

Flood forecasting system for the Tyrolean Inn River (Austria): current state and further enhancements of a modular forecasting system for alpine catchments

Matthias Huttenlau, Dr.¹; Johannes Bellinger¹; Paul Schattan¹; Kristian Förster¹; Felix Oesterle¹; Katrin Schneider¹; Stefan Achleitner²; Johannes Schöber³; Georg Raffaeiner⁴; Robert Kirnbauer⁵

ABSTRACT

Several severe flood events in Central Europe show the vulnerability of society living along water courses. On the one side, operational flood forecasting systems contribute to reduce vulnerability and increase resilience in flood risk management. On the other side, a runoff forecasting system used by energy providers also has an economic dimension in terms of their day-to-day business providing advanced planning capabilities used in the hydro-power plant operation. Combining these two aspects, the best way for its realization is a coordinated development, which is able to (i) fulfill its responsibility in the context of flood risk management and (ii) support the advanced hydro-power plant management of the energy provider. In this context, the following paper presents the current state and further enhancements of the flood forecasting system of the Tyrolean Inn River. Especially in its alpine catchments the operation of the forecasting system is challenging. Short times of runoff concentration times paired with a terrain of complex processes for runoff generation and flood wave propagation.

KEYWORDS

operational flood forecasting; hybrid hydrological/hydraulic system; Inn River; predictive accuracy; alpine hydrology

INTRODUCTION

The Austrian Province of Tyrol is a typical mountain region, where process dynamics are generally higher than in the low lands due to strong altitudinal gradients, which are relevant for flood forecasting at small spatial and temporal scales. Only a small proportion of the total area, which is concentrated in the valley floors in close vicinity to streams, is available for permanent human settlement. Tyrol is part of the Eastern Alps and covers an area of 12,640 km² with an elevation range from 462 m up to 3,798 m a. s. l. Due to topographically controlled limits, only 12.8 % of the area is available for permanent settlement of which only 0.4 % is declared as residential area populated by approximately 700,000 inhabitants (Amt der Tiroler Landesregierung, 2014). The circumstance that a very high proportion of the

1 alpS Centre for Climate Change Adaptation, Innsbruck, AUSTRIA, huttenlau@alps-gmbh.com

2 Unit of Hydraulic Engineering, University of Innsbruck (Austria)

3 TIWAG - Tiroler Wasserkraft AG, Innsbruck (Austria)

4 Hydrographic Service, Regional Government of Tyrol, Innsbruck (Austria)

5 Institute for Hydraulic and Water Resources Engineering, Vienna University of Technology, (Austria)

residential areas are located in valley floors leads consequently to a high exposure to flooding. In Tyrol, 105,330 people and a cumulative asset exposure of buildings and their contents (e.g. residential, public, trade and industry) of approximately EUR 7.6 billion are exposed within floodplains with a recurrence interval of 300 years (Huttenlau et al. 2010). The vulnerability of society living along watercourses in general was clearly shown by the severe European flood events in the years 1999, 2002, 2005 and 2013. Currently no reliable information about changes in the characteristics or the return periods of future flood events in Austria is available, especially under climate change conditions (Nachtnebel et al., 2014). Irrespective of different future damage potentials and damage symptoms, a reliable increase of the flood damages, mainly caused by the population growth and socioeconomic development, can be expected (König et al., 2014). Flood forecasting as a central component of early warning and decision support systems is an efficient instrument to minimize false alarms and enables effective emergency response for decision making. Beside other preliminary measures in the framework of integrated flood risk management (IFRM) like flood protection and land use planning, emergency management is one of the major pillars to reduce flood risk and a matter of public policy. Energy suppliers also apply runoff forecast systems to advance decision making in their day-to-day business and to support management decisions with respect to flood control through hydropower plants (often a requirement of official decisions). Combining these two aspects, the best way for its realization is a coordinated development, which is able to fulfill its responsibility in the context of flood risk management and also support the advanced hydro-power plant management of energy suppliers. Such a development of an operational forecasting system for the Tyrolean part of the Inn River was realized in a joint public-private research initiative of the affiliated institutions. In detail, the development of the system was mainly located at the research center “alpS – Centre for Climate Change Adaptation”, which participates on the COMET-program of the Austrian Research Promotion Agency (FFG). The program builds a platform for jointly defined research programs in the field of science-industry cooperation. Besides the partitioning of the costs the close cooperation includes furthermore regular communications about practical experiences as well as the latest scientific knowledge to fulfil the requirements. Especially the operationalization and advancement of such forecasting systems, with respect to complexity of runoff generation and flood wave propagation, is challenging. This is especially true considering alpine catchments, which are characterized by very short times of runoff concentration, which in turn limits the response time. This contribution presents the current state of the operational forecasting system HoPI (“Hochwasserprognose für den Tiroler Inn”), describes some operational applications, and shows ongoing research activities.

HISTORY AND SETUP OF THE FLOOD FORECASTING SYSTEM

Following the flood event in 2002, the development of the presented flood forecasting system started with the prototype of the modular-based, hybrid hydrological/hydraulic system (Senfter et al., 2009) from 2003 to 2006. Unfortunately, the system was not yet available for the operational flood forecasting service at the Hydrographic Office of the Province of Tyrol,

when a Vb (5b) track cyclone struck against the north side of the Alps in August 2005. This heavy precipitation event led to massive floods within the Alpine Ridge. In the Paznaun/Stanzer valley and the district Außerfern (see figure 1), floods were measured with return periods greater than 100 years. At the gauge Innsbruck, a return period of 200 years was observed (Godina, 2006). A verifiable reduction of the maximum instantaneous discharge of about 15 cm was attributable to the retention in several water reservoirs of the TIWAG and also to inter-basin diversion from the catchments of the Paznaun/Stanzer valley into water reservoirs of the Vorarlberger Illwerke. Thus, hydro-power plant operation helped to prevent the imminent overbank flooding in the city of Innsbruck (Schönlaub und Hofer 2009).

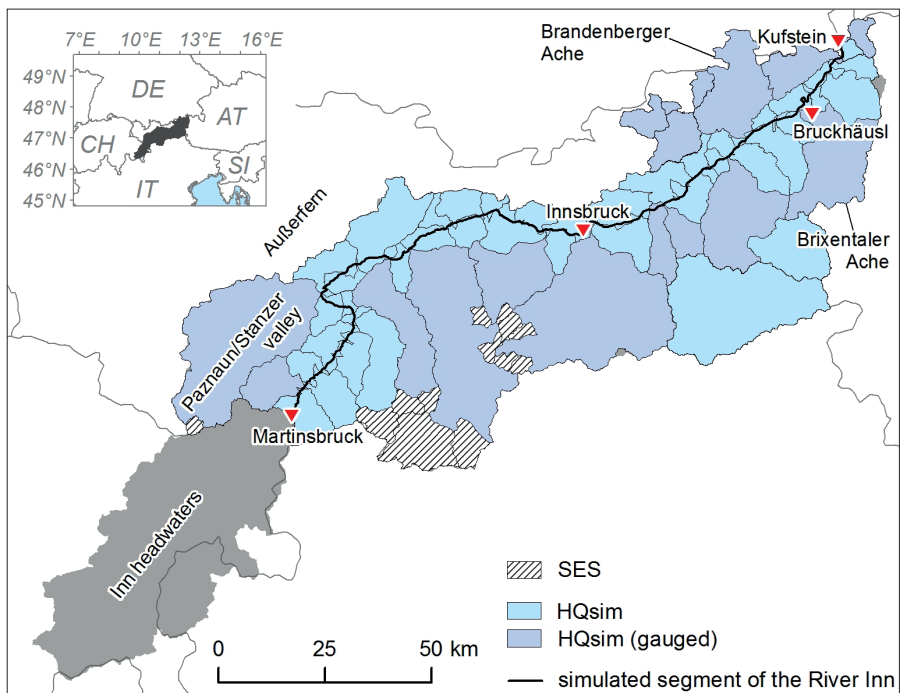


Figure 1: Spatial extent of the HoPI system including the hydrologic/hydraulic model components. The models for the Inn headwaters in Switzerland are currently under preparation.

After the successful integration into the operational flood forecasting service at the Hydrographic Office of the Province of Tyrol the developments of the subsequent project phase (2006-2009) were mainly characterized by further adaptations to requirements for practical use. This improvement ensured the reliability of the whole system and formed the basis for the current model optimization as well as the identification and quantification of system uncertainties. Achleitner et al. (2012) analyze the operational performance of the hydrological models and result in a strong dependency to the meteorological observations and

meteorological forecasts, respectively. Furthermore they propose the implementation of model state updating routines for further improving of the forecasting quality. The current operational forecasting system is set up as a permanently operating tool, running at hourly time steps, for the 200 km-long segment of the Austrian part of the River Inn between the Swiss-Austrian border and the Austrian-German border. The river catchment at the Austrian-German border covers an area of 9,700 km² in total. Forecasted discharges at the Austrian-German border are provided as input to the forecast model for Bavaria (Germany). The forecasting system HoPI comprises different types of deterministic models and data management software components. Its current implementation has a modular hybrid hydrological / hydraulic character (Achleitner et al., 2009) and is structured in (i) the data management and preprocessing, (ii) the hydrological simulation of tributary catchments and (iii) the hydraulic simulation of the Inn River. The procedure starts with the import of observed data since the last system run and the prognosis data for the upcoming forecast. Measured meteorological station data is interpolated and processed as input data for the models. For the forecasting period, the observed time series are extended with meteorological forecast data. Currently, the runoff generation from 10 glaciated sub-catchments, with an overall area of 620 km², is modelled with the fully distributed water-balance model SES (Snow and Icemelt Model) (Asztalos et al., 2007, Schöber et al., 2014). The accumulation and melt processes of snow, firn and ice are considered on basis of an energy-balance-equation on a 50 m grid. The simulated outflow of snow, firn, glacier ice, rock and subsurface flow to the catchments outlet is transformed via five Nash-Cascades. To run this model, data of precipitation, temperature, humidity, wind speed, and global radiation are required. Subsequently, the runoff modelled by SES is used as additional boundary conditions for the downstream hydrological model. By contrast, runoff generation from non-glaciated sub-catchments is modelled with the semi-distributed water balance model HQsim (Kleindienst, 1996) based on the HRU concept, which aggregate areas with similar soil type, aspect and elevation. At each HRU, processes of snow accumulation and melt (day-degree approach), evapotranspiration, interception, infiltration into the unsaturated zone as well as the saturated zone are included. Thereby the runoff is partitioned into surface flow, interflow and base flow. After calculation of runoff at each HRU, it is concentrated at the nearest point of the channel network and routed downstream by a non-linear storage cascade towards the catchment's outlet. In total, 50 tributary catchments, including 13 gauged catchments, are independently simulated. As before, the modelled runoff provides the boundary conditions for the commercial 1D-hydraulic model FluxDSS/DESIGNER/FLORIS2000, which represents the Tyrolean Inn segment from the gauge Martinsbruck at the Swiss border to the gauge Kufstein at the German border (fig. 1).

APPLICATION

The briefly described hybrid model has a temporal forecast period up to 48 h and is driven by hydro-meteorological parameters of the Integrated Nowcasting through Comprehensive Analysis (INCA) System provided by the Austrian Meteorological Office (ZAMG) on hourly

basis. At present, the models are initialized using online transmitted meteorological and hydrological data prior to the forecast, for which INCA provides all needed boundary conditions. Currently, HoPI is run every hour at the Hydrographic Office of the Province of Tyrol mainly for flood forecasts and also at TIWAG where it is used as well as decision support system for water management tasks. An additional instance is operated once a day at the research centre alpS, but to ensure the system safety the results are shared among the three stakeholders. However, further actions require decisions by a hydrologist on duty. For example, supported by HoPI predictions, the water level in the reservoirs of storage power plants can be lowered as early as possible by increased power generation, if an extreme event is expected to occur. In the case of a pumped-storage power station, water can be pumped from lower to upper stage reservoirs (Hofer et. al, 2013). In case of emergency the collaboration of relevant government departments (e. g. Tyrolean Regional Hazard Warning Centre, Tyrolean Fire Service Association) is legally predefined. The Hydrographic Office of the Province Tyrol informs, based on the runoff predictions of HoPI as well as expert assessments of the meteorological forecast, about the current flood risk and updates the situation by current measurements and predictions within the event. The hydro power plant management remains by the operators, who usually adapt the operating schedule to relieve the situation. If a danger to life and limb is foreseeable, the government agency could give eventual instructions to protect the general public interest. Since HoPI was implemented into the operational flood forecasting, no major flood event occurred at the River Inn in Tyrol. Within the extreme flooding in Central Europe in June 2013, an occluded front system reached the north side of the Alps (Hydrographischer Dienst Tirol, 2013). The heavy rainfall passed the HoPI catchments and hit the adjacent catchments. Nevertheless, floods with a return period of around 20/25 years were observed at the Inn tributary catchments “Brandenberger Ache” and “Brixentaler Ache”. Figure 2 (a) features the hydrograph of the gauge “Bruckhäusl” at the Brixental tributary. In May 2013 the runoffs were slightly overestimated using the measured data, but with the onset of the rainfall the model simulated the flood event very well. Solely the simulated peak runoff ($173 \text{ m}^3/\text{s}$) underestimates the observed value ($190 \text{ m}^3/\text{s}$) by around 9 %. Figure 2 (c) shows the HoPI-prognoses obtained several hours before the event. Due to their strong relation to the meteorological forecasts, the prognoses estimated the observed runoff not earlier than 18 hours before the event. Besides its initially defined target the flood forecasting, the HoPI system is currently used for several water management tasks, such as the prognosis of appropriate runoffs for flushing sediments from river power plants. Figure 2(b) depicts the HoPI-simulation of such a situation: within the second and third week in July 2014 a cyclone lead to heavy thunderstorms in the north of Tyrol with an increasing runoff exceeding the flood mark of the yearly return period at the gauge “Bruckhäusl”. Due to satisfactory hydrological forecasts of the HoPI system (Fig. 2 (d)), this event was used to flush the local hydro power plant by the TIWAG.

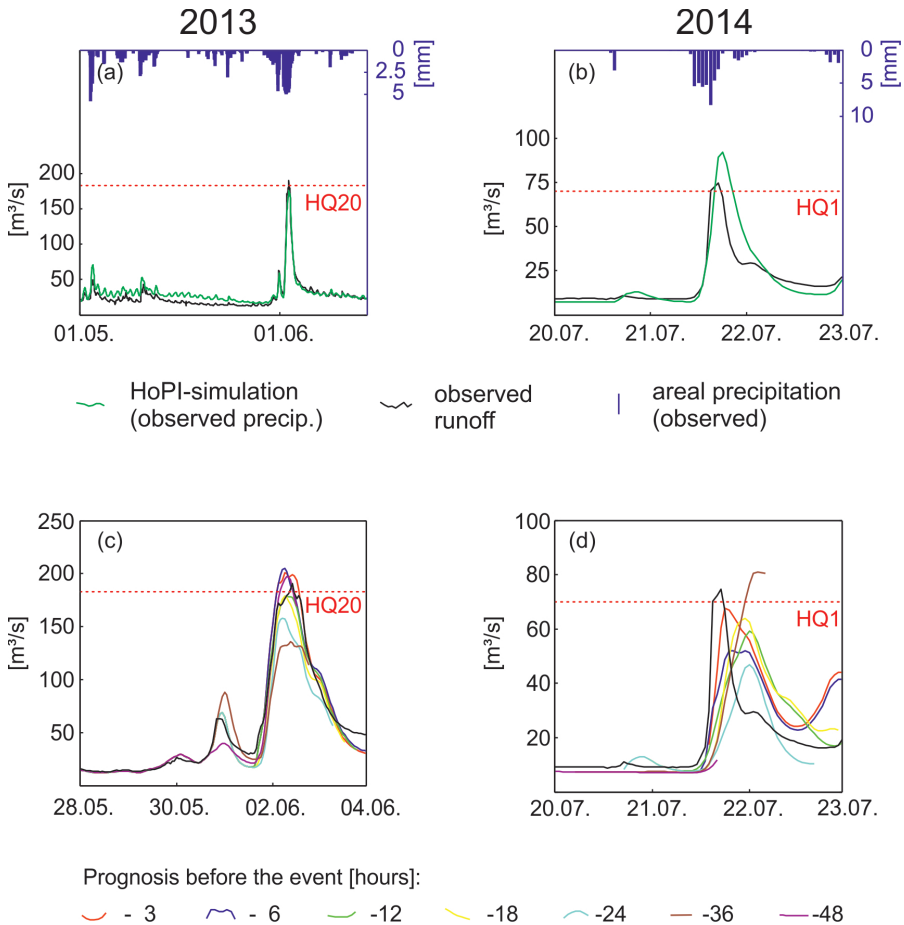


Figure 2: The figures (a) and (b) show observed and simulated hydrographs (with observed forcing data) of two exemplarily flood events at the "Bruckhäusl" gauge (Brixentaler Ache). Hydrographs in figures (c) and (d) show the accuracy of the HoPI-prognoses obtained several hours before the event.

CONCLUSION AND FURTHER ADVANCEMENTS

Overall, the presented forecasting system is a reliable and powerful tool for flood forecasting. Since nature is a very complex system, there will always be poorly predictable events, even if the presented applications deliver satisfactory results. To further increase the reliability and flexible use of the HoPI system for future tasks within the water resources management of Tyrol, different enhancements are planned such as:

- An alternative online coupling of both applied hydrological models to benefit from their specific advantages: the power of the SES model is doubtless the snow simulation of

- unforested areas, whereas a more sophisticated concept of soil processes and runoff routing is implemented in HQsim.
- Since the accuracy of the simulated runoff is mainly related to the input forcing data, the reliability of the predicted runoff up to 48 h depends as well as on the applied INCA data. Ensemble datasets for INCA, which became available recently, are to be used besides the main INCA run to introduce an uncertainty bandwidth in the forecast.
 - To provide an additionally medium-range forecast (up to 10 days), the current forecast period will be extended using statistically corrected Global Forecast System (GFS) data.
 - In alpine headwater catchments, both total solid precipitation and snow redistribution are major sources of uncertainty. Terrestrial laser scan campaigns and new methods for measuring snow water equivalent (SWE) at different spatial scales are applied to further develop snow-hydrological modelling.
 - To compensate for poor simulation of snow melt in spring periods (resulting from incorrect snow accumulation during winter), data assimilation from different snow data sets is planned. Remote sensing data from optical sensors (e.g. MODIS, Sentinell-2) will be used to provide information of the snow-covered area in daily or near daily temporal resolution. Synthetic Aperture Radar (SAR) based products will be used to assimilate areas where snow is melting. Despite few stations measuring SWE directly, an overall number of 100 snow gauges, distributed over the whole tributary catchments, will be used as additional data to estimate SWE from snow depth (Schöber 2015), serving as an additional calibration dataset besides runoff and snow cover.

LITERATURE

- Achleitner, S., Rinderer, M., and Kirnbauer, R. (2009): Hydrological modeling in alpine catchments: sensing the critical parameters towards an efficient model calibration, in: *Water Sci. Technol.* 60(6), S. 1507–1514.
- Achleitner, S., Schöber, J., Rinderer, M., Leonhardt, G., Schöberl, F., Kirnbauer, R., and Schönlaub, H. (2012): Analyzing the operational performance of the hydrological models in an alpine flood forecasting system, in: *J. Hydrol.*, 412-413, S. 90–100.
- Amt der Tiroler Landesregierung (2014): *Statistisches Handbuch Bundesland Tirol 2014*, Innsbruck.
- Asztalos, J., Kirnbauer, R., Escher-Vetter, H., and Braun, L. (2007): A distributed energy balance snow and glacier melt model as a component of a flood forecasting system for the Inn River, in: *Proceedings of the Alpine Snow Workshop*, 5-6. Oktober 2006, Berchtesgaden National Park research 53, S. 9–17.
- Godina, R., Lalk, P., Lorenz, P., Müller, G., and Weilguni, V. (2006): Hochwasser 2005 – Ereignisdokumentation, in: *Teilbericht des Hydrographischen Dienstes, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft*, Wien.
- Hofer, B., Schöber, J. and Perzlmaier, S. (2013): Flood control – Principles for the operation of existing and the planning of new storage power plants, in: *International Conference and*

Exhibition (Hydro 2013). Promoting the Versatile Role of Hydro. Sutton: Aqua-Media International, 18.06. Innsbruck

- Huttenlau, M., Stötter, J., and Stiefelmeyer, H. (2010): Risk-based damage potential and loss estimation of extreme flooding scenarios in the Austrian Federal Province of Tyrol, in: Nat. Hazards and Earth Syst. Sci. 10(12), S. 2451–2473.

- Hydrographischer Dienst Tirol (2013): Hochwasserereignis 31.5. bis 2.6.2013 im Tiroler Unterland. Hydrologischer Kurzbericht. URL https://www.tirol.gv.at/fileadmin/themen/umwelt/wasserkreislauf/downloads/Kurzbericht_Hochwasser_Juni_2013.pdf.

Kleindienst (1996): H. Erweiterung und Erprobung eines anwendungsorientierten hydrologischen Modells zur Gangliniensimulation in kleinen Wildbacheinzugsgebieten. Master Thesis, Ludwig Maximilians Universität München.

- König, M., Loibl, W., Steiger, R., Aspöck, H., Bednar-Friedl, B., Brunner, K. M., Höferl, K. M., Huttenlau, M., Walochnik, J., and Weisz, U. (2014): Der Einfluss des Klimawandels auf die Anthroposphäre, in: Österreichischer Sachstandsbericht Klimawandel 2014, APCC, S. 641–704. Verlag der Österreichischen Akademie der Wissenschaften, Wien, Österreich.

- Nachtnebel, H. P., Dokulil, M., Kuhn, M., Loiskandl, W., Sailer, R., and Schöner, W. (2014): Der Einfluss des Klimawandels auf die Hydrosphäre, in: Österreichischer Sachstandsbericht Klimawandel 2014, APCC, S. 411–466. Verlag der Österreichischen Akademie der Wissenschaften, Wien, Österreich. ISBN 978-3-7001-7699-2.

- Senfter, S., Leonhardt, G., Oberparleiter, C., Asztalos, J., Kirnbauer, R., Schöberl, F., and Schönlaub, H. (2009): Flood Forecasting for the River Inn, in: Veulliet, E., Stötter, J., and Weck-Hannemann, H.: Sustainable Natural Hazard Management in Alpine Environments, S. 35–67, Springer-Verlag, Berlin Heidelberg.

- Schöber, J., Schneider, K., Helfricht, K., Schattan, P., Achleitner, S., Schöberl, F., Kirnbauer, R. (2014): Snow cover characteristics in a glacierized catchment in the Tyrolean Alps – Improved spatially distributed modelling by usage of Lidar data, J. Hydrol. 519, S. 3492–3510.

- Schöber, J., Achleitner, S., Bellinger, J., Kirnbauer, R., Schöberl, F. (2015): Analysis and modelling of snow bulk density in the Tyrolean Alps, in: Hydrol. Res. (in press).

- Schönlaub, H., Hofer, B. (2009): Die Hochwassersituation bei abgeleiteten Bächen, in: WasserWirtschaft 09, S. 23-29.