M-AARE - Coupling atmospheric, hydrological, hydrodynamic and damage models in the Aare river basin, Switzerland

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ABSTRACT

The triggering mechanism and the temporal evolution of large flood events, especially of worst-case scenarios, are not yet fully understood. Consequently, the cumulative losses of extreme floods are unknown. To study the link between weather conditions, discharges and flood losses it is necessary to couple atmospheric, hydrological, hydrodynamic and damage models. The objective of the M-AARE project is to test the potentials and opportunities of a model chain that relates atmospheric conditions to flood losses or risks. The M-AARE model chain is a set of coupled models consisting of four main components: the precipitation module, the hydrology module, the hydrodynamic module, and the damage module. The models are coupled in a cascading framework with harmonized time-steps. First exploratory applications show that the one way coupling of the WRF-PREVAH-BASEMENT models has been achieved and provides promising new insights for a better understanding of key aspects in flood risk analysis.

KEYWORDS

model coupling; worst-case flood; flood risk; Aare river; Switzerland

INTRODUCTION

In Switzerland, floods are the major cause of significant economic losses. The amplitude of flood peaks and the flood volume depend on the intensity and track of the triggering precipitation events, the topography and geology of the catchments, the wetness of the catchments prior to precipitation events as well as the hydro-morphologic conditions in the floodplains. However, the detailed triggering mechanism and the temporal evolution of large flood events, especially of worst-case scenarios, are not yet fully understood. Regarding mesoscale catchments, insights on the precipitation patterns leading to the most extreme floods are missing. Consequently, the cumulative losses of worst-case floods are unknown. The knowledge of the worst-case flood or of flood discharge return periods of up to 10’000 years are important for managing critical infrastructures as well as financial risks, e.g.,

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for portfolio management of insurance companies. On a longer time scale, the question how the expected changes in precipitation intensities due to climatic changes influence the flood risk is of special interest. To study the link between weather conditions, discharges and flood losses it is necessary to couple atmospheric, hydrological, hydrodynamic and damage models. An attempt for coupling hydrologic with hydraulic models for flash flood predictions has been shown by Laganier et al. (2014). Various examples of coupling process models and vulnerability models were elaborated in the CRISMA project (Heikkilä et al. 2015). The focus in this project laid on the improvement of crisis management by simulating complex crisis scenarios of winter storm events, coastal submersion processes, earthquakes and for forest fires.
An example of coupling hydrologic, hydrodynamic and damage models is given by Kourgialas and Karatzas (2013).
The objective of the project "M-AARE – Coupling atmospheric, hydrological, hydrodynamic and damage models in the Aare river basin" is to test the potentials and opportunities of a model chain that relates atmospheric conditions to flood risks. Thus, the main question is whether the coupling of atmospheric, hydrologic, hydrodynamic and damage models could potentially contribute to a better understanding of the formation of flood events and their consequences. Another aim of this explorative study is to quantify the resources needed for simulating these processes in a model chain.
With the model chain, the discharges from the catchments to the floodplains for selected precipitation scenarios and the retention effects in lakes and floodplains should be quantified. This allows to predict the flooded areas and the related losses to exposed residential buildings. Beside the hydro-meteorological characteristics, a key aspect of the method is to characterize and capture the non-linear effects of flood retention in the valley bottom and in the lakes. Furthermore, the model chain will allow the quantification of potential losses for given scenarios based on flow depths and flow velocities and therefore provide a sound basis for risk analysis.
The model chain was developed and tested in the watershed of the river Aare upstream of Bern, Switzerland, with an area of approx. 3000 km^2. This river basin is a complex network of sub-catchments with different runoff characteristics including two larger regulated lakes. Most of the rivers are trained since the 18th and 19th century.

METHODS

The M-AARE model chain is a set of coupled models consisting of four main components: the precipitation module, the hydrology module, the hydrodynamic module, and the damage module (see Fig. 1). The selected models in each module will be inter-changeable or can be used in an ensemble-framework for further sensitivity and uncertainty assessments.

Precipitation module

The precipitation module provides precipitation scenarios as inputs for the rainfall-runoff model. The latter is set up for each tributary and delivers the input hydrographs for the hydrodynamic model. The precipitation scenarios are formulated using two different approaches: a) by defining representative spatio-temporal precipitation patterns represented in gridded datasets or b) by selecting extreme precipitation events from a long climate simulation of a Global Circulation Model (CESM1) and downscaling these selected cases with a Regional Climate Model (WRF). The first approach was used to estimate the probable maximum precipitation (PMP), which is done by applying a Monte Carlo approach. The identified spatio-temporal distributions with the most severe impacts feed subsequent models. For the second approach, a long-term climate simulation (a control simulation spanning more than 500 years) with the Earth System Model (ESM) provides a coarse-resolution dataset of several centuries of precipitation. From this data set, a number of case studies corresponding to extreme situations are selected as candidates for further analysis. However, the global model employs a coarse spatial resolution (1 degree) that precludes the accurate simulation of the precipitation in areas of complex topography such as Switzerland. Hence, these cases need to be dynamically downscaled with a Regional Climate Model (RCM). The applied RCM WRF implements a spatial resolution of 2 km over the entire alpine area, which allows a more realistic representation of precipitation induced by interactions between the large-scale forcing and orography. Outputs of both approaches in this module consist of gridded time series of temperature and precipitation of a selected number of scenarios.

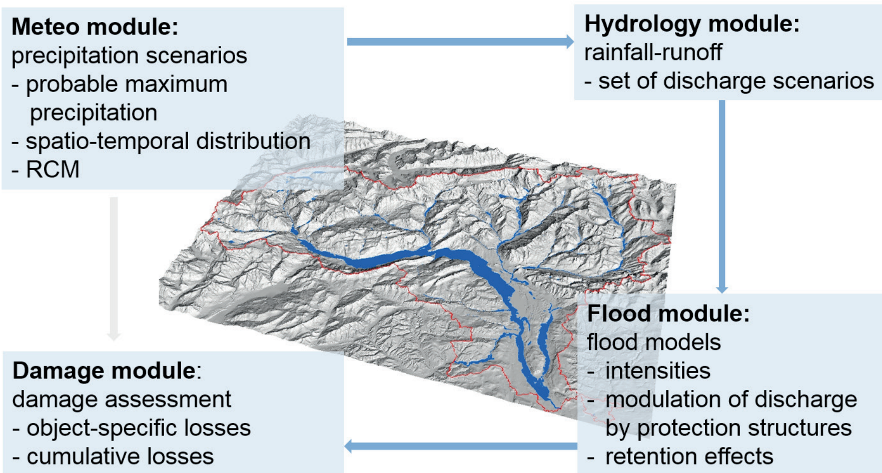

Figure 1. Conceptional setup of the model chain M-AARE in the Aare river basin.

Hydrologic module

For the rainfall-runoff modelling, we apply the hydrological model PREVAH (Viviroli et al. 2009). The model is set up for 15 sub-catchments that are located within the Aare basin with a spatial resolution of 1 km and hourly time steps. The delimitation of the catchments are presented in Fig. 2. The model is fed by the precipitation scenarios described above. The model output of the hydrologic module is used as the upper boundary condition of the hydrodynamic model.

Hydrodynamic module

The generated hydrographs are then routed with the hydrodynamic model BASEMENT-ETH (Vetsch et al. 2015) that accounts for the retention effects of lakes and floodplains. The hydraulic model was set up in two ways, a 1D- hydrodynamic model for all research questions regarding the flow routing only and a 2D-model used for coupling the damage module. The 1D model consists of cross sections along the whole valley bottom and considers the characteristics of the two lakes (lake Thun and lake Brienz) in modulating the flood hydrographs from the upper catchments. All of the main rivers considered in the 1D model were coupled in one integrated hydrodynamic model. This model consists of the Aare river from Meiringen to Bern including the two lakes and the area between the two lakes, the Gürbe valley, the Lütschine valley downstream from Gsteig, the Kander river downstream from the confluence with the Simme river. The river reaches in the main floodplains are implemented also in a 2D hydrodynamic model. Therefore, depending on the research question or on the damage model applied, these river reaches can either be modelled in 1D or in 2D, respectively. The 1D model was used for studying worst case discharges at the basin outlet in Bern. The 2D model was used to delimitate the flooded areas and as an input for the damage module. The spatial setup of the interface between the hydrologic and the hydraulic models is shown in Fig. 2.

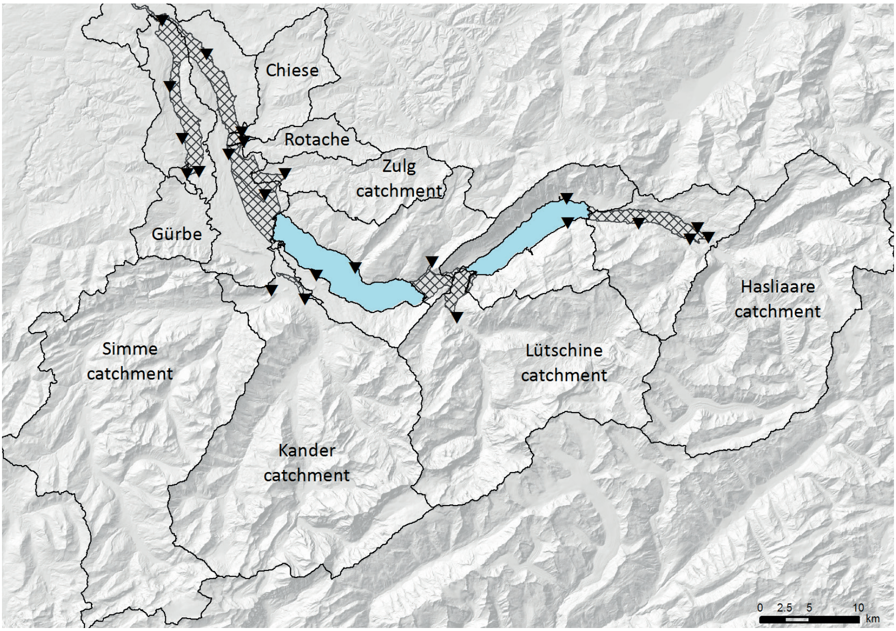

Figure 2. Spatial setup of the interface between hydrologic and hydrodynamic models. The black lines show the catchment delimitations. The calibrated catchments are indicated by labels. The black triangles indicate where the output of the hydrologic model will be used as input for the hydrodynamic model. The hatched areas represent the floodplains modelled in a 2D hydrodynamic model. The damage model is applied only in these areas.

Damage module

The hydrodynamic model – run in 2D mode – provides the basis for the damage module. This module consists of a dataset of buildings, each object classified by type, functionality, construction period, volume, reconstruction costs, and number of residents. The flood intensity maps resulting from the hydrodynamic module lead to the calculation of the object-specific vulnerability and therefore to the estimation of object-specific losses. The cumulative losses of a simulated precipitation scenario are summed up in a second step. Currently, a vulnerability function based on insurance data and reconstructed flood events is implemented. The method for the elaboration of the vulnerability curve follows the approach of Papathoma-Köhle et al. (2015), adopted to flood damages based on insurance data in Switzerland. The loss of life is calculated after Jonkman et al. (2008).

Coupling strategy

After Laganier et al. (2014), the model coupling strategy can either be of unidirectional or of bidirectional type. The first case is also called external coupling or a model cascade; the information is exchanged in one direction only. In the second case, the coupled sub-models interact between each other. In our case, the models are coupled in a cascading framework with harmonized time-steps. The coupling of the modules is controlled in a central timing and control device.

Calibration and validation

Each of the sub-models is calibrated and validated separately. The precipitation module is bias-corrected against gridded data sets of observations of precipitation in Switzerland. The hydrologic model is calibrated, if available, with observation data at the outflow of each sub-catchment (8 gauged sub-catchments). The models for the ungauged sub-catchments are regionalized by applying the parameter regionalization method proposed by Viviroli (2011). The hydrodynamic model was calibrated by empirically adjusting the friction coefficients. The values were adjusted by reconstructing observed flood events with particular regard to the water surface elevation in the main channel at peak discharge and the runtime of a peak discharge from one gauging station to another. The hydrodynamic model was validated based on watermarks along the rivers measured during the flood event in June 2014. The computed water surface elevations are within +/- 30 cm at nearly bankfull discharge. The 2D hydrodynamic model is calibrated in terms of reproducing the known channel capacity of the river reaches and in terms of reproducing the flooded areas of known flood events of 2005. The validation of the modelled flooded areas could not be quantified directly because the river geometry changed remarkably in some river reaches since the last observed floodings due to river training works. The damage model was validated in terms of reproducing the order of dimension of observed cumulative losses in past flood events. A direct validation of the damages to buildings was not possible because of lacking data at single objects level.

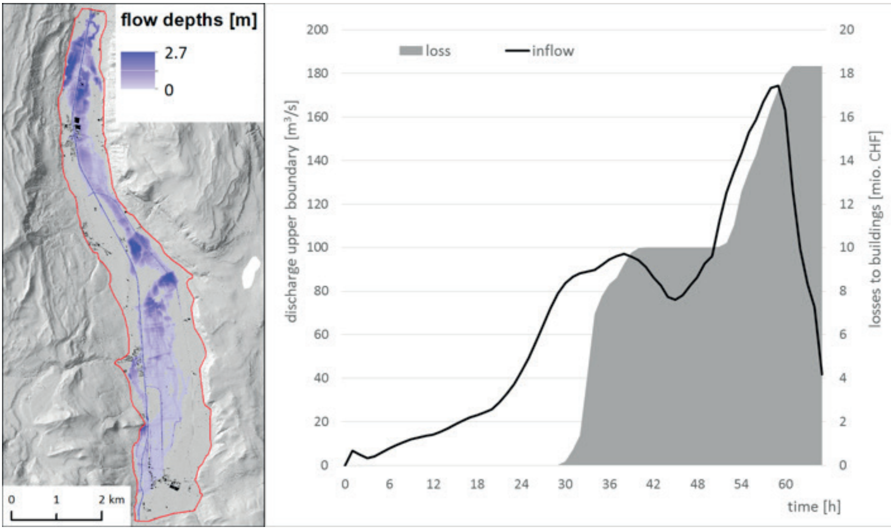

Figure 3. Flooded areas and losses to buildings in the subcatchment Gürbe related to a hydrograph resulting from one probable maximum precipitation scenario. The map at the left shows the flow depths at peak discharge, the diagram at the right shows the inflow hydrograph (continuous line) and the computed losses (grey area) over the time axis (hours).

RESULTS

The main result of the M-AARE project is the set up of a modelling chain of one-way coupled deterministic models. The first simulations of the model chain show that the chosen settings are suitable for modelling these natural processes, from precipitation to floods and flood losses. The meteo module provided numerous precipitation scenarios with different spatio-temporal distributions. These scenarios provide the input for the hydrologic model and the resulting discharges feed into the hydrodynamic model. The use of the downscaled global circulation model with a regional climate model showed that the latter is able to improve the simulation of precipitation compared to the GCM alone. Although, the large-scale flow and the location of the precipitation maxima is very similar at continental scales (as it is driven by the boundary conditions provided by the GCM) the spatial structure of the precipitation is refined at mesoscale scales, producing stronger precipitation gradients that allow to identify the main orographic barriers. Furthermore, much higher precipitation rates occur in some river catchments, which are indicative of potential disastrous situations at localised regions. The setting of the hydrodynamic model is able to consider retention capacities of lakes and floodplains, and to investigate the relationship between characteristics of process intensities and the related damages to residential buildings. The coupling between hydrologic and hydrodynamic models indicate that the relation between the input peak discharge and the modelled peak discharge at the outlet of the floodplains shows non-linear effects, which are usually neglected in extreme value statistical analyses. Further results of coupling the hydrologic and hydrodynamic models in probable maximum flood analyses are described in Felder et al. (subm.). Fig. 3 shows exemplarily the result of one of the simulated worst case scenarios. The map in Fig. 3 shows the modelled flow depths at peak discharge. The diagram in Fig. 3 shows exemplarily a hydrograph of one probable maximum precipitation scenario in one of the subcatchments and the related losses on buildings. The evolvement of the losses during the flood event is shown on the same time axis as the discharge.

CONCLUSIONS AND OUTLOOK

The results show that the one way coupling of the modules has been achieved and provides promising new insights for a better understanding of key aspects in flood risk analysis. The described model configuration allows to route the precipitation through different states of the river system and to take the retention effects of lakes and floodplains into account. The modelled magnitude of the effect of retention areas highlights the importance of considering such effects in extreme discharge estimations. First exploratory applications with the coupling of the WRF-PREVAH-BASEMENT models show the importance of clearly defined interfaces between the models. The coupling entails that all of the models are flexible enough to meet the requirements for the exchange of data, especially taking into account the different temporal resolution of each model. It is shown, that both the PREVAH model and the BASEMENT model are suited to be chained together and both are flexible enough to be operated by an external controller. In our case, the most important aspect is to harmonise the different time steps by using one framework. Therefore, the controller module is of strategic importance. Another important point is the definition of the location in space where the rainfall-runoff model delivers the computed discharges to the hydrodynamic model. These interfaces are located on the upper edges of floodplains in which remarkable effects of flood retention are to be supposed. The first applications of the damage model show that the vulnerability functions are crucial for calculating the damages. This module needs to be further improved and validated.

In conclusion, the M-AARE model chain has shown that the coupling of deterministic models offers a high potential to address further research questions and offers opportunities to provide a sound framework for different tasks in flood risk management. However, a successful implementation requires a high demand on specific knowledge and an interdisciplinary approach. Each of the modules needs knowledge and the coupling itself requires a rigorous definition of the interfaces between the models and an expertise in setting up of the controller module. Overall, the described model chain may provide the basis for further investigations:

– The model chain will simulate more scenarios of physically plausible peak discharges in the study area that are determined by the most extreme situations leaded by the large-scale circulation within the GCM. This will enable the analysis and characterization of worst-case floodings whose return period exceeds several centuries.
– With this model chain, it is possible to quantify the cumulative effects of all river training works or to assess the sensitivity of river reaches to the effects of climatic changes. This allows analysing the lake regulation procedures in case of a worst case flood.

– It allows forecasting flood damages on the basis of discharge forecasts in selected river reaches due to the analysed discharge-damage-relationships.
– The implementation of a multi-modelling approach in the hydrologic, hydrodynamic and damage modules will provide the possibility to quantify and describe the uncertainties in more detail.
– The M-AARE model chain may also provide a platform for planning of flood corridors and studying their effects in terms of flood hydrograph modulation on basin scale.
– Up to now, only buildings are considered in the computation of losses. The damage module has to be extended to other categories, e.g. losses to infrastructures etc.

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