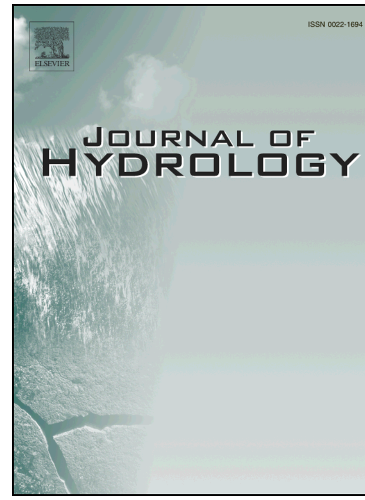
Accepted Manuscript



Research papers

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PII: S0022-1694(17)30272-X
DOI: http://dx.doi.org/10.1016/j.jhydrol.2017.04.052
Reference: HYDROL 21983

To appear in: *Journal of Hydrology*

Received Date: 28 October 2016
Accepted Date: 26 April 2017

Journal of Hydrology

The effect of coupling hydrologic and hydrodynamic models on probable maximum flood estimation

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Abstract Deterministic rainfall-runoff modelling usually assumes stationary hydrological system, as model parameters are calibrated with and therefore dependant on observed data. However, runoff processes are probably not stationary in the case of a probable maximum flood (PMF) where discharge greatly exceeds observed flood peaks. Developing hydrodynamic models and using them to build coupled hydrologic-hydrodynamic models can potentially improve the plausibility of PMF estimations. This study aims to assess the potential benefits and constraints of coupled modelling compared to standard deterministic hydrologic modelling when it comes to PMF estimation. The two modelling approaches are applied using a set of 100 spatio-temporal probable maximum precipitation (PMP) distribution scenarios. The resulting hydrographs, the resulting peak discharges as well as the reliability and the plausibility of the estimates are evaluated. The discussion of the results shows that coupling hydrologic and hydrodynamic models substantially improves the physical plausibility of PMF modelling, although both modelling approaches lead to PMF estimations for the catchment outlet that fall within a similar range. Using a coupled model is particularly suggested in cases where considerable flood-prone areas are situated within a catchment.

Keywords Model coupling, hydrodynamic model, PMP, PMF

1. Introduction

Safety is a priority for communities when it comes to sensitive or potentially hazardous infrastructure like hydropower dams or nuclear power plants. In some cases, legal requirements define that such infrastructure has to be protected against any conceivable natural hazard that could occur. Therefore, governmental institutions as well as insurance companies are interested in a quantification of the possible worst-case scenario. Thus, various approaches for calculating the probable maximum flood (PMF) have been developed and applied in the course of the last several decades.

The World Meteorological Organization (WMO) defines the PMF as "the theoretical maximum flood that poses extremely serious threats to the flood control of a given project in a design watershed." It is derived by converting the probable maximum precipitation (PMP) into runoff (WMO 2009). The concept and the uncertainty of PMP estimation has been assessed in several recent studies (Micovic et al. 2015; Papalexiou et al. 2013; Salas et al. 2014). The PMP is usually converted to the PMF using deterministic hydrological models calibrated with observed data (e.g. Beauchamp et al. 2013; Kienzler et al. 2015; Zeimetz et al. 2015). This method assumes the hydrological system to remain steady, meaning that the system behaviour during the calibration period or the calibration event is presumed to be the same as it is during a PMF event. However, this assumption is questionable, since many protection measures are dimensioned to protect against design floods with return levels of 100 or 300 years. As soon as a catchment-specific threshold is reached, the system may no longer be steady (Sivakumar 2009). At or beyond this threshold, new emerging retention areas (Lammersen et al. 2002), new flow paths (Huang et al. 2007; Vorogushyn et al. 2012) and changing runoff processes (Rogger et al. 2012a, 2012b) can strongly affect the hydrograph shape and the peak discharge, due for example to failing protection measures or overflowing lateral dams. The peak discharge of a PMF is expected to exceed such catchment specific thresholds, making these factors relevant for PMF calculation. In the present study, we focus on such non-stationarities in the runoff process that are due to retention and inundation processes.

In contrast to a hydrologic model, a hydrodynamic model can be used to simulate the runoff process in complex terrain settings and wide floodplains in a more physically based way and may be more robust in cases when discharge exceeds the range of the observed data. This is due to the fact that in hydrodynamic modelling routing is calculated by solving the physically based Saint-Venant equations at every calculation node within the model domain. In contrast, a hydrologic model calculates the routing rather conceptually, e.g. using a sequence of single linear storages in the HBV model (Bergström 1995). The application of a hydrodynamic model allows for the consideration of the effects of retention areas, dykes, bridge piers and other physical obstacles. Numerous studies show that hydrodynamic models are particularly useful for considering retention effects due to floodplain inundation (Dutta et al. 2013; Meire et al. 2010; Skublics et al. 2014) and dyke breaches (Apel et al. 2009, Vorogushyn et al. 2010). Therefore the application of a hydrodynamic model potentially increases the plausibility of extreme flood estimations. Considering such retention effects in extreme flood estimations can be either trivial or of crucial importance, depending on catchment and riverbed characteristics. However, it is assumed that inundation and retention effects become non-negligible when it comes to PMF. This assumption can be checked by applying synthetic design hydrographs with various peak discharges (Serinaldi and Grimaldi 2011) in a hydrodynamic model. This enables the identification of thresholds for the presence of widespread inundation and retention processes.

When calculating the PMF, the unsteadiness of the hydrological system that is induced by retention and inundation effects can be accounted for by coupling hydrologic and hydrodynamic models. This technique is particularly promising when the expected peak discharge may considerably exceed the observed maximum discharge or the river discharge capacity. A hydrologic model is used to determine the conversion from rainfall to runoff for a number of sub-catchments. The resulting hydrographs are used as upper boundary conditions of a hydrodynamic model. With computation power increasing over the past decade, coupled modelling approaches have been developed for flood estimation. Several case studies (e.g. Biancamaria et al. 2009; Bonnifait et al. 2009; Kim et al. 2012, Laganier et al. 2014; Lian et al. 2007) show the applicability of coupled hydrologic-hydrodynamic models in reconstructing observed flood events. A case study by Castro-Bolinaga and Diplas (2014) confirms the applicability of a hydrodynamic model for modelling extreme floods.

Despite the potential of coupling hydrologic and hydrodynamic models to increase the physical plausibility of PMF estimation, there is no systematic assessment of the effects of model coupling on PMF estimation. Although several above cited studies have shown that the application of a coupled hydrologic-hydrodynamic better represents inundation and retention processes than hydrological modelling alone, the influence of the choice of the modelling approach on PMF estimation itself remains unclear. The aim of the present study is therefore to evaluate whether coupling hydrologic and hydrodynamic models improves the plausibility of PMF estimation. This is done in three steps:

- The existence of catchment-specific thresholds for non-steady runoff processes is assessed by forcing a hydrodynamic model with a continuous series of synthetic design hydrographs. This process allows for the identification of catchment-specific thresholds for widespread inundations that lie beyond the design flood levels.
- The PMP is fed into a deterministic semi-distributed hydrologic model. This is the most common PMF estimation method (e.g. Beauchamp et al. 2013; Kienzler et al. 2015; Zeimetz et al. 2015).
- The same PMP is fed into a deterministic semi-distributed hydrological model which is externally coupled to a hydrodynamic model.

The hydrographs generated with the coupled model are then compared to the hydrographs generated with the standard hydrologic model using the same precipitation input. In this way, the applicability of both modelling approaches in terms of PMF estimation can be compared. The results are interpreted through the identification of catchment-specific discharge thresholds for inundation and retention effects. This comparison of a hydrologic and a coupled hydrologic-hydrodynamic model in terms of PMF estimation contributes to a better understanding of the effect modelling approach selection on the resulting estimation, and therefore it informs the setup of future PMF studies and applied PMF estimations.

2. Study area

2.1 Physical characteristics and data availability

The study area is the Aare catchment at the northern edge of the Swiss Alps. It covers an area of about 3000 km^2 and its mean elevation is about 1600 m a.s.l. A map of the study area is shown in Fig. 1. The catchment can be roughly divided into an upper section and a lower section. The upper section of the catchment consists of a steep mountainous and partly glaciated landscape. The sub-catchments in this mountainous area drain directly into two connected lakes that cover 30 and 49 km^2 and that are partially regulated. The outflow of the lower lake crosses over into the lower part of the catchment, which is a relatively wide valley with extensive flood-prone areas.

The mean annual rainfall in the catchment amounts to 1500 mm, of which 500 mm evaporate and 1000 mm are discharged. The discharge regime is influenced by the presence of glaciers that cover about 8% of the total area, meaning that mean discharge is relatively low (70 m^3s^{-1}) in winter and relatively high (180 m^3s^{-1}) in summer. The catchment is well-researched and its hydrology is relatively well-known as a result of numerous studies that have been completed in the area (e.g. Roessler et al. 2014; Wehren 2010). The highest observed peak discharges during the observation period 1918-2015 have been well documented and reconstructed by the Swiss Federal Office for the Environment (FOEN 1991; FOEN 2000; FOEN 2008; FOEN 2009).

Meteorological data are provided by the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss). Hourly time series from 30 stations that are situated within or near the catchment were used for calibration of the models. Discharge data are provided by the Swiss Federal Office for the Environment (FOEN) and the Bernese State Office for Water and Waste (AWA). For the catchment outlet, the time series covers 98 years (1918-2015) in daily resolution and 42 years (1974-2015) in hourly resolution. Within the catchment, there are 18 gauging stations with hourly resolutions, most of them covering more than 50 years. For the two lakes that are situated within the catchment, hourly resolved lake level time series are available from 1974 to 2015.

2.2 Division into sub-catchments

For modelling purposes, the catchment can be divided into 13 sub-catchments, as shown in Fig. 1. Eight of them are situated in the upper part of the catchment and drain into one of the two lakes. The other five sub-catchments are situated in the lower part of the catchment and drain directly into the Aare River. Two additional areas within the catchment are constituted by the two major lakes themselves. The main flood-prone areas are located around the two lakes and in the lower part of the catchment along the main river.

3. Methods

This study was carried out in four steps. First, synthetic design hydrographs were calculated and modelled hydrodynamically, allowing for the examination and identification of catchment-specific thresholds for widespread inundation. Next, PMP scenarios that could be used to force the two different modelling approaches were generated. Finally, two modelling approaches were applied. The first approach entails the use of a deterministic hydrological model that was set up for the catchment. The second approach entails hydrological modelling of the sub-catchments within the catchment, where the hydrographs of the sub-catchments were used as upper boundary conditions for a subsequent hydrodynamic model. An overview of the river network, the coupling points between the hydrologic and hydrodynamic models and the spatial range of the hydrodynamic model is provided in Fig. 1.

3.1 Derivation and application of synthetic design hydrographs

Synthetic design hydrographs for the Aare catchment were derived using the guidelines proposed by Serinaldi and Grimaldi (2011). The synthetic unit hydrograph was calculated by fitting a two parametric gamma distribution as described by Nadarajah (2007) and Rai et al. (2011) to the structural hydrograph depicted by Serinaldi and Grimaldi (2011). The procedure was applied to generate synthetic design hydrographs for a continuous series of peak discharges in intervals of 50 m^3s^{-1}. The synthetic design hydrographs were used as upper boundary conditions for the lower part of the hydrodynamic model (lower 30 km of total 80 km, orange cross sections in Fig. 1). The application of synthetic design hydrographs in the hydrodynamic model is based on the assumption that the full discharge volume flows through the lower part of the hydrodynamic model, which is not necessarily the case due to lateral inflows between the upper and lower boundaries of the hydrodynamic model. However, it is assumed that possible discharge thresholds for the occurrence of inundation and retention effects can reasonably be identified. The synthetic design hydrographs that are used as upper boundary conditions can be directly compared to the according hydrograph that results as lower boundary condition. As long as the discharge stays in the riverbed, the shape of the hydrograph is expected to stay unchanged, apart from a small temporal shift that results from the flow duration between the upper and the lower boundary of the hydrodynamic model and a slight flattening of the wave. As soon as the riverbed capacity at a certain point within the catchment is exceeded, new retention areas are wetted and new flow paths occur, changing the shape of the downstream hydrograph. By applying various hydrographs with differing peaks, thresholds for various points along the river at which the riverbed capacity is exceeded can be identified.

3.2 PMP estimation and spatio-temporal representation

The PMP for the event durations of 12 h, 24 h, 48 h, and 72 h were estimated following WMO guidelines (WMO 2009). In order to identify the distributions that may cause the highest peak discharge at the study area outlet, the spatio-temporal distribution of the estimated PMP was deduced using a Monte-Carlo approach (Felder and Weingartner 2016). Numerous randomly generated, physically plausible spatio-temporal distributions were tested by applying a hydrologic model where the random distribution was restricted to consider internal dependencies and correlations. In this case, approximately 10^6 PMP distributions were tested with the total precipitation amount held constant. The 100 physically plausible distributions that led to the highest peak discharges were considered most severe and are therefore applied in this study. The sample size of 100 spatio-temporal distributions is a compromise between the need for a large representative sample of distributions on the one hand and available computation power on the other. To ensure identical initial conditions for all model runs, the same observed meteorological environment was applied in modelling runs for each precipitation distribution. The meteorological environment represents medium summer conditions in terms of antecedent moisture. Summer conditions are used because the highest PMP estimation is based on summer atmospheric conditions.

This approach was chosen because it enables the derivation of a high number of slightly varying precipitation distributions. Applying a high number of varying PMP input scenarios allows for an assessment of the two different modelling approaches that is not dependent on how input data are chosen.

3.3 Hydrologic model PREVAH

The hydrologic modelling was done using PREVAH (Viviroli et al. 2009a), which is a deterministic, semi-distributed, HRU-based hydrological model that makes calculations on hourly time steps. The model structure is comparable to that of the well-known HBV model (Bergström 1996) in which incoming precipitation in liquid or solid state passes a cascade of linear storages. Information about temperature, global radiation, sunshine duration, vapour pressure and wind speed are required for the calculation of the evapotranspiration. The model has been extensively tested and applied in studies that deal with extreme hydrological events (FOEN 2009; Orth et al. 2015; Viviroli et al. 2009c; Zappa et al. 2015). These studies demonstrate the applicability of PREVAH to catchments like the Aare catchment. In the PREVAH model, the HRU's are directly routed to the catchment outlet. After modelling, additional routing can be applied by sequentially running several sub-models and incorporating intermediate lake modules that represent the lakes as single linear storages. In this study, the sub-catchments (see Fig. 1) were independently modelled. Sub-catchments that drain into a lake were fed into the respective lake module. The sub-catchments situated between the lower lake and the catchment outflow were fed into an additional routing module.

The model has 12 parameters to be calibrated. The gauged sub-catchments were calibrated using the PEST calibration tool developed by Doherty (2015). Information about parameter uncertainty and parameter sensitivity are provided by Viviroli et al. (2009b). The resulting NSE was between 0.70 and 0.92 for the calibration period (2001-2010) and between 0.65 and 0.88 for the validation period (2011-2014). The free parameters for the five ungauged contributing sub-catchments were estimated using the parameter regionalization approach developed by Viviroli et al. (2009c). Although it is not possible to evaluate this kind of parameter estimation specifically for ungauged catchments, Viviroli et al. (2009c) demonstrates that the parameter regionalization approach is appropriate.

3.4 Hydrodynamic model BASEMENT

The hydrodynamic model BASEMENT is a free hydrodynamic modelling system. The model is based on the continuity equation and solves the Saint-Venant equations for unsteady one-dimensional flow. A detailed derivation of the mathematical model applied in BASEMENT is illustrated in Vetsch et al. (2015).

In order to consider floodplains and storages outside the riverbed, the river cross sections were expanded to potential flood-prone areas. Cook and Merwade (2009) show that this procedure is advisable for modelling flood wave propagation, although the spatial details of the simulation of inundation depth and area are not as exact as in a 2D modelling environment. Cross sections of the riverbed and the directly adjacent levees were provided by the Swiss Federal Office of Environment FOEN. These cross sections were expanded to potential flood-prone areas beyond the levees using data from a digital elevation model with 0.5 m resolution and a vertical accuracy of 0.2 m. Considering the aim of this study, this resolution is sufficient for hydrodynamic modelling outside the riverbed because topographic details with major influence on flow paths and flow behaviour are sufficiently incorporated (Cook and Merwade 2009; Mejia and Reed 2011). The cross sections were set straight and perpendicular to the flow direction with average cross section spacing of approximately 150 m, as recommended in studies of other catchments (Ali et al. 2015; Castellarin et al. 2009; Samuels 1990).

The hydrodynamic model was calibrated by empirically adjusting the Strickler coefficients (k_{str}). The values were adjusted by reconstructing the water surface elevation and the propagation time of the peak discharge of observed flood events. Particular attention was given to the peak discharge and the time to peak at different gauging stations along the river. The k_{str} values were set between 33 and 45 in the riverbed and between 22 and 30 in the floodplains outside the riverbed. Additionally, hydrodynamic parameters that define the characteristics of weirs (factor µ of the Poleni equation) and pipes (contraction factor) were adjusted. The artificial lake management tools were set in a way that the discharge out of the lakes was maximized, as this is likely to be the case during flood events. The hydrodynamic model was then able to reconstruct the rating curve at the catchment outlet with an error of ±2 cm in water level for observed flood events. In the range of a typical flood event, this corresponds to an error of approximately ±5 m^3s^{-1} or 1% of discharge, which is comparable to the error of the gauging station of about ± 1 cm (FOEN 1998). The error is assumed to be slightly higher in the PMF case during which areas would be affected that were not flooded during the calibration flood events.

3.5 Model coupling

The outputs of the hydrologic model are fed into the hydrodynamic model as upper boundary conditions or as lateral inflows. The model coupling is external, which means that there is no direct interaction between the models and backwater effects are only involved within the spatial range of the hydrodynamic model. The range of the hydrodynamic model was set to incorporate all significant flood-prone areas and potential retention areas. It is assumed that minor retention areas inside the sub-catchments have a negligible effect on the peak flow at the catchment outlet.

The coupling points between the hydrological and the hydrodynamic model are shown in Fig. 1. There are two cases where a coupling point lies significantly upstream of the sub-catchment outflow (see the most eastern and the most western coupling points in Fig. 1). In these cases, areas situated downstream of the coupling points were separately modelled and then added to the hydrodynamic model, following the suggestions of Lerat et al. (2012). The hydrological model was not applied on the lakes within the catchment because they directly receive the precipitation that falls above them, and evaporation from the lakes was considered negligible. In these cases, precipitation was directly fed into the hydrodynamic model.

4. Results

4.1 Thresholds derived from the hydrodynamic modelling of synthetic design hydrographs

The calculated synthetic design hydrographs (see section 3.1) and the results of the hydrodynamic modelling of these synthetic design hydrographs are shown in Fig. 2. The synthetic design hydrographs (on the left side of Fig. 2) that were used as upper boundary conditions are uniformly shaped. The hydrographs derived by hydrodynamic modelling (on the right side of Fig. 2) are identically shaped when peak discharges are below approximately 500 m^3s^{-1}. This corresponds to a peak discharge with a 30 year return period. Above that level, there are three clearly visible steps at approximately 570, 700 and 860 m^3s^{-1}. These thresholds indicate the occurrence of inundation and retention processes with significant influence on discharge processes. In consequence, the peak discharges of the synthetic design hydrographs on the model input side and the peak discharges of the calculated hydrographs on the model output side are no longer congruent. Two significant thresholds for emerging inundation and retention processes (700 and 860 m^3s^{-1}) are considerably above the 300 year return level flood; hence these thresholds do not affect floods below the 300 year return level but are possibly of crucial importance for PMF estimation.

4.2 Modelling the PMF

The hydrographs that were derived by hydrological modelling are shown in Fig. 3. The hydrographs that were modelled by applying the coupled hydrological-hydrodynamic model are shown in Fig. 4. The hydrographs represent the modelled catchment response to the 100

PMP distributions described in section 3.1, where the precipitation event lasts from hour 0 to hour 72 or less depending on the temporal distribution of the PMP.

4.2.1 Hydrograph behaviour before peak discharge

The hydrographs resulting from hydrological modelling generally increase relatively quickly at the beginning of the event. In contrast, the hydrographs resulting from the coupled model generally rise more slowly. Comparing the shapes of the hydrographs from the two modelling approaches shows that the hydrographs derived by hydrologic modelling increase constantly and relatively smoothly. The hydrographs derived by the coupled model reflect distinct steps at certain discharge levels, e.g. at 700 m^3s^{-1}. This is due to the exceeded riverbed capacity and consequential inundations, which delay further water level rise at the outlet. The hydrologic model is not able to capture this effect.

4.2.2 Peak discharge and PMF estimate

The peak discharges are between 1010 and 1320 m^3s^{-1} based on the hydrologic model and between 880 and 1220 m^3s^{-1} based on the coupled model. A comparison of the modelled peak discharges of all model runs is shown in Fig. 5. The plot shows that the coupled model generates lower peak discharges than the hydrologic model for most of the PMP distributions. However, there are also some scenarios where the coupled model generates a higher peak discharge than the hydrologic model. This is due to the retarding effect of lakes that are situated within the catchment. Precipitation distributions for which the coupled model generates the highest peak discharge are the ones that lead to a superposition of sub-catchment reactions. In such cases, in the first phase of the event the most intense precipitation occurs in the sub-catchments that drain into a lake. Subsequently, the lake water level rises. In the course of the event, the most intense precipitation shifts to the sub-catchments that are situated between a lake and the catchment outlet. This leads to the superposition of maximum lake outflow and maximum discharge from other sub-catchments. The hydrological model, with its relatively simple representation of the lakes, is not able to reproduce this effect in detail.

The time between the beginning of the precipitation event and the peak discharge (time to peak) of each model run is shown in Fig. 6. As demonstrated by the hydrographs in Fig. 3 and Fig. 4, there are considerable differences in time to peak between the two modelling approaches. The hydrological model generates peaks that occur from 25 to 87 h after the start of precipitation, while the coupled model generates peaks between 48 and 85 h after the start of precipitation. There is less temporal variation in the hydrographs generated by the coupled model than in those generated by the hydrological model. Considering that the total precipitation amount (PMP) was always held constant, Fig. 7 shows that the peak-to-volume ratios do not differ systematically.

4.2.3 Hydrograph behaviour after peak discharge

In both modelling approaches, the hydrographs drop considerably after the peak discharge is reached. In the coupled model, there are step changes visible again at various discharge levels toward the end of the events (570, 620, 700, 860 m^3s^{-1}). These levels correspond to thresholds of the riverbed capacity at various cross sections thus the step changes can be explained by the flooding of floodplains. In a first phase, the discharge at the catchment outlet is reduced due to the amount of water that exceeds the riverbed capacity and inundates surrounding areas. In a second phase, the discharge at the same cross section falls below the discharge capacity of the river reach, and the inundating water masses flow back into the riverbed. In a last phase, when the surrounding areas are drained they do not contribute to discharge anymore, leading to a distinctive kink in the hydrograph.

5 Discussion

The hydrodynamic modelling of synthetic design hydrographs shows that retention effects are more pronounced when the estimated discharge considerably exceeds the maximum discharge of the calibration period. This is reasonable due to the fact that protection measures along the riverbed are often aligned to design floods of 30, 100 or 300 years, and not to floods with the magnitude of a PMF.

The hydrologic model and the coupled hydrologic-hydrodynamic model generate differently shaped hydrographs at the catchment outlet. The main difference in the two modelling approaches has to do with the representation of physical processes that occur within the catchment. The hydrological model represents the catchment reaction by using a set of calibrated parameters that usually define storage sizes, infiltration rates, evapotranspiration rates, and various other catchment characteristics. The calibrated model usually reproduces catchment behaviour that corresponds to catchment behaviour during the calibration period. However, the synthetic design hydrographs used in hydrodynamic modelling show that the catchment may deviate from its known behaviour due to the influence of effects that were absent during the calibration period. The deceleration of water flow due to changing riverbed characteristics, the storage and retention effects of inundated areas, as well as the depletion of lake storage capacity are possible reasons for such changing runoff characteristics. The hydrologic model does not consider non-stationary catchment behaviour that is caused by inundation and retention effects or the superimposing effects that occur when discharge considerably exceeds the highest observed peak discharges of the calibration period, which presumably would occur in the case of a PMF event. Therefore it quickly routes heavy precipitation input to the catchment outlet. In contrast, the coupled model approach is less dependent on the occurrence of extreme events within the calibration period as it captures and reproduces the effects of high precipitation on the watershed. The representation of non-linear retention effects in the coupled approach allows for a more verifiable and a physically more reliable PMF estimation.

The differences between the hydrologic and the coupled model in terms of the representation of runoff processes have direct consequences for the shapes of the hydrographs and for the PMF estimation. The coupled model simulates peak discharges that are slightly lower than the ones generated with the hydrologic model. The time to peak is generally lower for the outputs generated by the hydrologic model than for those generated by the coupled model due to the relatively immediate routing of the runoff to the catchment outflow and the neglect of runoff-delaying processes like inundations in the hydrologic model. As these differences are caused by the distinct representations of the routing process in the two modelling approaches, they are of general nature. However, the magnitude of these effects may vary from catchment to catchment. In case of simple channel geometries or riverbed capacities that continuously exceed the magnitude of the PMF, these differences are expected to decrease, although the application of a hydrodynamic model still increases the reliability of the estimation.

An additional benefit of the coupled model approach is that it allows for the identification and mapping of affected areas and floodplains within the catchment. This allows for a better estimation of the possible consequences of a PMF event. The additional information on possibly affected areas is highly important for insurance and re-insurance purposes as well as for the planning of sensitive infrastructure or protection measures. However, various studies show that identification and mapping of affected areas are uncertain due to several critical factors, i.e. the model calibration (Pappenberger et al. 2005; Pappenberger et al. 2006; Remo et al. 2009; Di Baldassare et al. 2009), the lack of computation power limiting the consideration of various parameter sets (Altarejos-García et al. 2012), and uncertain design flood profiles (Brandimarte and Di Baldassare 2012). Chatterjee et al. (2008) show that 1D-2D model coupling improves the modelling of areal extent, water velocities, and the emptying process of retention areas in comparison to a 1D model, whereby it leads to comparable results in terms of peak discharge. However, such an approach requires significantly more computation power, a factor that limits the consideration of a high number of varying precipitation scenarios.

The setup and application of a coupled model is data-intensive and relatively time consuming. It usually requires pre-processing and calibration for every considered sub-catchment, the setup and calibration of a hydrodynamic model, and some effort for the coupling itself. Moreover, applying a coupled model involves a relatively long computation time. The availability of a high-resolution digital terrain model and river cross sections is required for coupled modelling. In contrast, the hydrological modelling approach only requires calibration of the sub-catchments, and the computation time is substantially lower than the computation time of a coupled model. Considering the similar range of peak discharges that were modelled by the two approaches, a hydrological model can reasonably be applied for rough PMF estimation in cases where only the catchment outlet is of interest or where the catchment is characterized by negligible potential retention areas. On the other hand, the coupled model better reflects physical reality when it comes to extreme floods. Using this approach is particularly imperative when retention areas in the catchment of interest may strongly influence PMF estimation.

6 Conclusion and Perspectives

In this study, PMF estimations were derived by applying a hydrologic model and a coupled hydrologic-hydrodynamic model in order to assess the advantages and constraints of these two modelling approaches. The two modelling approaches were tested with 100 PMP scenarios with the same volume of precipitation but different spatio-temporal precipitation distributions. The resulting hydrographs can be used to assess the applicability of the modelling approaches for estimating PMF at the catchment outlet and to evaluate the representation of physical processes within the catchment. The hydrological model is suitable to roughly estimate a PMF, particularly in cases where no significant retention areas are situated in the catchment. The application of a coupled hydrologic-hydrodynamic model is recommended for a better understanding of the physical processes within the catchment, for mapping purposes, or for the planning of flood prevention measures. A PMF event comprises substantially larger discharge volumes and substantially higher peak discharges than observed events. In the case of a PMF, flood protection measures that are dimensioned for specific return levels fail; thus widespread floodplain inundation and non-linear processes occur. This calls for the incorporation of a physical perspective to make estimation more reliable and understandable. The difference in the model outputs indicates the importance of studying the benefits and constraints of modelling approaches applied for PMF estimation.

Acknowledgements

This study is funded by the University of Bern and the Mobiliar Lab for Natural Risks. The authors would like to thank the Federal Office of Environment (FOEN), the Federal Office for Meteorology and Climatology (MeteoSwiss) and the Department for Water and Waste of the Canton of Bern (AWA) for providing the necessary input data. Anne de Chastonay is acknowledged for her thoughtful comments.

References

Ali A., Di Baldassare, G., Solomatine, D.P. 2015 Testing different cross-section spacing in 1D hydraulic modelling: a case study on Johor River, Malaysia. *Hydrological Sciences Journal*, 60:2, 351-359. doi: 10:1080/02626667.2014.889297.

Altarejos-García, L., Martínez-Chenoll, M.L., Escuder-Bueno, I., Serrano-Lombillo, A. 2012 Assessing the impact of uncertainty on flood risk estimates with reliability analysis using 1-D and 2-D hydraulic models. *Hydrol. Earth Syst. Sci*. 16, 1895-1914. doi:10.5194/hess/16-1895-2012.

Apel, H., Merz, B., Thieken, A.H. 2009 Influence of dike breaches on flood frequency estimation. *Comput. Geosci.* 35, 907-923. http://dx.doi.org/10.1016/j.cageo.2007.11.003.

BASEMENT – Basic Simulation Environment for Computation of Environmental Flow and Natural Hazard Simulation. Version 2.5, © ETH Zurich, VAW, Vetsch D., Siviglia A., Ehrbar D., Facchini M., Gerber M., Kammerer S., Peter S., Vonwiller L., Volz C., Farshi D., Mueller R., Rousselot P., Veprek R., Faeh R., 2006-2015.

Beauchamp, J.R., Leconte, R., Trudel, M. and Brissete, F. 2013. Estimation of the summer-fall PMP and PMF of a northern watershed under a changed climate. *Water Resour. Res*., 49(6): 3853-3862. doi: 10.1002/wrcr.20336

Bergström, S. 1995. The HBV model. In: Singh, V.P. (ed) Computer models of watershed hydrology. Water Resources Publications, Highland Ranch, Colorado, U.S.A..

Biancamaria, S., Bates, P., Boone, A., Mognard, N. 2009 Large-scale coupled hydrologic and hydraulic modelling of the Ob river in Siberia. *Journal of Hydrology*, 379, 136-150. doi:10.1016/j.jhydrol.2009.09.054

Bonnifait, L., Delrieu, G., Le Lay, M., Boudevillain, B., Masson, A., Belleudy, P., Gaume, E., Saulnier, G.-M. 2009 Distributed hydrologic and hydraulic modelling with radar rainfall input: Reconstruction of the 8-9 September 2002 catastrophic flood event in the Gard region, France. *Adv, Water Resour*. 32, 1077-1089. doi:10.1016/j.advwatres.2009.03.007

Brandimarte, L. and Di Baldassare, G. 2012 Uncertainty in design flood profiles derived by hydraulic modelling. *Hydrol. Res*. 43 (6). doi:10.2166/nh.2011.086

Castellarin, A., Di Baldassare, G., Bates, P.D., Brath, A. 2009 Optimal Cross-Section Spacing in Preissmann Scheme 1D Hydrodynamic Models. *J. Hydraul. Eng*. 135, 96-105. doi:10.1061./(ASCE)0733-9429(2009)135:2(96)

Castro-Bolinaga, C.F., and Diplas, P. 2014 Hydraulic Modeling of Extreme Hydrologic Events: Case Study in Southern Virginia. *J. Hydraul. Eng*. 2014, 140.

Chatterjee, C., Förster, S., Bronstert, A. 2008 Comparison of hydrodynamic models of different complexities to model floods with emergency storage areas. *Hydrol. Process.* 22, 4695–4709. doi:10.1002/hyp.7079

Cook, A., Merwade, V. 2009 Effect of topographic data, geometric configuration and modelling approach on flood inundation mapping. *Journal of Hydrology*, 377, 131-142. doi:10.1016/j.jhydrol.2009.08.015

Di Baldassare, G., Castellarin, A., Brath, A. 2009 Analysis of the effects of levee heightening on flood propagation: example of the River Po, Italy. *Hydrological Sciences Journal*, 54:6, 1007-1017, doi:10.1623/hysj.54.6.1007

Doherty, J. 2015. Calibration and Uncertainty Analysis for Complex Environmental Models. Watermark Numerical Computing, Brisbane, Australia. ISBN 978-0-9943786-0-6.

Dutta, D., Teng, J., Vaze, J., Lerat, J., Hughes, J., Marvanek, S. 2013 Storage-based approaches to build floodplain inundation modelling capability in river system models for water resources planning and accounting. *Journal of Hydrology*, 504, 12-28. doi:10.1016/j.jhydrol.2013.09.033

Felder, G., Weingartner, R. 2016 An approach for the determination of precipitation input for worst-case flood modelling. *Hydrological Sciences Journal*. doi: 10.1080/02626667.2016.1151980

FOEN (Federal Office for Environment), 1991. *Event-analysis of the 1987 Flood*. Nr. LHG-14-D. Bern, Switzerland.

FOEN, 1998 Manual of streamflow gauging. LHG-26-D.

FOEN (Federal Office for Environment), 2000. *Flood 1999. Data Analysis and statistical classification*. Nr. LHG-28-D. Bern, Switzeland.

FOEN (Federal Office for Environment), 2008. *Event-analysis of the 2005 Flood. Part 2: Analysis of processes, measures and hazards*. Nr. UW-0825-D. Bern, Switzerland.

FOEN (Federal Office for Environment), 2009. *Event-analysis of the August 2007 Flood*. Nr. UW-0927-D. Bern, Switzerland.

Huang, S., Rauberg, J., Apel, H., Disse, M., Lindenschmidt, K.-E. 2007 The effectiveness of polder systems on peak discharge capping of floods along the middle reaches of the Elbe River in Germany. *Hydrol. Earth Syst. Sci*, 11, 1391-1401. doi: 10.5194/hess-11-1391-2007

Kienzler, P., Norina, A., Näf-Huber, D., Zappa, M. 2015 Derivation of extreme precipitation and flooding in the catchment of Lake Sihl to improve flood protection in the city of Zurich. *HyWa* 59, 48-58. doi:10.5675/HyWa_2015,2_1

Kim, J., Warnoc, A., Ivanov, V., Katopodes, N. 2012 Coupled modeling of hydrologic and hydrodynamic processes including overland and channel flow. *Adv. in Water Resour*. 37, 104-126. doi:10.1016/j.advwatres.2011.11.009

Laganier, O., Ayral, P.A., Salze, D., Sauvagnargues, S. 2014 A coupling of hydrologic and hydraulic models appropriate for the fast floods of the Gardon River basin (France). *Nat. Hazards Earth Syst. Sci* 14, 2899-2920. doi:10.5194/nhess-14-2899-2014

Lammersen, R., Engel, H., van de Langemheen, W., Buiteveld, H. 2002 Impact of river training and retention areas on flood peaks along the Rhine. *Journal of Hydrology*, 267, 115-124. doi: 10.1016/S0022-1694(02)00144-0

Lerat J., Perrin, C., Andréassian, V., Loumagne, C. Ribstein, P. 2012 Towards robust methods to couple lumped rainfall-runoff models and hydraulic models : A sensitivity analysis on the Illinois River. *Journal of Hydrology*, 418-419, 123-135. doi:10.1016/j.jhydrol.2009.09.019

Lian, Y., Chan, I., Sing, J. Demissie, M., Knapp, V. 2007 Coupling of hydrologic and hydraulic models for the Illinois River Basin. *Journal of Hydrology*, 344, 210-222. doi:10.1016/j.jhydrol.2007.08.004

Meire, D., De Doncker, L., Declercq, F., Buis, K., Trosch, P., Verhoeven, R. 2010 Modelling river-foodplain interaction during flood propagation. *Nat. Hazards*, 55(1): 111-121. doi: 10.1007/s11069-010-9554-1

Mejia, A.I., Reed, S.M. 2011 Evaluating the effects of parameterized cross section shapes and simplified routing with a coupled distributed hydrologic and hydraulic model. *Journal of Hydrology*, 409, 512-524. doi:10.1016/j.jhydrol.2011.08.050

Micovic, Z., Schaefer, M., Taylor, G. 2015 Uncertainty analysis for Probable Maximum Precipitation estimates. *Journal of Hydrology*, 521: 360-373. doi:10.1016/j.jhydrol.2014.12.033

Nadarajah, S. 2007 Probability models for unit hydrograph derivation. *Journal of Hydrology,* 344: 185-189. doi: 10.1016/j.jhydrol.2007.07.004

Orth, R., Staudinger, M., Seneviratne, S., Seibert, J., Zappa, M. 2015 Does model performance improve with complexity? A case study with three hydrological models. *Journal of Hydrology*, 523, 147-159. doi:10.1016/j.jhydrol.2015.01.044

Papalexiou, S.M., Koutsoyiannis, D., Makropoulos, C. 2013 How extreme is extreme? An assessment of daily rainfall distribution tails. *Hydrol. Earth. Syst. Sci.*, 17: 851-862.

Pappenberger, F., Beven, K., Horrit, M., Blazkova, S. 2005 Uncertainty in the calibration of effective roughness parameters in HEC-RAS using inundation and downstream level observations. *Journal of Hydrology*, 302, 46-69. doi:10.1016/j.jhydrol.2004.06.036

Pappenberger, F., Matgen, P., Beven, K., Henry, J., Pfister, L., de Fraipont, P. 2006 Influence of uncertain boundary conditions and model structure on flood inundation predictions. *Adv. Water Resour.* 29, 1430-1449. doi: 10.1016/j.advwatres.2005.11.012

Rai, R.K., Sarkar, S., Singh, V.P. 2008 Evaluation of the Adequacy of Statistical Distribution Functions for Deriving Unit Hydrograph. *Water Resour Manage* 23, 899-929. doi:10.1007/s11269-008-9306-0

Remo, J., Pinter, N., Heine, R. 2009 The use of retro- and scenario-modeling to assess effects of 100+ years river of engineering and land-cover change on Middle and Lower

Mississippi River flood stages. *Journal of Hydrology*, 376, 403-416. doi:10.1016/j.jhydrol.2009.07.049

Roessler, O., Froidevaux, P., Börst, U., Rickli, R., Martius, O. and Weingartner, R., 2014. Retrospective analysis of a nonforecasted rain-on-snow flood in the Alps – a matter of model limitations or unpredictable nature? *Hydrol. Earth Syst. Sci.*, 18:2265-2285. doi: 10.5194/hess-18-2265-2014.

Rogger, M., Kohl, B., Pirkl, H., Viglione, A., Komma, J., Kirnbauer, R., Merz, R. and Blöschl, G., 2012a. Runoff models and flood frequency statistics for design flood estimation in Austria – Do they tell a consistent story? *Journal of Hydrology*, 456–457:30–43. doi: 0.1016/j.jhydrol.2012.05.068

Rogger, M., Pirkl, H., Viglione, A., Komma, J., Kohl, B., Kirnbauer, R., Merz, R. and Blöschl, G., 2012b. Step changes in the flood frequency curve: Process controls. *Water Resour. Res.*, 48(5). doi: 10.1029/2011WR011187.

Salas, J.D., Gavilán, G., Salas, F.R., Julilen, P.Y., Abdullah, J., 2014. Uncertainty of the PMP and PMF, in: Eslamian, S. (Ed.), Handbook of Engineering Hydrology, Book II: Modeling, Climate Change and Variability. CRC Press. Taylor & Francis Group, Boca Raton, FL, pp. 575-603.

Samuels, P. G. (1990) Cross section location in one-dimensional models. In: Int. Conf. on River Flood Hydraulics (ed. by W. R. White), 339–350. John Wiley & Sons Ltd., Chichester, UK

Serinaldi, F., Grimaldi, S. 2011 Synthetic Design Hydrographs Based on Distribution Functions with Finite Support. *Journal of Hydrologic Engineering*, 16, 434-446. doi:10.1061/(ASCE)HE.1943-5584.0000339.

Sivakumar, B. 2009 Nonlinear dynamics and chaos in hydrologic systems: latest developments and a look forward. *Stoch Environ Res Risk Assess*, 23: 1027-1036. doi: 10.1007/s00477-008-0265-z

Skublics, D. Seibert, S., Ehret, U. 2014 Modelling flood retention with hydrological and hydrodynamic models under different boundary conditions – Sensitivity analysis on the

Danube reach from Neu-Ulm to Donauwörth. *HyWa* 58, 178-189. doi:10.5675/HyWa_2014,3_1

Vetsch D., Siviglia A., Ehrbar D., Facchini M., Gerber M., Kammerer S., Peter S., Vonwiller L., Volz C., Farshi D., Mueller R., Rousselot P., Veprek R., Faeh R. 2015. System Manuals of BASEMENT, Version 2.5. Laboratory of Hydraulics, Glaciology and Hydrology (VAW). ETH Zurich. Available from http://www.basement.ethz.ch. [access 21.09.2016].

Viviroli, D., Zappa, M., Gurtz, J., Weingartner, R. 2009a An introduction to the hydrological modelling system PREVAH and its pre- and post-processing tools. *Environmental Modelling & Software*, 24, 1209-1222. doi:10.1016/j.envsoft.2009.04.001

Viviroli, D., Zappa, M., Schwanbeck, J., Gurtz, J., Weingartner, R. 2009b Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part I: Modelling framework and calibration results. *Journal of Hydrology*, 377, 191-207. doi:10.1016/j.jhydrol.2009.08.023

Viviroli, D., Mittelbach, H., Gurtz, J., Weingartner, R. 2009c Continuous simulation for flood estimation in ungauged mesoscale catchments of Switzerland – Part II: Parameter regionalisation and flood estimation results. *Journal of Hydrology*, 377, 208-225. doi:10.1016/j.jhydrol.2009.08.022

Vorogushyn, S., Merz, B., Lindenschmidt, K.-E., Apel, H. (2010) A new methodology for flood hazard assessment under consideration of dike breaches. *Water Resour. Res.*, 46(8), W08541. doi: 10.1029/2009WR008475.

Vorogushyn, S., Lindenschmidt, K.-E., Kreibich, H., Apel, H., Merz, B. 2012 Analysis of a detention basin impact on dike failure probabilities and flood risk for a channel-dike-floodplain system along the river Elbe, Germany. *Journal of Hydrology*, 436-437, 120-131. doi:10.1016/j.jhydrol.2012.03.006

Wehren, B., 2010. The Hydrology of the Kander River – yesterday, today, tomorrow. Analysis and Modelling of the floods and their spatio-temporal dynamics. Thesis (PhD). University of Bern, Switzerland.

WMO (World Meteorological Organization), 2009. *Manual on Estimation of Probable Maximum Precipitation (PMP)*. Nr. 1045. Geneva, Switzerland.

Zappa, M., Andres, N., Kienzler, P., Näf-Huber, D., Marti, C., Oplatka, M. 2015 Crash tests for forward-looking flood control in the city of Zürich (Switzerland). *Proc. IAHS*, 370, 235-242. doi:10.5194/piahs-370-235-2015

Zeimetz, F., Garcia-Hernández, J., Schleiss, A.J. 2015 Extreme flood estimations on a small alpne catchment in Switzerland, the case study of Limmerboden. *Proc. IAHS,* 370, 147-152. doi:10:5194/piahs-370-147-2015

Figure 1: The Aare catchment situated at the northern edge of the Swiss Alps, and the division of the catchment into 13 sub-catchments and the range of the hydrodynamic model. The black triangles indicate the coupling points between the hydrological and the hydrodynamic model. The red lines indicate cross sections of the hydrodynamic model.

Figure 2: Synthetic design hydrographs that were used as upper boundary conditions of the hydrodynamic model and the resulting hydrographs at the catchment outlet. The grey lines indicate discharges with return periods of 30, 100, and 300 years. The peak discharges of the given return levels are derived by fitting a GEV distribution to the annual maximum discharges (based on a discharge time series from 1918 to 2014). The data as well as the statistical estimation of the return levels are provided by the Swiss Federal Office of Environment FOEN.

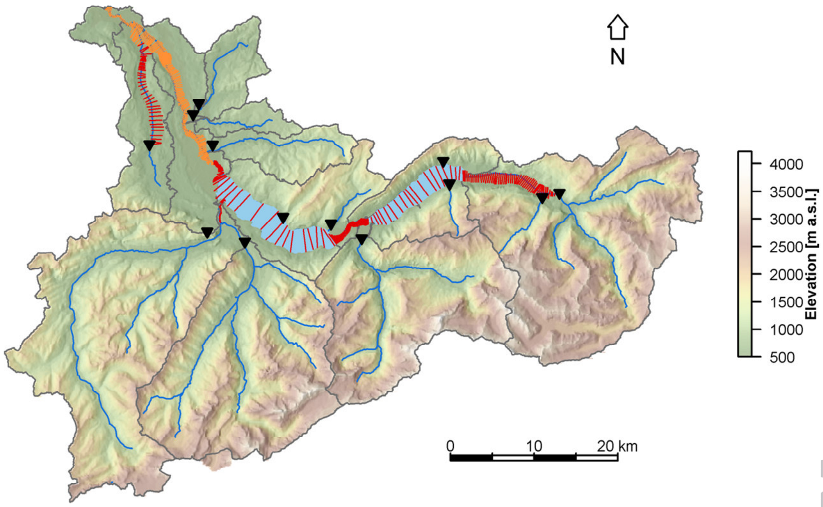
Figure 3: Hydrographs generated by the hydrologic modelling of the 100 PMP scenarios at the outlet of the catchment.

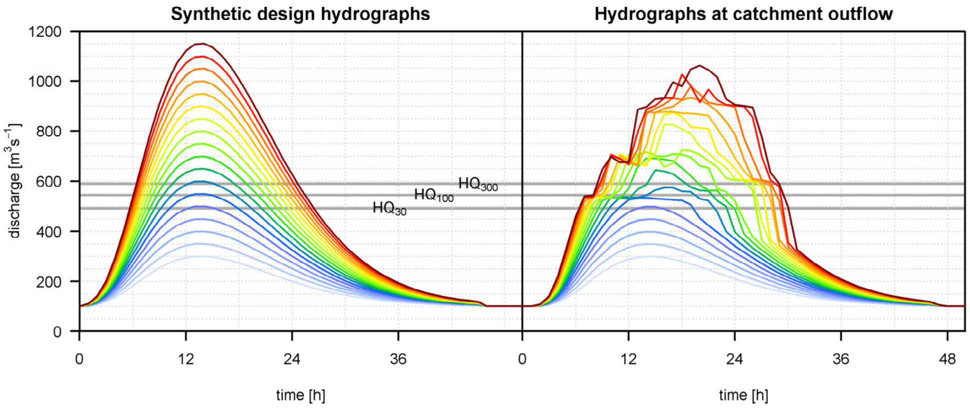
Figure 4: Hydrographs generated by the coupled hydrologic-hydrodynamic modelling of the 100 PMP scenarios at the outlet of the catchment. The red lines indicate thresholds for the occurrence of significant retention effects.

Figure 5: Peak discharges that result from the two modelling approaches.

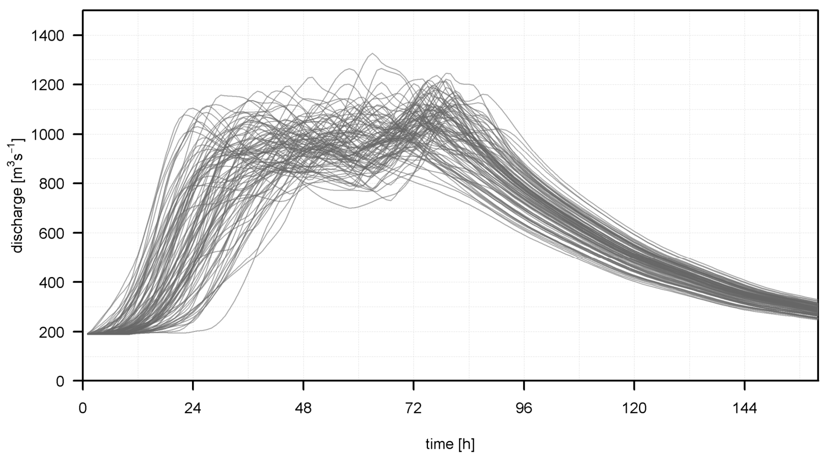
Figure 6: Time to peak that result from the two modelling approaches in hours. The vertical and the horizontal lines indicate the end of the precipitation event.

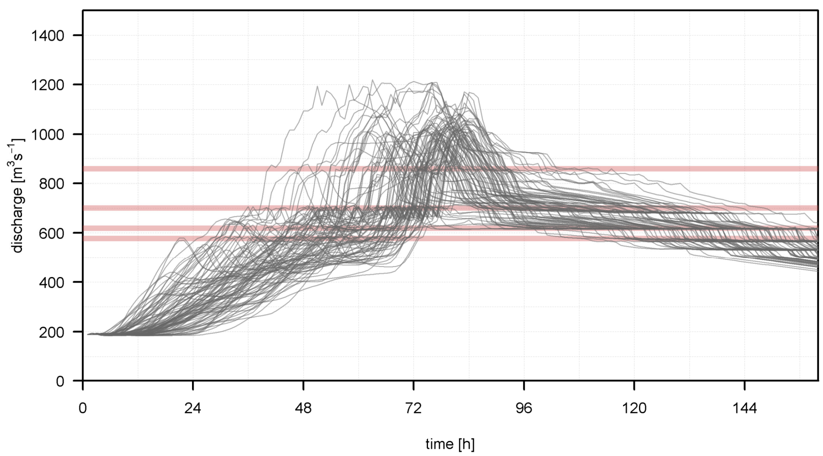
Figure 7: Peak-to-volume ratios that result from the two modelling approaches.


N
4000
3500
3000
2500
2000
1500
1000
500
Elevation [m a.s.l.]
0
10
20 km



Synthetic design hydrographs
Hydrographs at catchment outflow
discharge [m3s-1]
1200
1000
800
600
400
200
0
HQ300
HQ100
HQ30
0
12
24
36
48
time [h]
time [h]


1400
1200
1000
800
600
400
200
0
discharge [m^{3}s^{-1}]
0
24
48
72
96
120
144
time [h]


1400
1200
1000
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discharge [m^{3}s^{-1}]
0
24
48
72
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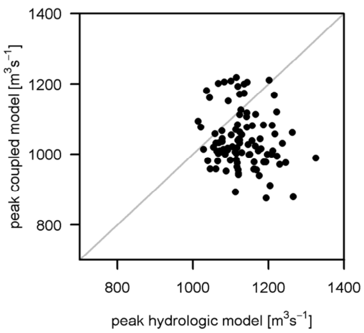
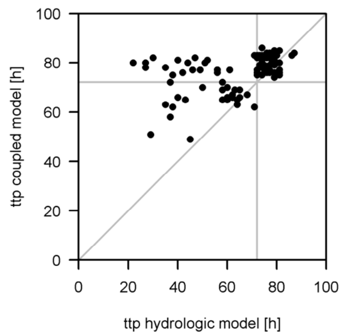
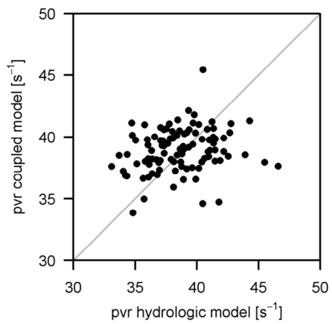
120
144
time [h]



1400
1200
1000
800
peak coupled model [m^{3}s^{-1}]
800
1000
1200
1400
peak hydrologic model [m^{3}s^{-1}]



ttp coupled model [h]
ttp hydrologic model [h]
0
20
40
60
80
100
0
20
40
60
80
100


50
45
40
35
30
pvr coupled model [s^{-1}]
30
35
40
45
50
pvr hydrologic model [s^{-1}]

Highlights

- Widespread inundation lowers peak discharge and causes unsteady catchment behaviour
- Coupled models are able to model complex processes that dampen peak discharge
- The dampening of peak discharge particularly affects PMF estimations