years (BAFU 2006, HZB 2006, Blöschl et al. 2006, LFU 2006)



**Fig. 2.2** The flood in Innsbruck on August 23, 2005. The discharge at the time (4.48 p.m.) the picture was taken was at around  $1,395 \text{ m}^3/\text{s}$ . Only a few centimetres of freeboard are protecting the city of Innsbruck and the university (picture) from catastrophic damage

The discharge is influenced by several reservoirs and power stations in the Swiss catchment area of the Inn. Along the Tyrolean length of the Inn three run-of-river power stations and diversion hydropower facilities are used to produce electricity: the weir at Runserau with a power station in Imst, the power plant in Kirchbichl and in Langkampfen (Fig. 2.1). Several peak-load power plant reservoirs in the catchment areas (reservoir Gepatsch for the Kaunertal power station, reservoir Finstertal and Längental for the group of Sellrain-Silz power stations, the Achensee power station) influence the runoff situation on the Inn through demand-oriented operations as well as being able to store large volumes of water in the case of an impending flood (Widmann 1989).

The hydrological situation reflects the alpine character of the Inn catchment area. Large differences in altitude result in a high average slope of the subcatchments, which in turn leads to a heightened flow velocity and a more rapid response of the hydrograph to rainfall (Baumgartner and Lieb-scher 1996).

Consequently, the model is highly sensitive in regard to rainfall input and its spatial and temporal distribution.

### **2.1.2 Risk Management and Flooding**

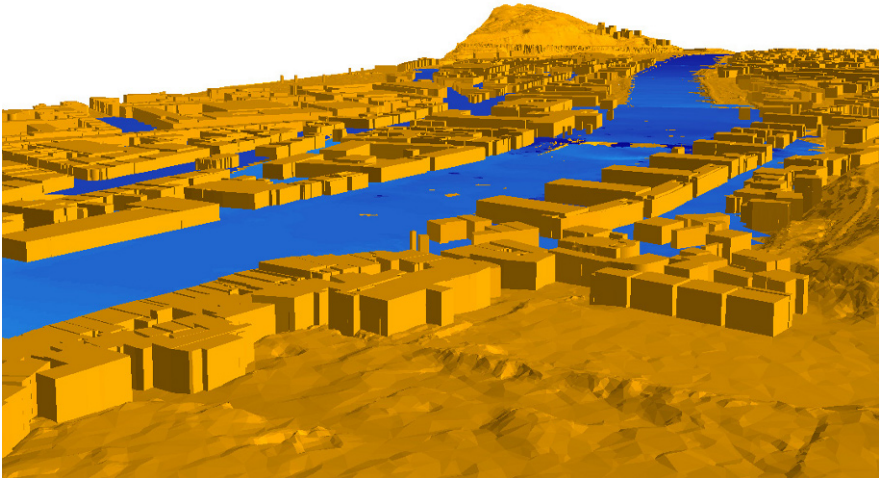
Risk as a product of occurrence probability and effect depends substantially on the potential damage in the areas affected by flooding. The Inn Valley as the most important settlement and economic area in Tyrol has been opened up to more intense agricultural, construction and industrial use in the last decades and centuries through numerous protection measures and river training. The concentration of important infrastructure in the valley region enhances the vulnerability of the area in the case of a catastrophic event, which increases the design discharge of protection measures. An important feature of integral risk management is to deal with exactly these events.

Thus, the central question is how to prepare for these rare events to minimize the damage using the restricted space to its optimum, while at the same time taking the sustainability of protection measures into consideration. Protection measures, in particular levees along the river-side which reduce the area around the river, have led to the regions downriver being more greatly affected by flooding. In regard to a sustainable and cross-national approach towards river basins, increasing the level of protection with new protective measures along the river, should be critically questioned.

In the alpS Centre for Natural Hazards Management, two different strategies concerning flooding are being pursued: the detailed scenario-based analysis and the provision of early warning with the help of forecasting.

#### ***Detailed Scenario-Based Analysis***

Well-defined areas, for which a detailed appraisal is advisable, are dealt with more specifically in the detailed scenario-based analysis. This is because these districts are either of great importance, due to their enhanced risk potential, or due to an especially protection-worthy infrastructure and financial values. The scenarios can be based on previous events and scaled up to extreme ones. On this foundation the effects of extreme events can be investigated in advance and an analysis in regard to preventive risk management can be made. The interpretation of these scenarios is the basis for risk regulation such as the design of protection measures or the conception of a plan of action for emergency organisations. Figure 2.3 shows an example of a detailed hydrodynamic flood analysis.



**Fig. 2.3** Detailed scenario-based analysis Innsbruck: flood modelling based on detailed terrain data.

### ***Early warning with the help of forecasting***

The aim of forecasting is to offer early and reliable warning for the affected areas and to be able to estimate the expected intensity of an event. Based on a forecast it is possible, with the help of the prepared scenarios from the detailed analyses, to develop an optimized strategy to deal with the threat. Thereby it is essential to maintain a temporal advantage as well as the enhanced reliability and objectivity of the statements particularly in comparison with the usual observation of the gauges and the rainfall situation, which demands a high degree of experience with the local conditions. A combination of the models and the experience supported appraisal of the complex information can in future lead to an elevated quality of flood forecasting.

#### **2.1.3 An Overview of the Forecast Model**

The flood forecast model for the Tyrolean Inn is a modular-based, hybrid system conceived and built with three main components (Fig. 2.4). The first part is the meteorological data from observation stations in the whole Tyrolean Inn catchment area as well as meteorological forecast data from the numerical weather models of the **ZentralAnstalt für Meteorologie und Geodynamik (ZAMG)** in Vienna (Central Institute for Meteorology and Geodynamics). These data are used in the second component, which con-

sists of the hydrological model HQ<sub>SIM</sub> (Kleindienst 1996) and the glacier model SES (Asztalos 2004). The models are calibrated with historically observed data and use the current data to calculate the discharge from the tributary catchments. In the third component, the flow along the river Inn is represented by a hydrodynamic, one-dimensional model, which integrates the inflows from all the tributaries. The hydrodynamic model represents the wave propagation on the Inn whilst including the influence of the run-of-river power stations and diversion hydropower facilities. A rule-based operation of the reservoirs of the Inn's power stations can be represented with this model.

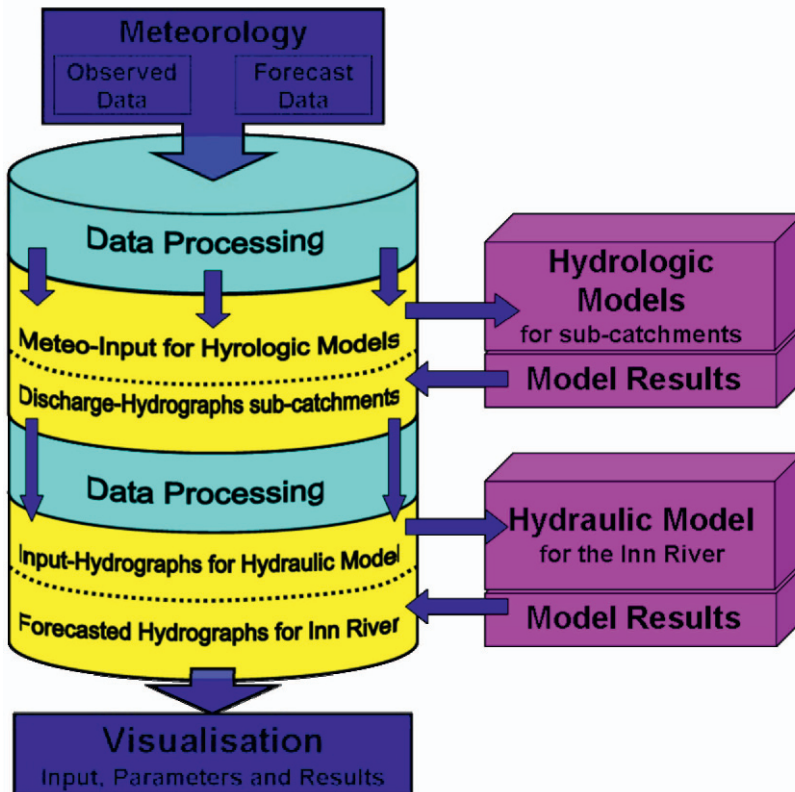


Fig. 2.4 Concept of the flood forecasting model

## 2.2 Meteorological Data

Meteorological data that are fed into the flood forecast are based on numerical weather models as well as data from observation stations in the Tyrolean Inn catchment area. A discharge prediction for the river Inn would also be possible with the use of only the latter; however, the inclusion of forecasts extends the lead time of the forecast significantly.

### 2.2.1 Forecast data

#### ***Nowcasting and NWP (Numerical Weather Prediction)-Models***

Meteorological forecasts can be divided into two groups depending on their prediction period. If a prediction is made of up to 6 hours into the future one can speak of *Nowcasting*, but when faced with a longer prediction period one speaks of *Numerical Weather Prediction (NWP)-Models*.

For the Tyrolean Inn flood forecast system *Nowcasting* data from the tool INCA (Integrated Nowcasting through Comprehensive Analysis) (Csekits et al. 2001) operated by ZAMG is used. To operate INCA it is necessary to access meteorological data from the catchment area in short intervals (10-60 min). Thereby, nowcasting based on measured data (observation stations, satellite data, and radar data) and NWP forecasting data is combined as a time-weighted mean. INCA also provides forecast data for the time period of +6 till +48 hours (refers to prediction point in time), which is identical with the output of the NWP-Model ALADIN-AUSTRIA also operated by ZAMG. INCA supplies analyses and predictions of rainfall, temperature, atmospheric humidity, wind and wind speed, global radiance as well as cloud coverage. The horizontal resolution of ALADIN-AUSTRIA is 9,6km, while the vertical discretisation comprises 45 layers (Wang et al. 2006).

By including additional measured data as well as data from a weather radar the quality of *Nowcasting* can be further increased. Through the planned installation of a second radar in the Inn catchments a further improvement of *Nowcasting* for Tyrol can be expected.

### 2.2.2 Observed Data

In Tyrol several different institutions operate meteorological observation stations which form an exceptionally compact network. A total of 80 sta-

tions run by the following operators can be accessed to obtain flood prediction data:

- Hydrographischer Dienst Tirol (Hydrographic Service Tyrol) - 30 stations
- Lawinenwarndienst Tirol (Avalanche Warning Service Tyrol) - 7 stations
- **ZentralAnstalt für Meteorologie und Geodynamik** (Central Institute for Meteorology and Geodynamics ZAMG) - 26 stations
- **Tiroler Wasserkraft AG** (Tyrolean Hydropower Company – TIWAG) - 12 stations
- **VERBUND** (Österreichische Elektrizitätswirtschafts-AG) (Austrian Hydro Power AG) - 5 stations

All stations conduct rainfall and temperature measurements. The data are retrieved automatically numerous times daily.

Long-term meteorological data from 1994 to 2001 were used for the calibration of the hydrological model  $HQ_{SIM}$  as well as the snow and ice melt model SES (Schnee- und EisSchmelzmodell). These data were also supplied by the previously mentioned station operators, whereby only stations were used which in the next years will also supply real time measurements and will therefore also be incorporated in the flood forecast. On account of the large amount of data it was necessary to incorporate the time series in a database for easier management. Because most of the data had not been corrected, they had to be put through a quality inspection. The thereby used algorithms, such as plausible value check could also be used in the automatic quality control of the real-time data in future.

The calibration time period (1994-2001) was chosen because of the data availability. For each part of the catchment area a dataset with hourly rainfall distribution and vertical temperature profile was calculated. In addition, hourly information about the relative humidity, the wind speed and the global radiance was needed for the calibration of the snow and ice melt model. The rainfall data was interpolated on a 5x5 km grid using an IDW (Inverse Distance Weighting) algorithm. The vertical temperature profile of the surrounding stations was derived with a resolution of 100m using linear interpolation.



## 2.3 Hydrological Model HQ<sub>SIM</sub>

### 2.3.1 Model Description

The hourly hydrological modelling of the Inn tributaries is carried out with the continuous, sub-area based precipitation-discharge model HQ<sub>SIM</sub> (Kleindienst 1996), an enhancement of the water balance model BROOK (Federer und Lash 1978).

Through the use of HQ<sub>SIM</sub> it is possible to represent the heterogeneous soil composition and the equally heterogeneous geological composition of the Tyrolean Inn catchment area in the hydrological modelling. Based on specifically chosen reference subcatchments (Table 2.2) in the main geological units the most important parameters for the model were determined and then transferred to other subcatchments in the same geological units (Kirnbauer and Schönlaub 2006).

**Table 2.2** Description of the reference subcatchments. The location of the areas can be seen in Fig. 2.6

Subcatchment area	Geology	Glaciated	Influenced by hydro-power plants
Brixentaler Ache	Greywacke Zone		
Brandenberger Ache	Northern Calcareous Alps		
Fagge	Metamorphic Basement Units	X	X
Ötztaler Ache	Metamorphic Basement Units	X	
Ziller	Metamorphic Basement Units	X	X

HQ<sub>SIM</sub> represents catchment areas in the form of homogenous sub-areas (hydrotopes). The runoff formation in every hydrotope is described by a combination of storages (Kleindienst 1996). These are the intercepted precipitation, snow cover and soil storage. The latter is divided into an upper soil zone, an unsaturated zone and a ground water zone.

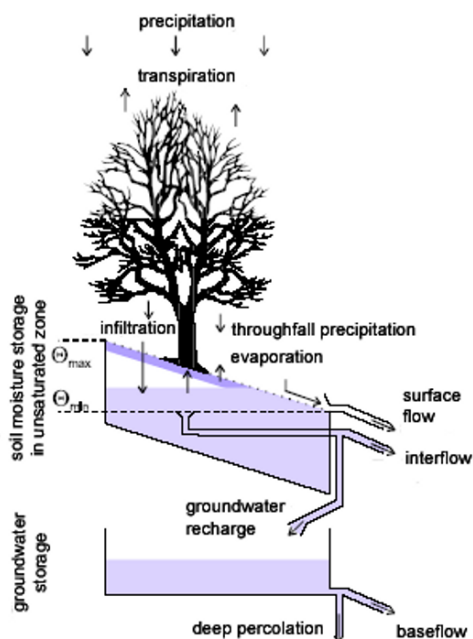
All the partial processes and storages included in HQ<sub>SIM</sub> are depicted in Fig. 2.5, except for snow melt, which is determined with a modified degree day factor technique.

The vegetation is described with the leaf area index (LAI) and trunk area index. To determine evaporation Hamon's calculated potential

evapotranspiration (Federer and Lash 1978) in dependency of the available water is used (Kleindienst 1996).

The throughfall precipitation or the snow melt is separated into surface runoff and infiltration based on the degree of soil saturation of the individual sub-area. Water can evaporate from the upper soil-layer, and the discharge from this layer reaches down into the unsaturated zone.

The outflow from the unsaturated zone depends on soil moisture and can be determined with the help of the Mualem-Van Genuchten approach (non linear storage). With the help of a coefficient the outflow is split into interflow to channel and inflow into the saturated zone. The groundwater storage is conceived as a linear storage, which means that the discharge is proportional to the storage space (dependency is also applicable in a nonlinear storage). A further coefficient divides the outflow from the saturated zone into base flow and deep percolation, which is not taken into consideration in this model.



**Fig. 2.5** Runoff formation in HQ<sub>SIM</sub>: processes and storages, from Kleindienst (2001)

To represent runoff concentration, the three discharge components (surface-, inter-, and base flow) of each hydrotape are routed by a translation

into the channel. Each hydrotape is divided into areas of different flow times using isochrones.

Each channel reach receives inflow from the hydrotapes and the upstream reaches. The flow velocity in the reach can be calculated according to Rickenmann (1996) or Strickler, or set to a constant value.

Intake from and return flow to a reach can be considered whereas it is not possible to model backwater.

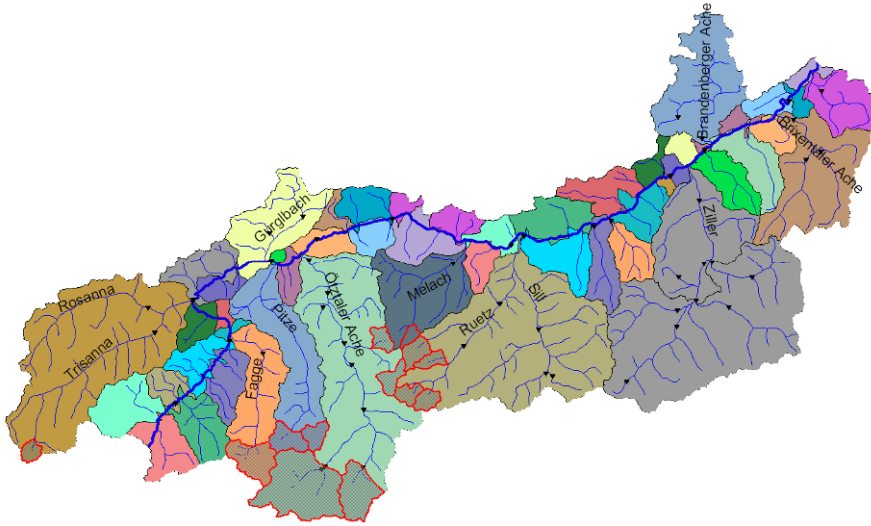
### **2.3.2 Data**

A Digital Elevation Model with a grid size of 250m is available for the Tyrolean Inn catchment area (data set courtesy of the Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology), from which slope and aspect can be deduced. The further GIS data sets stream network, catchment area boundaries, land use and soil are taken from the Digital Hydrological Atlas of Austria (BMLFUW 2005) and are available as vector datasets (shapefiles). In addition, a more detailed stream network (data set courtesy of the Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology), which includes artificial intake and return flow, is used.

The meteorological input data needed for hydrological modelling are temperature and rainfall at an hourly resolution. In addition, wind speed, cloud cover and relative humidity can be used.

### **2.3.3 Calibration**

Due to limitations on the number of tributaries that can flow into the hydraulic model, small catchment areas must be merged. In Fig. 2.6 the combined catchment areas are depicted; the regions with red borders were modelled using the snow and ice melt model SES (Asztalos 2004, Section 2.5.1).



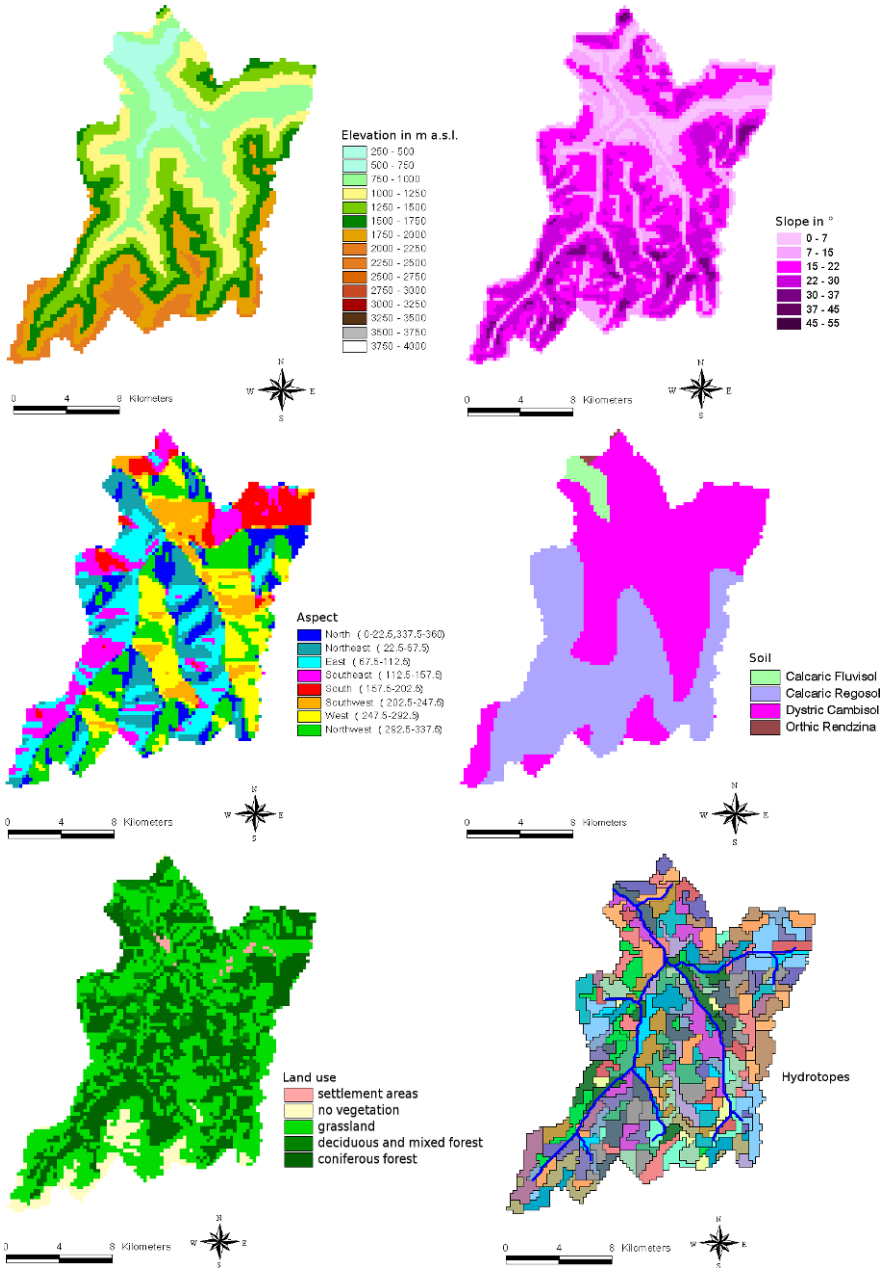
**Fig. 2.6** Inn catchment area in Tyrol and merged small subcatchments. Areas with red borders: glaciated catchment areas modelled with SES

### 2.3.4 Definition of the Hydrotopes

The definition of the hydrotopes (also called **H**ydrological **R**esponse **U**nits HRUs) for one catchment area was achieved through the superposition of regional characteristics such as topography, slope, aspect, and soil and land use.

On the basis of the classified data the hydrotopes were manually identified (Fig. 2.7). Thereby it was ensured that not more than two classes of topographic characteristics were comprised in one hydrotope, which means that the altitude range is less than 500m, the slope range is less than 15° and the aspect range less than 90°.

Small-scale land use units were re-classified in favour of larger hydrotopes. Furthermore, the spatial connection of the hydrotopes was taken into consideration.



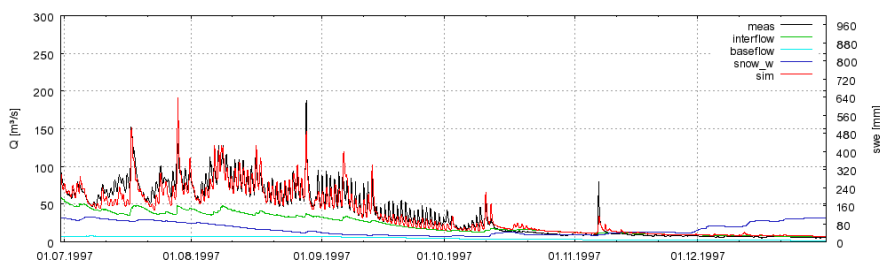
**Fig. 2.7** Brixentaler Ache catchment: elevation distribution, slope in °, aspect, soil, land use and hydrotopes (from top left to right bottom)

For small catchments a simplified method was applied. Elevation-classes (max. 500m difference) and the soil type were used for the definition of the hydrotopes. This resulted in 3 to 12 hydrotopes depending on the size of the catchment. Slope, aspect and vegetation were averaged (achieved with the help of the leaf area index over one seasonal cycle).

The soil parameters and the snow melt parameters have the strongest influence on the quality of the simulation.

The initial values for the model parameters were chosen based on the results of the calibration of the Brixentaler Ache catchment using daily mean values (Drabek 2004) as well as on the values from different references for the following topics:

- Physical characteristics of soil (Leij et al. 1999; Richard and Lüscher 1983, 1987)
- Surface runoff and soil moisture (Wilson et al. 2005; Fritsche 2001)
- Degree day factor (DDF) (Hock 2003; Lundberg and Beringer 2005)
- Leaf area index (Buermann et al. 2001; Scurlock et al. 2001) Calibration Results for the Oetztaler Ache catchment can be seen in Fig. 2.8



**Fig. 2.8** Measured hourly mean discharge and modelled runoff and snow-water equivalent (SWE) of the snow cover with  $HQ_{SIM}$  for the Oetztaler Ache at the Brunau gauge in 1997. Black – measurement, red – channel discharge modelled with  $HQ_{SIM}$ , green – interflow, lightblue – base flow, blue – snow-water equivalent (SWE)

## 2.4. Glacier Model SES

### 2.4.1 Model Description

To include the glaciated areas of the tributary catchments in the optimal way, they are modelled using an advanced version of the snow and ice melt model SES (Asztalos 2004).

SES is a distributed energy balance model that is used for the calculation of snow, firn and ice melt at hourly intervals, which is linked to a run-off-model (consisting of parallel cascades of linear reservoirs).

Generally short wave radiation supplies the largest input of melt energy to the alpine snow cover, and therefore the albedo of the snow cover or the firn or ice surface of a glacier is of special importance. The albedo changes drastically with progressing metamorphosis of the snow cover and is influenced by possible pollution (e.g. Sahara dust), as well as exhibiting diurnal variation. Therefore, a module was developed for SES to take the temporal change of the albedo as a function of the consumed energy input into account when modelling the glacial melt (Asztalos, 2004, Kirnbauer and Schönlaub 2006). In a following step the modelled melt water amount is routed to the channel via the SES-runoff module.

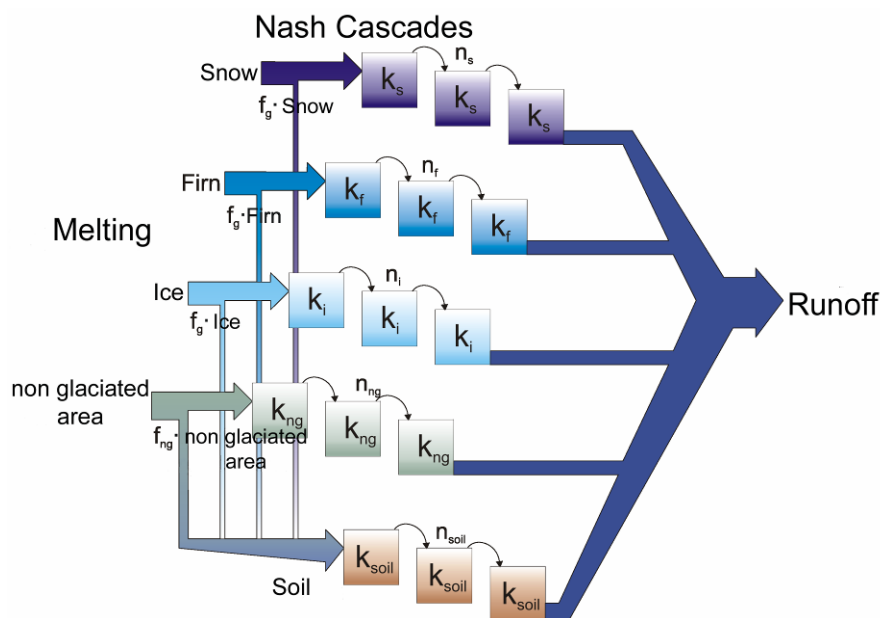
The runoff module of SES consists of five parallel Nash Cascades for snow, firn, ice, non glaciated area and soil (Fig. 2.9). Each of these storage units is defined by the parameters  $n$  and  $k$  of the Nash Cascade. A portion of the melt from the glaciated ( $f_g$ ) or non glaciated ( $f_{ng}$ ) areas, which is determined by a coefficient, reaches the slower reacting soil storage. The sum of the output from the five reservoirs then forms the runoff.

### 2.4.2 Data

For high quality snowmelt modelling with SES it is necessary to include terrain data with high spatial resolution. In the glaciated areas (Table 2.2) a Digital Elevation Model with a grid size of 10m is available (supplied by the State of Tyrol). This model was lumped to a resolution of 50m.

Topographic characteristics such as slope, aspect, curvature and local horizon were determined from the digital elevation model with a resolution of 50x50m. Besides air temperature and precipitation, meteorological data such as temperature gradient, relative humidity, global radiation and wind speed are needed for the SES.

These factors were determined for the centre of each respective glaciated catchment area.



**Fig. 2.9** Scheme of the runoff concentration in SES

### 2.4.3 Calibration

The calibration of the glaciated areas with SES was achieved in two steps. Firstly, the snowmelt module of SES was calibrated by means of the patterns of snow-free areas derived from photographs taken by an automatic camera on the Schwarzkögele above the Vernagtferner, set up by the Committee for Glaciology of the Bavarian Academy of Sciences and Humanities. These photographs were rectified to a map scale and compared to the depletion patterns simulated by SES. In addition, the hydrograph and cumulative curves of the runoff at the highly glaciated gauging station Vernagtbach were used to refine the calibration of this module. Secondly, the parameters of the runoff concentration module were calibrated against measured discharge at the gauges at Vent upstream of Niedertalbach, Vent downstream of Niedertalbach and Obergurgl.



## 2.5 The Hydrodynamic Model

### 2.5.1 Model Description

As mentioned in section 2.1.3, the scope of the hydrodynamic model is the calculation of the flood wave propagation in the river channel. Compared with hydrological flood routing methods, a lot more data about the river channel must be available to build a hydrodynamic model.

The flow in a river channel can be described mathematically by a set of partial differential equations known as the Saint-Venant-Equations, a simplification of the Navier-Stokes-Equations (Chanson 2004). These equations are solved numerically by the hydrodynamic model. The model used in this system is referred to as a one-dimensional (1D) model, which indicates that the flow velocity is assumed to be uniform over the entire cross-section of the river channel. This is of course a simplification but 1D-models have proven to be accurate enough for many applications. Of course multidimensional models (2D, 3D) are more accurate, but they require a lot more terrain data as well as computational resources and therefore computing time.

A hydrodynamic model used within a forecast system must guarantee numerically stable simulations over a wide range of discharges and simultaneously provide accurate results. Furthermore, most of these models are large as they cover a long reach of a river as a whole. As in the case of an impending flood new simulations should be performed quite frequently (up to every hour), the computation time must be kept as short as possible.

The model of the river Inn represents a section of 196.517km and was created with the software Flux<sup>DSS/DESIGNER</sup> which uses the code Floris<sup>2000</sup> (Reichel et al. 2000) as computational core. Important factors in this choice were the ability to represent the operation of weirs and run-of-river power plants in the model and a history of successful applications in other forecast systems.

### 2.5.2 Data

To set up a 1D-hydrodynamic model, cross section data from the course of the river is needed to define the geometry. In the case of a natural or semi-natural river, the cross section data should not be too old, as the river bed is constantly changing due to erosion and deposition of bedload material.

To keep the forecast system up to date, the cross section data should be updated regularly.

For the Tyrolean section of the river Inn, more than 800 cross sections are available. Cross section surveys are carried out every seven to eight years, the last one after the flood event in 2005.

As input data the inflow hydrographs at the upstream boundary and from tributaries are used. Inflow from tributaries can be incorporated into the model between two cross sections. As the model represents a long reach of the river Inn, not all tributaries are considered individually. While large tributaries are represented separately, smaller ones are combined into groups on the basis of their size and the location of their catchment area. The definition of the represented tributaries is of course coordinated with the hydrological model (see section 2.3.3).

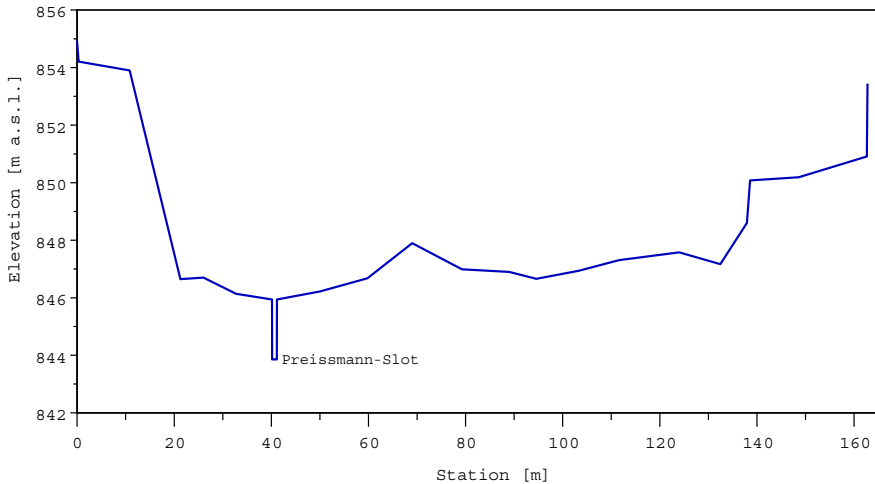
As boundary conditions at the downstream end of the model, a stage-discharge-relationship or a water level hydrograph is needed. Along the river Inn several gauging stations and weirs are located which can be used as a downstream boundary as well as for model control.

The upstream boundary is the gauging station at Martinsbruck at the Swiss-Austrian border, while the run-of-river power station Ebbs-Oberaudorf is used as a downstream boundary.

### ***Data Preparation***

Before incorporating the cross section data into the hydrodynamic model, they had to be prepared to ensure numerical stability and model accuracy.

The surveyed cross section points should be situated along a line perpendicular to the flow direction. If this was not the case, they were projected onto the perpendicular. The survey data of a cross section might include parts located much higher than the river which will never be below the water level. Those parts were eliminated as they would have decreased the spatial resolution of cross-section related data in the vertical direction. In cross sections extending into the floodplains the boundary between the river channel and the floodplain was defined. To avoid very low flow depths or completely dry cross sections at low flow conditions or in river branches with only residual flow, so called Preissmann-slots (Cunge et al. 1980) were inserted, which enable the use of a more efficient numerical scheme for the simulation (Fig. 2.10).



**Fig. 2.10** Cross section geometry at river-km 382.009 with a Preissmann-slot inserted at the lowest point

### 2.5.3 Calibration

After setup the model has to be calibrated – certain model parameters are modified so that observed events can be reproduced as well as possible. In a 1D-hydrodynamic model the main calibration parameters are the roughness coefficients of the cross sections representing the flow resistance of the river bed. In the applied code, roughness coefficients given by the Gauckler-Manning-Strickler-Formula (Chanson 2004) ( $k_{st}$ ) are used. If observed water level-data for a known discharge is available, the deviations between the calculated and the measured water level can be minimized by adjusting the roughness coefficients.

#### **Method**

Calibration can be done manually, usually through trial and error, which can be quite time consuming if a lot of observed water level data is available.

The software used to set up the model offers a so-called inverse modeling function which allows the automatic estimation of several model parameters, including the roughness coefficients, and therefore an automated calibration. Inverse modelling is an indirect method – the problem is not stated inversely but the equations are repeatedly solved with varying pa-

rameters. An objective function expressing the weighted residuals between measured and calculated data is minimized with the Marquardt-Levenberg-Algorithm (Nash 1990). The weights can be used to take measuring errors (Reichel and Baumhackl, 2000) into account. Furthermore, initial values for the roughness coefficients have to be defined. Usually, several inverse simulations are carried out consecutively, each using the results of the previous one as initial values.

Given the size of the model and the amount of available data, inverse modelling was chosen as the calibration method, rather than manual calibration. Leonhardt et al. (2006) compared the two methods using data from a reach of the river Inn and discussed the application of inverse modelling in cases of different availability of water level data.

For better handling, the model was divided into 10 sections bounded by gauging stations and weirs respectively. The inverse modelling function was then used to calibrate the model sections under steady state conditions. The calibrated roughness coefficients were transferred into the overall model.

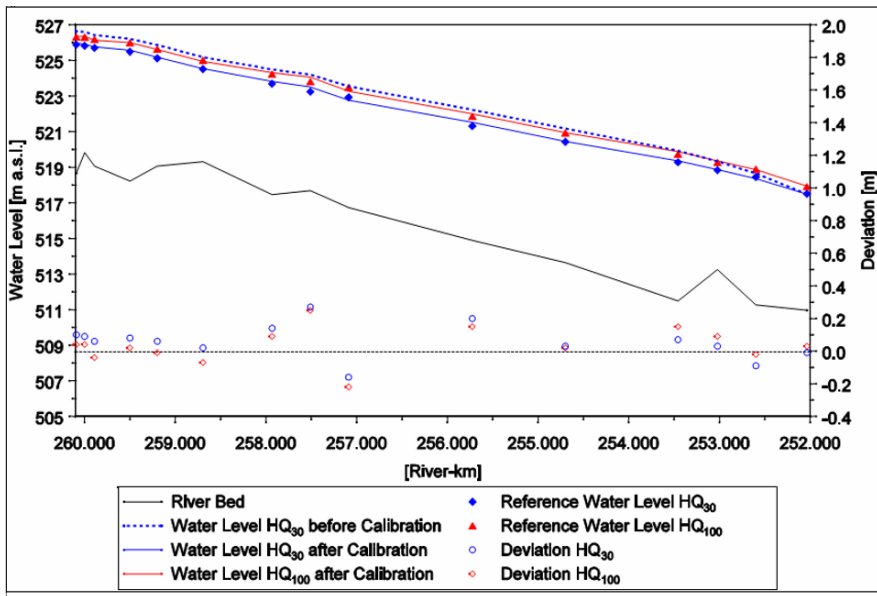
The objective of the calibration was to achieve water level deviations lower than 0.2m.

## **Data**

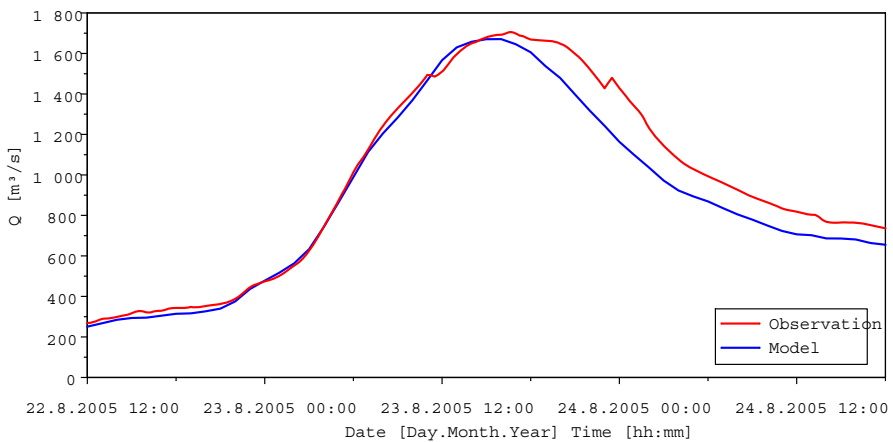
The first data used for calibration were water levels for design discharges ( $HQ_{30}$ ,  $HQ_{100}$ ) at all cross-sections obtained from another investigation with a numerical model (TIWAG 1999-2003). The values for the  $HQ_{30}$  discharge served as calibration data while the  $HQ_{100}$  discharges were used for model verification. Figure 2.11 shows the computed water level before and after calibration for the river section between Rotholz and Brixlegg.

The flood event in August 2005 provided a lot of important data to evaluate the hydrodynamic model. Not only discharge and water level data from the gauging stations was available, but also a survey of the marks of the maximum water levels at many cross sections was carried out a few days after the event.

The evaluation of the model with the data from the flood event proved that the flood wave propagation can be reproduced satisfactory. The deviations between the calculated and the observed maximum discharge at the gauging stations were small, considering that data from small tributaries was not available. Among the gauging stations which are not heavily influenced by run-of-river power plants, the maximum deviation was -5.3%. Looking at the hydrographs in Fig. 2.12 it is evident that the rise could be reproduced better than the decline.



**Fig. 2.11** Calibration of the section Rotholz – Brixlegg using inverse modelling. Calibration data: HQ<sub>30</sub> design discharge; validation data: HQ<sub>100</sub> discharge



**Fig. 2.12** Flood hydrograph at the gauging station at Rotholz on August 23<sup>rd</sup>, 2005 – observation and model output

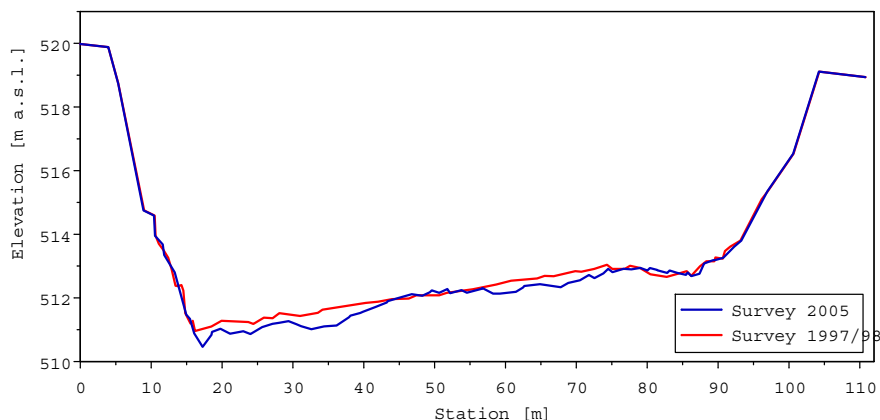
Compared with the observed data the calculated maximum water level was too high at many cross sections. Simulation results showed deviations

up to 1,5m. One reason for this could be bed degradation and the intense bedload transport occurring in the river Inn during flood events, which are not considered in the model. The occurrence of bed degradation can be proven by comparing different surveys of the same cross section (Fig. 2.13).

As a new cross section survey was conducted after the flood event in August 2005, it was decided that this would be a good time to develop the model further and update it accordingly. Therefore, a new calibration was necessary, which was carried out with the help of the data gained during and after the flood event.

The inverse modelling function was used again for calibration. Hydrographs from the flood event and the survey of the maximum water levels were used as calibration data. As inverse modelling only works satisfactorily in steady state simulations, corresponding inflows for the latter had to be determined. A simulation with the flood hydrographs as input was conducted to determine the maximum discharge for every cross section and to estimate the error caused by neglecting small tributaries without a gauging station. As the latter was quite small, no additional inflow was added for correction. Then the steady state inflow from all tributaries was determined, so that the steady state discharge at all cross sections was equal to the maximum flood discharge.

The calibration results were evaluated with steady state discharge as well as the flood hydrograph.



**Fig. 2.13** Cross section at km 252.035; data from the cross section surveys conducted in 1997/98 and 2005 (after the flood event in August 2005)

## Results

As already presented in the example by Leonhardt et al. (2006), satisfying results were achieved for most cross sections within a few simulations, while for a few cross sections water level deviations remained too large. For the latter, a manual refinement of the calibration was necessary, including adjustment of the roughness coefficients as well as modifications of the cross section geometry. Cross section modifications were carried out in the riverbed and sometimes in the floodplain. In most cases the riverbed had to be lowered, which is justifiable when modelling flood flow without considering bedload transport.

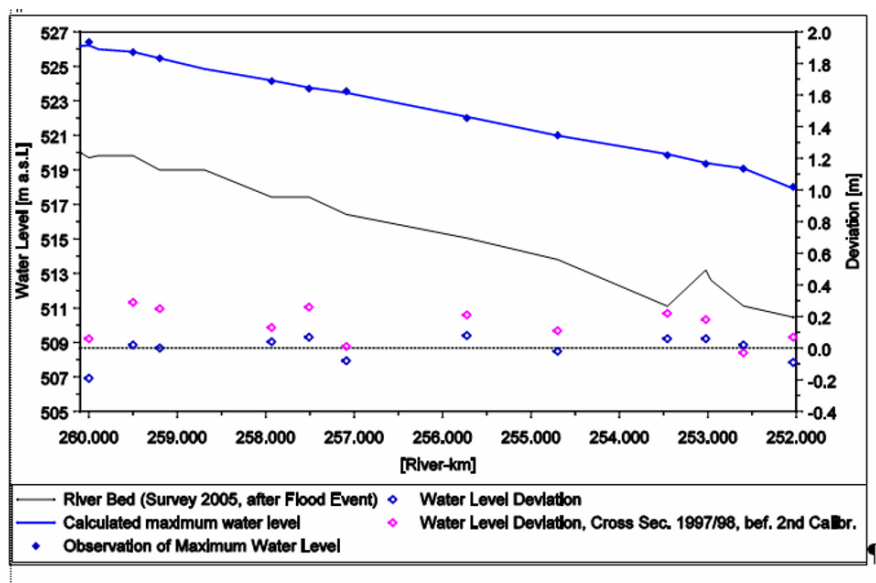
The roughness coefficients determined by inverse modelling are often very high (corresponding to a very smooth bed). Some of them are as high as  $70\text{m}^{1/3}/\text{s}$ , values which certainly do not correspond to the natural condition of the riverbed. This might of course in part be a compensation for the neglect of bedload transport and erosion, but not completely. As a low flow resistance might cause supercritical flow (which does not occur in a natural river) and therefore numerical problems, an upper limit for the roughness coefficients was determined for different reaches and higher values were reduced to that limit. For the river Inn, those limits were set to  $k_{St} = 40\text{m}^{1/3}/\text{s}$  for the reach upstream of Innsbruck and  $k_{St} = 50\text{m}^{1/3}/\text{s}$  for the reach downstream, respectively. Although this was a major change to some values, the water level results were not significantly influenced and remained satisfactory (Fig. 2.14).

In the vicinity of run-of-river power stations, calibration had to be carried out taking weir operation into consideration. The special problems of those areas are discussed in Section 2.5.4.

## Conclusions

Calibration of the hydrodynamic model is of major importance for a correct prediction of the water level, which still remains a challenging task.

Results of a calibration with inverse modelling are of equal quality with those of a manual calibration, but for large models and large amounts of calibration data they can be acquired with less time effort. A manual refinement is necessary and unrealistically smooth friction factors can be corrected without a major influence on the water level results (Leonhardt et al. 2006).



**Fig. 2.14** Second calibration of the section Rotholz – Brixlegg using inverse modelling with manual refinements/upper limit of the roughness coefficients (Strickler). Data: Cross section survey 2005, August 2005 flood hydrograph, marks of maximum water level (for comparison the deviation of the maximum water level in the first model evaluation is included)

## 2.5.4 Rule-Based Operation of Power Plants

In the hydrodynamic model the management of the run-of-river and diversion power stations on the Inn can be taken into consideration. There are three power stations on the Tyrolean Inn that use weir plants and therefore reservoir storage in the river channel.

### ***Power plants Kirchbichl and Langkampfen***

The power plant at Kirchbichl, about 60km downstream of Innsbruck, is situated on a distinctive meander (Fig. 2.1). The headwater is conducted into the power plant via a canal that cuts off the river bend. The power plant does not make use of hydropneumatics. The constant water level of 497m a.s.l. is regulated via turbine discharge of up to  $300\text{m}^3/\text{s}$  (design discharge). If the discharge exceeds  $300\text{m}^3/\text{s}$  the water level is regulated by



the weir and water is released into the residual flow reach. If the discharge exceeds  $700\text{m}^3/\text{s}$  then the plant shuts down and free flow is established at the weir (Reindl 2004).

The low-pressure barrage plant at Langkampfen is situated 6.2km downstream of Kirchbichl (Fig. 2.1). The backwater reaches up to the bend at Kirchbichl and consequently is connected directly to the power plant there. The weir level is held at a constant 487,3m a.s.l. At a discharge of over  $1,287\text{m}^3/\text{s}$  the power plant shuts down and allows free flow.

### ***Power plant Imst and weir plant Runserau***

The weir plant Runserau lies 94km upstream from Innsbruck close to Landeck. The headwater is diverted at the weir and is conducted via a 12,5km long gallery to the power plant near Imst (Fig. 2.1). After its use in the power plant, at a design discharge of  $85\text{m}^3/\text{s}$ , the water is then released back into the Inn via a canal.

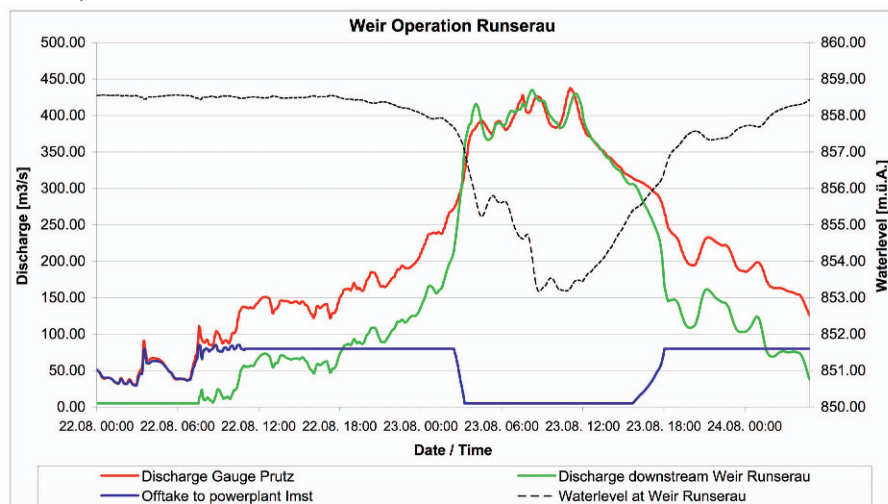
The maximum diverted amount at the weir Runserau lies between 75 and  $80\text{m}^3/\text{s}$ . A minimum instream flow of 1 to  $3\text{m}^3/\text{s}$  is maintained in the bypass reach of the river. If the discharge of the Inn exceeds  $80\text{m}^3/\text{s}$  at the gauge at Prutz, excess water is passed into the bypass reach. In the case of a further increase of discharge the water level at the weir is reduced from 858.5m a.s.l. to 855m a.s.l. At a discharge of  $300\text{m}^3/\text{s}$  the weir gates are opened and free flow is established. When the discharge is low, a portion of the reservoir storage is used for hydropeaking on a daily basis (Reindl 2004).

**Table 2.3** Simplified weir operation Runserau

Discharge at Prutz Gauge	Water level weir Runserau	Discharge in bypass reach
Up to $80\text{m}^3/\text{s}$	858.5m a.s.l.	1 to $3\text{m}^3/\text{s}$
80 to $300\text{m}^3/\text{s}$	Lowering down to 855m a.s.l.	Amount of flow exceeding the design discharge of the intake
Over $300\text{m}^3/\text{s}$	Free flow at the weir	Total discharge

The following example shows the modelled power plant operation for the flood event on August 23, 2005 (Fig. 2.15). At the beginning of the event (up to 7.30 a.m., August 22) only the minimum acceptable flow was conducted into the bypass reach (green hydrograph in Fig. 2.15). The power plant flow rate (blue) was being regulated at this time so the water-level at the weir was being held at 858.5m a.s.l. When the design discharge in the tributary exceeded  $80\text{m}^3/\text{s}$ , the excess amount of water was released into the bypass reach (up to 2.30 a.m. on the 23<sup>rd</sup>). As soon as the dis-

charge upstream of the weir exceeded  $300\text{m}^3/\text{s}$  (red hydrograph), operation at the power plant was shut down (from 2.30 a.m. on the 23<sup>rd</sup> onwards) and the weir gates were opened (see water level hydrograph, black dashes). As soon as the inflow was lower than  $300\text{m}^3/\text{s}$ , the weir level was raised and operation in the power plant started again (from 4 p.m. on the 23<sup>rd</sup> onwards).



**Fig. 2.15** Modelled operation at the Runserau weir for the flood in August 2005

### ***Aim of modelling power plant operation***

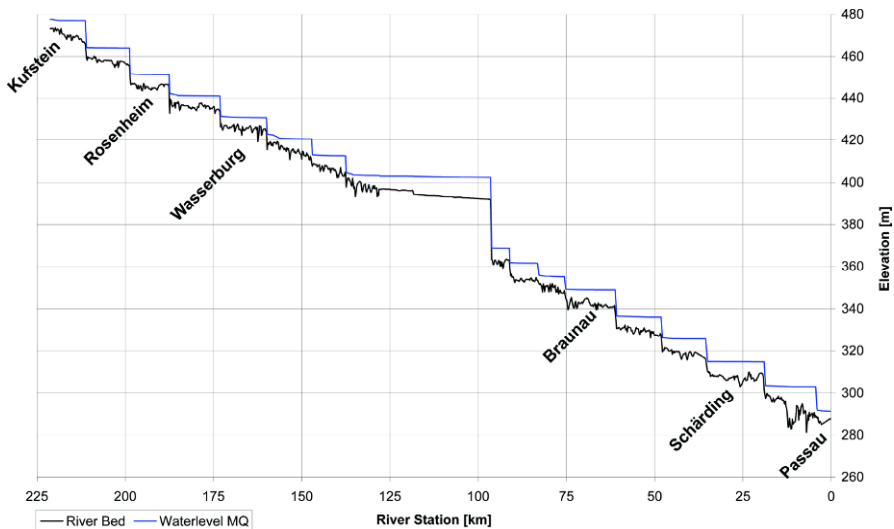
The aim of integrating the operation of power plants into the hydraulic model is to be able to incorporate their influence in a flood situation into the forecast. The actual chosen operational plan can vary from that of the model. Normally, when the final forecast is generated, there are no exact operational plans available, because these plans often have to be adjusted very quickly according to the approaching flood wave and changes in the discharge. For this reason, the standard operational plan that was chosen in the model offers a good assessment of the expected situation for the residents downstream of the power plant.

### **2.5.5 Hydrodynamic Model for the Bavarian Inn**

The hydrodynamic model was generated for the Bavarian section of the Inn from Kufstein to the confluence with the Danube at Passau. This was done in cooperation with the Bavarian State Office for Environmental Pro-

tection (Bayerisches Landesamt für Umwelt) and SCIETEC River Management Corporation (SCIETEC Flussmanagement GmbH). This model differs from the Tyrolean one due to the large influence of run-of-river power plants. About 85-90% of the course of the river lies in the direct backwater areas of one of the 16 power plants (Fig. 2.16).

Additionally, the calibration of the model for the Bavarian Inn had to take other prerequisites and data into consideration. In contrast to the Tyrolean section of the Inn, the water levels and corresponding discharges were not available for every cross section. The calibration was based on only a few gauge measurements for every section, which is the reason why several cross sections in the model were calibrated with the same roughness coefficient. The maximum values (flood peak) of the measured discharge and stage hydrographs were used for the calibration. The available measurements for some sections of the highest water level during the passage of a flood wave correlated in several areas very badly with the corresponding gauge measurements. Consequently, these measurements were mostly not used for the calibration.



**Fig. 2.16** Longitudinal section of the riverbed and water level on the Bavarian Inn at average discharge (MQ). The stepped water level course is created by the backwater from the power plants' weirs

One of the problems that arose were the high Strickler coefficients in the backwater of the power plants, which resulted from the calibration using the available water level data. The reason for these unrealistically smooth conditions was found in the change of the cross section geometry during a

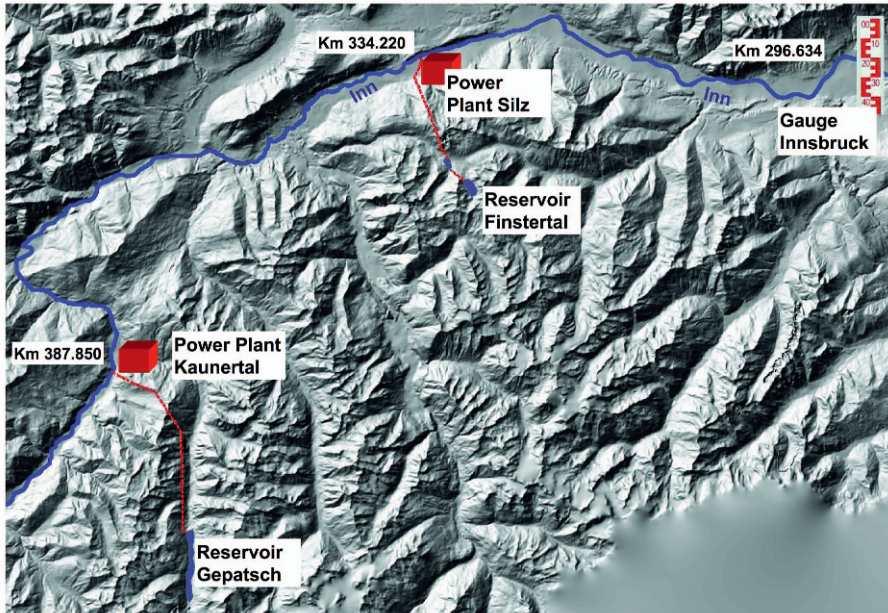
flood event due to the mobilisation of large amounts of bed material. Subsequently, erosion leads to a fall in the water level, which can be represented in a model using stable cross sections only by a rise of Strickler coefficients (reduction in roughness). In agreement with the model operators and after variation calculations for the estimation of sensitivity, a combination of an upper limit for the Strickler coefficients and the modification of the cross section geometry was chosen as the best approach.

### **2.5.6 Potential for the Optimization of the Operational Management of Alpine Reservoirs – Example Based on the Flood in August 2005**

It was possible to reduce the flood peak in the lower Inn for the August 2005 flood by optimizing the operational management of the power plant reservoirs in the upper reaches of the river Inn. The reservoirs of the TIWAG Tiroler Wasserkraft AG (Tyrol electricity provider) (Kaunertal and Sellrain-Silz – Fig. 2.17) and the intakes of the Vorarlberger Illwerke AG (Vorarlberg electricity provider) from streams in the Paznaun-Region in the southwest of Tyrol caused a reduction in the maximum discharge of ca.  $60\text{m}^3/\text{s}$  for the Innsbruck gauge (Hofer 2005). The operational management of the TIWAG power plants Kaunertal and Sellrain-Silz was examined in more detail with the hydraulic model performing simulations of different scenarios.

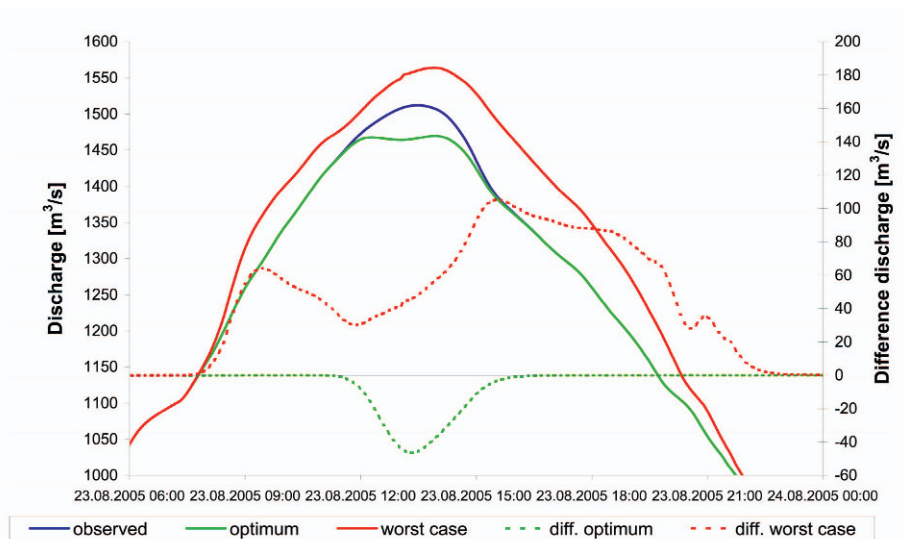
It is important to mention that these ex-post analyses were made using observed gauge data which was not available to the power plant operators during the event. The forecast system was not yet ready in 2005. This survey was meant to show and enable a discussion of the potential of the optimized operational management.

In the future decisions could be based solely on flood forecasts. The quality of the forecast will influence the results of the optimization quite essentially.



**Fig. 2.17** Location of the components of the variation calculation: reservoirs and power plants Sellrain Silz and Kaunertal, river kilometre (Km) of the tailwater discharges and the gauge at Innsbruck

The analysis was performed with the hydrodynamic model developed for the forecast system. Observed hydrographs of the Inn and its tributaries were used as input data and the calculated output hydrograph for the Innsbruck gauge was used as the basis for the analysis. The operational management of the power plants Kaunertal and Sellrain-Silz was varied in numerous scenarios to see how the maximum discharge could be reduced. The figure below (Fig. 2.18) compares the observed hydrograph with the worst-case scenario (complete design discharge during the whole event) and the optimized operational management variant. The actual management strategy implemented a reduction of about  $52\text{m}^3/\text{s}$  in the maximum discharge at Innsbruck in comparison with the worst case scenario. With the optimized variant the peak discharge at the gauge Innsbruck could have been reduced by another  $43\text{m}^3/\text{s}$  (which equals about 9cm in water level). These marginal values could be quite significant when considering the small remaining freeboard in the centre of Innsbruck.



**Fig. 2.18** Discharge hydrographs for the gauge in Innsbruck: observed, worst-case scenario, optimized variant

The example shows that, in the case of a relatively accurate forecast, it is possible, without needing a great deal of extra storage capacity, to make a decisive difference through the potential optimization of reservoir management. It is also possible to see how the quality of the forecast decisively influences the success of any measures taken. Optimum timing can only be found in very good forecasts. Through the operation of the model in the coming years it will be observable, whether the quality of the forecast can meet the requirements in the actual event.

## 2.6 Summary

A flood forecast system is an important contribution to effective flood risk-management. Particularly in the case of events potentially exceeding the design discharge of protection measures, it is essential to provide reliable information as early as possible.

While the first flood forecast systems were mostly based on empirical models, the hybrid approach using hydrological as well as hydrodynamic models is becoming more popular (Godina 2006). By using different models to describe the different processes contributing to the formation of a flood, it is possible to consider several regional distinctions. In the case of the river Inn, the alpine topography (snow line), glacier runoff and the influence of hydroelectric power plants (alpine reservoirs as well as run-of-

river power stations) are important factors considered in the forecast system. In contrast to a detailed local analysis of a particular problem, different issues have to be emphasized when setting up models of the forecast system. For instance, the stability and the computing time of the hydrodynamic model is of greater relevance in the forecast system. Integrated and reliable data management is essential for large amounts of input data and to provide unproblematic data flow between the different models as well as for the visualization of the results.

The forecast system provides a lot of detailed information. Therefore, it must be operated by experts who have a good knowledge of the river Inn and its catchment area and are therefore able to interpret and review the results. Additionally, the system should be constantly enhanced and updated as every flood event provides new experiences and information.

As the presented examples show, not only the public authorities responsible for flood warning and protection, but also hydropower operators can benefit from the flood forecast system. The forthcoming test period will be the first challenge for the forecast system and its operators and will possibly show some potential for optimization.

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