Chapter 4
Validation of the Hydrological Modelling in DANUBIA

Wolfram Mauser

Abstract The physically based, spatially distributed hydrological and land surface model PROMET is used in GLOWA-Danube to simulate the land surface and hydrologic processed as well as the impact of hydraulic structures on the natural water flows. The unique features, which make PROMET suitable for global change impact analysis in the field of hydrology within GLOWA-Danube, are explained, and PROMET was extensively validated for an extended climatic period from 1971 to 2003. The validation consisted of three steps which include the annual variability of the water balance over a climatic period, the daily variation of run-off and the annual peak discharges and low flows. The validation was carried out for the whole basin and selected subbasins differing in size and conditions. The validation shows good to very good results. Weak results can be attributed to human interventions as well as failures in hydraulic structures, which are not covered by PROMET.

Keywords GLOWA-Danube • PROMET • Ungauged watersheds • Hydrologic modelling

4.1 Introduction

The most accurate modelling of the hydrological cycle and the associated flows of water between the various hydrological components of the Upper Danube basin is a crucial feature for the exploration of future changes in the water cycle and the diverse consequences that result therefrom. The hydrological model that is used must be capable of providing accurate results under a broad range of environmental conditions, i.e. it can correctly simulate the flows of water in the basin, even under conditions in the future that may be remarkably different from today's situation.

W. Mauser (✉)
Department of Geography, Ludwig-Maximilians-Universität München (LMU Munich),
Munich, Germany
e-mail: w.mauser@lmu.de

The changes in the conditions relate to a wide range of factors, including, among others:

1. Climate change
2. Changes in land use and land cover (this includes the response of the vegetation to increased water stress and changes in CO_2 concentrations, as well as possible intensification of agriculture)
3. Changes in the water management and supply infrastructure as a result of the construction of new hydraulic structures (reservoirs, diversions, hydropower plants, flood protection measures, etc.)
4. Changes in the use of water, e.g. the introduction of irrigation

4.2 The Hydrological Model PROMET as a Supplement to DANUBIA

In the development of the DANUBIA components that describe the hydrological processes occurring at the land surface, considerable effort was made to realise the mutual interactions via appropriate interfaces, through which data is exchanged. The data represents the mutual interactions between the components. This effort generated the *Surface*, *Soil*, *Biological* and *Snow and Ice* components in DANUBIA. With a total of over 100 interfaces over which data exchange takes place, these components constitute a very comprehensive model system that reproduces well the complexity of the processes at the land surface. This structural complexity has corresponding effects on the performance of the *Landsurface* component. For this reason, it was decided to modify and make equivalent in its results the hydrological model PROMET (Mauser and Schädlich 1998; Mauser and Bach 2009) for operational purposes of simulating long and computationally intensive DANUBIA scenarios. PROMET was not developed in the context of the project and essentially is a non-object-oriented hydrological land surface model, which was developed in FORTRAN. It was integrated with DANUBIA to replace the DANUBIA's *Landsurface* component in order to increase the performance in the practical implementation of DANUBIA. The physical basis of PROMET is virtually identical with the original *Landsurface* component in terms of its description of the hydrological processes at the land surface, but avoids the high complexity of the interfaces because the components are internally coupled. The following principles are implemented in both DANUBIA and PROMET:

- Comprehensive physical and physiological description of the processes in the context of the flows of water in a mesoscale alpine drainage basin. This comprises the following processes:
  - Ingestion of meteorological drivers, either from regionally downscaled and bias-corrected climate models (Chap. 51) or from spatially and temporally interpolated station data (Chaps. 49 and 50).

  – Energy and mass exchange between the land surface and the atmosphere, including the physiological control of gas exchange (interception, evapotranspiration, sensible heat flow, carbon exchange, radiation balance, momentum exchange).
  – Dynamic, vegetation canopy development, which describes mechanistically the physiological processes related to photosynthesis, respiration, phenological development, canopy development and yield.
  – The dynamics of snow and ice.
  – Vertical and lateral, as well as saturated and unsaturated, flows of water (infiltration, interflow, surface discharge, groundwater flow).
  – Channel run-off and flows through natural lakes as a self-organised process dependent on relief.
  – Flows through hydraulic structures such as run-of-the-river hydropower stations, reservoirs and diversions, sewage plants, etc.

• Rigorous adherence to the laws of conservation of mass and energy.
• Spatial distribution in modelling the processes based on an isotropic spatial grid.
• Ensuring physical consistency and the predictive ability by largely avoiding calibration. This means that basin-wide the same rules apply to determine the spatially distributed values for the model parameters from first-order physical and/ or physiological principles. This implies that parameter optimisation in sub-catchments of the basin using measured discharges at singular locations of gauges is not applied. Instead, values from literature, measurements (on the ground or via remote sensing) and detailed relief analyses are used to initialise the spatially distributed model parameters. All methods used for determining parameter values are implemented in the same consistent way over the entire basin and that no separate rules and methods are applied to subbasins. In this way, it can be ensured that the method used for calculating the spatial distribution of a parameter also covers a broad range of values.

The interactions of the different elements of the hydrological cycle in PROMET are described in detail in its current form in Mauser and Bach (2009) and the cooperation between it and DANUBIA is shown in Fig. 4.1.

4.3 Validation of the Model

PROMET was set up as described above. The water flows for the meteorological period from 1970 to 2003 were modelled for the entire Upper Danube basin. This study period is longer than the typical climate period of 1971-2000. The extra initial year was included to spin up the groundwater reserves; the period was also intentionally extended to include the exceptionally warm year 2003 in the analysis. Simulation of the entire period was conducted continuously and with a 1-h model time interval. Analysis of the results was performed using measured discharges at sample gauges in the Upper Danube basin. These comprise both the outlet gauge at
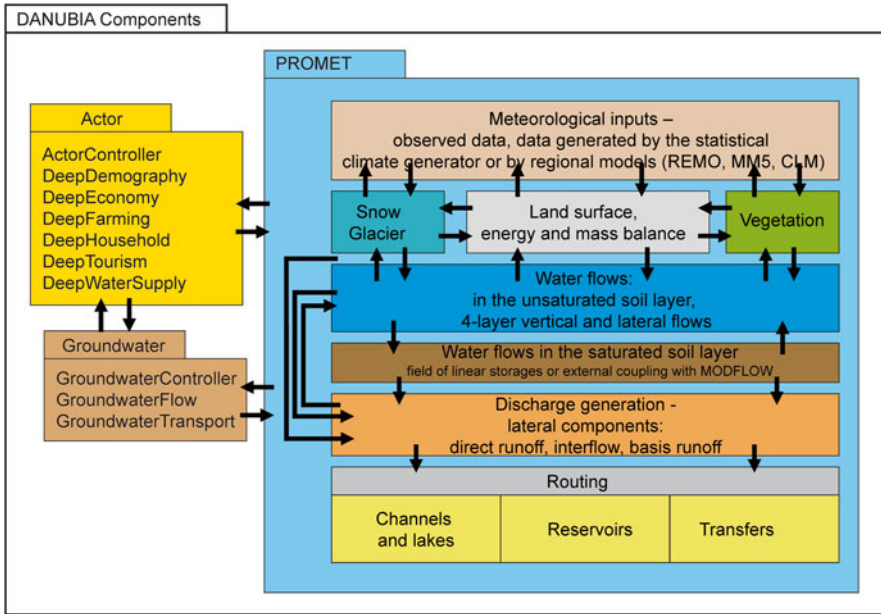
Fig. 4.1 Integration of subcomponents of the hydrological PROMET model and DANUBIA

Table 4.1 Selected gauges for the validation of PROMET 1971–2003

Gauge/river	Area [km²]	Elevation gradient	MQ [m³/s]	Discharge coefficient
Achleiten/Danube	76,673	2.96	1,590	0.55
Hofkirchen/Danube	46,496	2.09	640	0.57
Dillingen/Danube	11,350	1.67	162	0.57
Oberaudorf/Danube	9,715	4.07	307	0.78
Plattling/Isar	8,435	2.34	175	0.58
Laufen/Salzach	6,112	3.46	239	0.80
Heitzenhofen/Naab	5,431	1.48	49.8	0.40
Weilheim/Ammer	607	1.63	15.4	0.74

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Achleiten near Passau and gauges in the subbasins, selected such that a wide array of basin sizes and hydrological regimes were covered. The gauges selected and their basins are listed in Table 4.1.

Table 4.1 indicates the large variation in the size of the basins that were selected. They sometimes differ considerably in elevation gradient and in discharge coefficients from those at gauge Achleiten at the outlet of the Upper Danube. The modelled region of the Central Alps is primarily drained via the Inn and Salzach rivers. The corresponding gauges at Oberaudorf and Laufen have high discharge

coefficients and elevation gradients. Parts of the northern alpine foothills drain via the Isar and Ammer/Amper rivers and their gauges (Plattling and Weilheim). They exhibit average discharge coefficients and elevation gradients. The lowest values come from the Naab subbasin in the northern part of the Upper Danube.

Validation of the hydrological model took place in three steps: first, the annual water balance was calculated for the whole basin and the subbasins. The results of this analysis give an indication of the validity of the surface model component to simulate water balance. Because of the high degree of temporal aggregation, they are not able to provide information about the validity of simulation of soil processes and lateral flows.

4.3.1 Annual Water Balance

Table 4.2 presents the results of a regression analysis (slope S, coefficient of determination R^2) as a complement to these results. The regression line was chosen such that it intersects the zero point. This approach results in the strictest possible criterion for a comparison between measurement and simulated values, since it is assumed that when a discharge is measured as 0 m^3/s, the modelling likewise yields 0 m^3/s and hence there is no offset. If the slope S has a value of 1.0, then there is no systematic under- or overestimation of the discharge by the model. If the coefficient of determination R^2 were also 1.0, then the measured and modelled datasets would be identical.

In general, the slopes approach a value of 1.0, with the highest positive deviation of 14 % originates from an overestimate at gauge Dillingen and the greatest underestimate of 7 % occurs at the gauge Salzach. The respective coefficients of determination are consistently high to very high, a result which suggests that the overall annual variability of the discharges over the 33-year period is well modelled both in the entire basin and in the partial subbasin areas.

Table 4.2 Gradient S and coefficient of determination R^2 of the linear regression of modelled and observed annual discharge at selected gauges in the Upper Danube basin, 1971–2003

Gauge	Gradient S	Coefficient of determination R^2
Achleiten	1.05	0.93
Hofkirchen	1.12	0.93
Dillingen	1.14	0.93
Oberaudorf	0.99	0.80
Plattling	1.03	0.88
Laufen	0.93	0.85
Heitzenhofen	1.01	0.86
Weilheim	1.09	0.88

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4.3.2   Daily Run-Off

In the second step, the hourly discharges were aggregated to form daily values. These were compared with the data measured at the gauges. The aggregation is required since artefacts would otherwise create larger discrepancies between the measured and modelled discharges. These discrepancies are caused by the fact that the temporal allocation of the hourly precipitation totals within the "Mannheim hours" (time intervals at 7:30, 14:30 and 21:30) (see Chap. 49 spatial interpolation) is not unequivocal (in contrast to hourly discharge measurements) and hence there are undefined temporal shifts in the modelled hourly discharges of approximately 5 h on average.

Figure 4.2 shows the pattern of measured and modelled daily discharges at gauge Achleiten for the years 1971–2003. It is notable that the measured and modelled courses are generally quite similar in terms of low flows and peak discharges. Relatively wet periods around 1980 are contrasted with dry periods, for example, in the years 1971 or 2003. To more closely examine the relationship between the two discharge curves in Fig. 4.2, they were subjected to a regression analysis using the same method that was used for the annual discharges above (see Table 4.2). The result is shown in Fig. 4.3. The modelled results indicate a slight trend towards overestimation of discharges (3 %) and a very high coefficient of determination, $R^2 = 0.87$. However, extreme discharges above 4,000 m³/s depict a fairly high degree of variation, suggesting that flood events are not modelled with the same precision as the more moderate discharges.
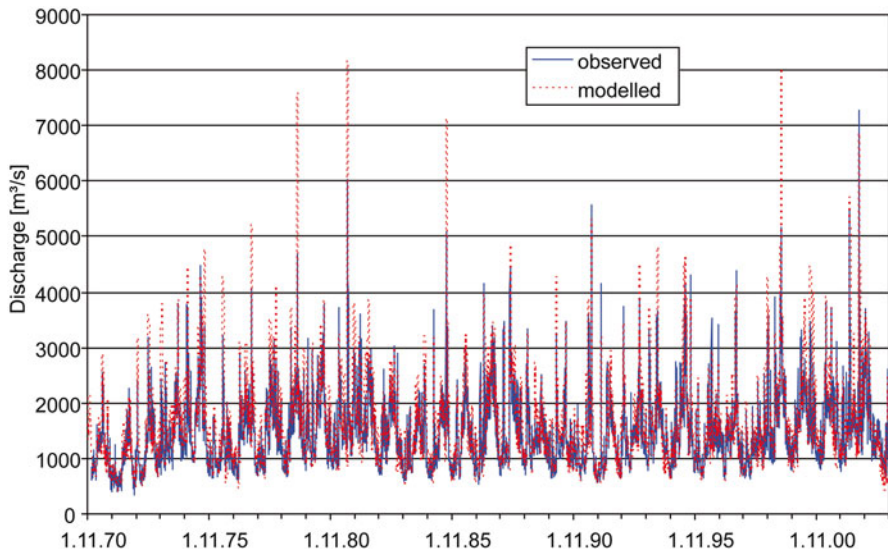
Fig. 4.2 Observed and modelled daily discharges at gauge Achleiten for the time period 1971–2003 (Adapted from Mauser and Bach 2009, p. 372)

Fig. 4.3 Comparison of observed and modelled daily discharges at gauge Achleiten for the time period 1971–2003 (Reprinted from Mauser and Bach 2009, p. 372, with permission from Elsevier)
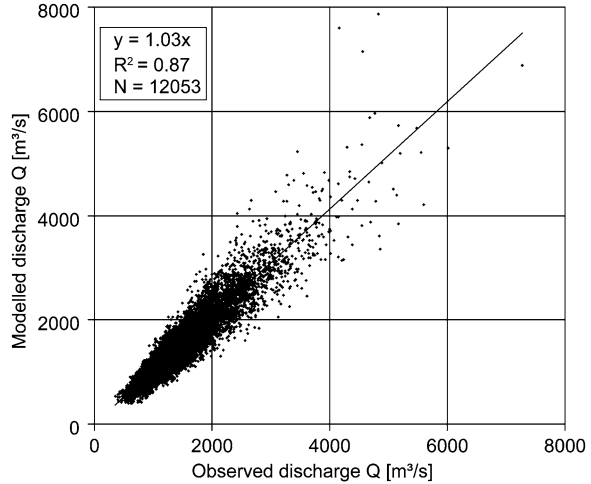
Table 4.3 Gradient S and coefficient of determination R^2 of linear regression and Nash-Sutcliffe coefficient of modelled and observed daily discharges at the selected gauges in the Upper Danube drainage basin, time period 1971–2003

Gauge	Gradient S	R^2	Nash-Sutcliffe coefficient
Achleiten	1.03	0.87	0.84
Hofkirchen	1.11	0.87	0.81
Dillingen	1.13	0.84	0.72
Oberaudorf	0.94	0.81	0.80
Plattling	1.08	0.75	0.47
Laufen	0.86	0.85	0.80
Heitzenhofen	0.99	0.78	0.79
Weilheim	0.98	0.73	0.69

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The method outlined in Fig. 4.3 was applied to all selected gauges and yielded the values shown in Table 4.3.

Compared to Table 4.2, in which the annual discharge volumes were contrasted for the various gauges, the differences in the slopes for the daily discharges are more marked. They range from a moderate overestimate by 13 % at Dillingen to a moderate underestimate of discharges by 14 % at gauge Laufen/Salzach. The coefficients of determination for the daily discharges are consistently high, but lower than those for the annual discharges (see Table 4.2); this result is the consequence of the greater variability of the daily discharges. Gauge Plattling is the most striking in terms of the coefficient of determination and the Nash-Sutcliffe coefficient; in this case, both values are relatively low and the modelling does not render a good result. The relatively poor correspondence between the measured and modelled daily discharges at this gauge is primarily the result of the influence of the Sylvenstein reservoir and the various diversions, for example, in the Inn region. Although the Sylvenstein reservoir

is implemented within the model, its operation follows simple, normalised monthly rules that produce discharges based on the fill level (see also Chap. 29). These simple rules sometimes differ significantly from the actual operation of the Sylvenstein dam, which from an outside perspective is hard to comprehend. Data on the real operation of the dam was not available to the project. This highlights the limitations of physically based hydrological modelling that are imposed by human interventions, especially if the modelling should provide results about future changes in discharges based on climate change.

Therefore, if the catchment of the Isar up to gauge Plattling is excluded from further analyses, the coefficient of determination between the modelled and measured daily discharges in relation to the size of the subbasins can be examined. This analysis reveals a linear relationship between the coefficient of determination and the log of the subbasin area (see Fig. 4.4). The decrease in the coefficient of determination with decreasing subbasin area is not unexpected, since the number of proxels and hence the number of spatial sampling points in the model decrease at the same time. However, because of the fact that the indicated slope already explains 80 % of the variation in the data that form the basis of Fig. 4.4, it also appears that the coefficient of determination apparently only marginally depends on the location or the regime of the selected subbasin.

### 4.3.3 Return Periods of Extremes

For the third step in the validation, return periods were calculated from the measured and modelled annual discharge maxima and minima at gauge Achleiten and were then compared. The measured and modelled highest daily discharges for the period 1971–2003 are shown in Fig. 4.5.

$$y = 0.066x + 0.558$$
$$R^2 = 0.8$$
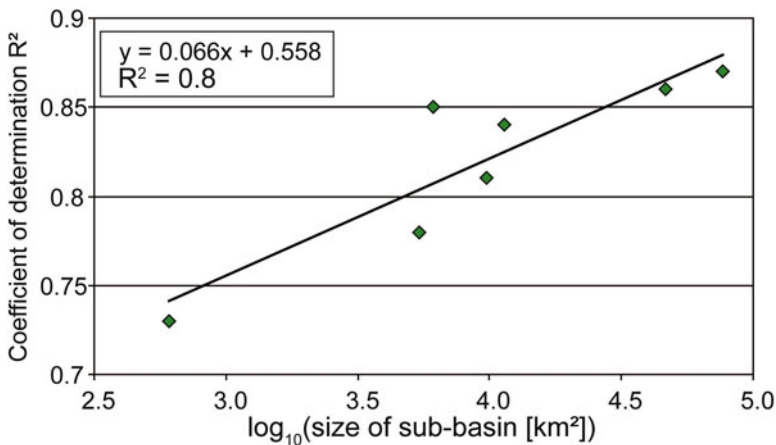
Fig. 4.4 Dependence of coefficient of determination R^2 on the area of the selected subbasin gauge Plattling wasn't included, due to the strong anthropogenic influences
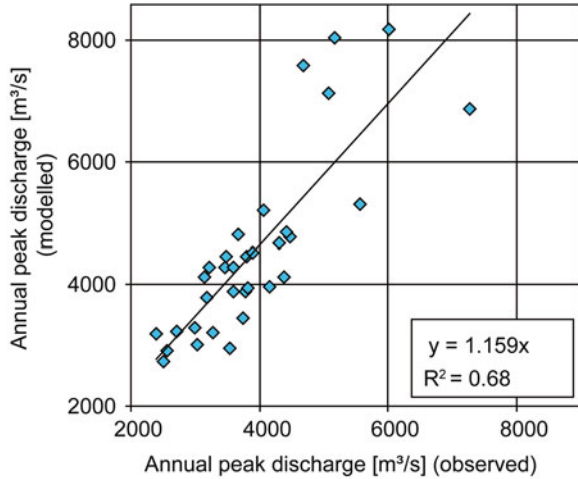
As was indicated already in Fig. 4.2, in this figure there is a systematic overestimation of the peak discharges by an average of 16 % in the modelling results. The reason is the omission of inundation water diversions, which act as water storages in the case of larger flood events. The result is a reduction of the peak discharges. These cases of dam breaches are not accounted for in the modelling of the channel discharges. Also not included in the simulations are the specific operational control measures for the reservoirs present in the basin to partially retain the flood waves (e.g. by drawdown of the reservoir prior to the event). As shown by the example of the flood in August 2005 (LfU 2006), these strategies can contribute substantially to reducing the peak discharges. They add a totally new dimension to flood control and determination of design floods and need consideration of human decisions based on incomplete information. These decisions are currently not implemented within the model. Figure 4.6 illustrates the annual low flow discharges at gauge Achleiten. In this case, the mean 7-day discharge (NMQ7) is considered (see also Sect. 53.2).

There is no clear systematic deviation between measurements and simulations in case of low flows. Only 2 years stand out from the otherwise quite stable trend and show much higher measured values compared to the modelled low water discharges. The reasons for this deviation of simulated low flows could not be resolved.

Annualities of the return periods were determined from the annual maxima and minima by fitting probability distribution functions. The guidelines from the DVWK (1999) were used in this approach for the case of flood peaks. In the case of the low flows, it was assumed that a log-normal distribution best approximates the natural variability of low flow in the basin. The calculated return periods for high and low water are compared in Fig. 4.7. They correspond well with the values determined from measured data.

Fig. 4.6 Comparison of
modelled and observed
annual low flow discharges
(NM7Q) at gauge Achleiten
for the time period 1971–
2003 (Adapted from Mauser
and Bach 2009, p. 372)
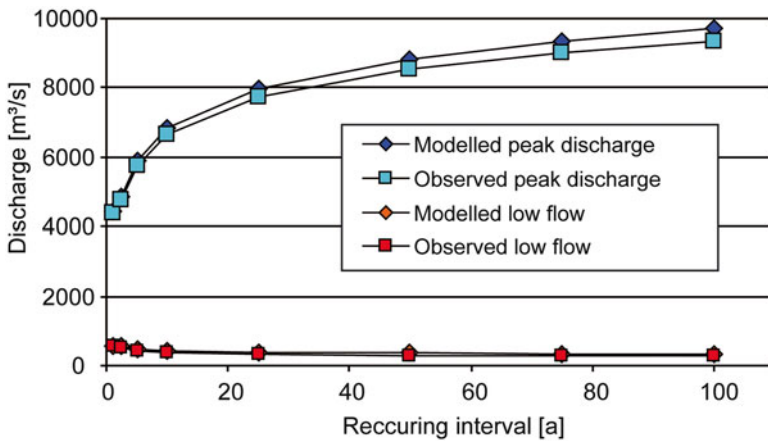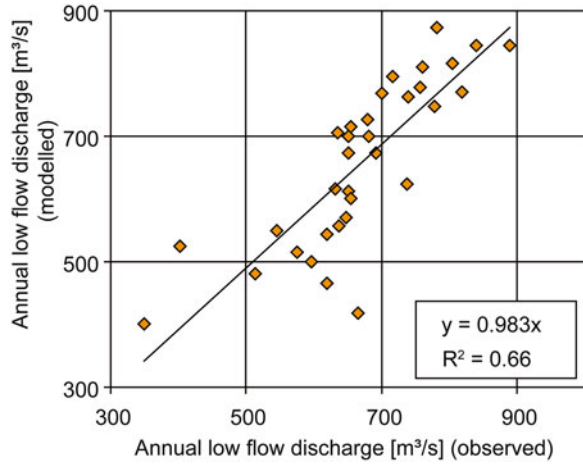
Fig. 4.7 Comparison of modelled and observed recurring intervals for flood and low flow discharges in Achleiten, 1971–2003 (Adapted from Mauser and Bach 2009, p. 374)

4.4   Summary

The validation process has shown that the method used in PROMET can model the
spatial and temporal variability of the water flows in the Upper Danube basin with
high accuracy. This is true both on seasonal and daily bases and for subbasins down
to an area of around 1,000 km². The dynamics of the extremes are well modelled,
with a slight tendency to overestimate the flood peaks. Since these sub-catchments
include a large variety of natural conditions from high alpine watersheds to temper-
ate lowland watershed, PROMET has proven to be able to cover a broad range of

hydrological situations without specific calibration. We therefore conclude that it is capable of covering the changes in the hydrological situation induced by future climate change, which may happen in the analysis period from 2011 to 2060.

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