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Simulation of flood hazard and risk in the Danube basin with the Future Danube Model

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ABSTRACT

Major river and flash flood events have accumulated in Central and Eastern Europe over the last decade reminding the public as well as the insurance sector that climate related risks are likely to become even more damaging and prevalent as climate patterns change. However, information about current and future hydroclimatic extremes is often not available. The Future Danube Model (FDM) is an end-user driven multi-hazard and risk model suite for the Danube region that has been developed to provide climate services related to perils such as heavy precipitation, heat waves, floods, and droughts under recent and scenario conditions. As a result, it provides spatially consistent information on extreme events and natural resources throughout the entire Danube catchment. It can be used to quantify climate risks, to support the implementation of the EU framework directives, for climate informed urban and land use planning, water resources management, and for climate proofing of large scale infrastructural planning including cost benefit analysis. The model suite consists of five individual and exchangeable modules: a weather and climate module, a hydrological module, a risk module, an adaptation module, and a web-based visualization module. They are linked in such a way that output from one module can either be used standalone or fed into subsequent modules. The utility of the tool has been tested by experts and stakeholders. The results show that more and more intense hydrological extremes are likely to occur under climate scenario conditions, e.g. higher order floods may occur more frequently.

Practical implications

The severity of extremes such as flash floods, fluvial floods and droughts is compounded by climate change, and this has come into the awareness of the public sector and insurance industry over the past decade. The insurance industry, for example, has hitherto based its catastrophe loss assessment on historical experience data and is now looking to, and examining how to bring the impact of climate change on natural and elemental perils into the equation when modelling catastrophe risk.

Furthermore, to protect people and assets in the Danube region, e.g., management strategies, flood defenses and drainage systems must be adapted to the changed conditions. To adapt the drainage and flood control systems however raises practical questions. Where and how much will the flood risk change, what kind of water damage can be expected, what improvements need to be made to maintain or increase the acceptable safety levels of flood and drainage systems? Engineering practice usually rely on fixed design values that are inferred from historical observations.

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Given the observed accumulation of major river and flash flood events in the Danube region over the last decades that fall in line with the projected increases in flood risk due to climate change, it is imperative that these design values are updated. However, the development of adaptive measures not only raises engineering issues, it also has an impact on the financial foundation of such developments. If, in the foreseeable future, significant building tasks need to be undertaken to ensure an adequate protection against increasing occurrences of floods with high levels of water damage, support and acceptance by policy makers and society in general is key.

The Future Danube Model (FDM) suite provides quantitative information and risk assessment based on state-of-the-art knowledge, aimed at improving decision-support at all levels for which the implications of a changing climate are an issue, ranging from public administrations to business operators, including the insurance industry. Importantly, there is complete transparency with respect to the methods used along all parts of the modelling chain. It is also a practical example of how scientific research and modelling work of European academic institutions within the discipline can join forces with the technical experts of the insurance industry to provide a far greater transparency when assessing flood risk along the entire length of the Danube river thus forming a public-private partnership. There is currently no flood model used in the industry that combines detailed vulnerability functions with climate change scenarios. However, insurers are required by their supervisory authority to calculate realistic disaster scenarios, and make financial provisions accordingly. The combination of know-how and forces behind the FDM may be a benchmark for policymakers, scientists and practitioners from the public sector and the insurance industry in this regard.

The model suite is comprised of five exchangeable modules, which seamlessly fit together, but can be used individually or together according to the users' preferences. All data products are delivered in standardized formats. They are also fully compliant with the open source Oasis Loss Modeling Framework (see below), i.e. to specially provide for the insurance industry.

Module	Output	Format
Weather/ climate	200000 years of synthetic weather data, based on four state-of the art climate models, covering a historical period and two climate scenarios: RCP4.5 (high mitigation scenario) and RCP8.5 (unmitigated scenario).	Gridded data, spatial
Hydrology/ Hazard	Historical and projected daily water discharges, fluvial floods, pluvial floods & droughts	Gridded data, spatial (basin)
Risk	Estimated vulnerability for specific areas/sectors tailored to the needs of the users, water and inundation levels (pluvial and fluvial floods), regional and/or local risk assessment	Inundation, fluvial/pluvial flood risk maps
Adaptation	Output from the different modules are fully compliant with a cost-benefit framework, which can be tailored to the user's requirements	NA
Visualization	Easy-to-use GIS based interface based in OpenStreetMap technology, all data are compliant with OasisHub tools	GIS

The following case examples serve to illustrate the applicability of the FDM:

1. The role of reservoirs in flood protection in the case of very large rivers like the Danube is traditionally very low. Hence, flood protection largely relies on the efficiency of physical flood defenses. The design value of the height of the flood protection infrastructures on the Hungarian section of the Danube is currently based on the flood level that has a 1% chance of being equaled or exceeded in any given year, also known as the 100-year flood or base flood. The design value of the 1% flood level was last modified in 2014 on the basis of the observed flooding and the calculated flood levels of the 1% exceeding probability discharge along the Danube in 2013 (see Kovács et al., 2016). It is imperative to know if the increased standards, which will underpin the decided improvements since 2013, will also be appropriate in the future or whether they need to be further amended to climate change. The FDM is an ideal tool to answer this question and to provide the necessary information for policy makers and practitioners to decide on suitable adaptations, if needed.
2. The awareness and importance of pluvial floods caused by extreme rainfall is growing as a result of recent flood events, e.g., in Budapest, and climate change projections. Pluvial floods threaten cities particularly due to their high value of people, property and critical infrastructure per unit area combined with the high proportion of impervious surfaces. Urban drainage systems provide the principal line of protection against inundations caused by flashfloods. In order to design new infrastructure and/or upgrade existing systems accordingly, it is essential to have reliable estimates of future extreme rainfall but also to know the exposure of urban areas to pluvial floods. From this perspective, pluvial flood hazard and risk maps as delivered by the FDM suite constitute an essential tool for decision-makers and engineers.
3. The EU Floods Directive demands for a trans-boundary consistent estimation of current and future flood risks. This has not been done in the current reporting cycle and remains to be done in the next iteration. The FDM, because it is implemented for the entire catchment and calculates also climate change impacts, is an ideal tool to support the implementation of the Flood Directive in communication with the national experts and representatives.

In general, interdisciplinary cooperation is urgently needed to understand the practical implications of climate change. The Danube multi-hazard and multi-risk model is designed to be a model for how this unification process can work.

1. Introduction

Recently, the world has faced an unprecedented increase in the intensity and frequency of extreme meteorological events and associated damages to human life, property and assets (reaching an US$180 billion in annual losses, Swiss Re, 2014). To facilitate appropriate and climate informed adaptation actions to reduce the vulnerability of our societies and economies, it is paramount to adequately understand and quantify these climate related risks (Cortekar et al., 2016). Analysis of historical flood events as well as projections into the future for Central

and Eastern Europe show that the intensity and frequency of floods is likely to increase (EEA, 2012; Petrow and Merz, 2009; Hattermann et al., 2014, 2016). At the same time, a trend towards more intense heatwaves and longer periods of little or no precipitation has already been observed (Della-Marta et al., 2007; EEA, 2012; Russo et al., 2015; Dong et al., 2017; Hoy et al., 2017), impacting water supply, hydropower, and agricultural production. Countries and administrations all over Europe are currently struggling with the implementation of water and climate-related European frameworks such as the EU Floods Directive (EU-FD), the EU Water Framework Directive and the corresponding adaptation and mitigation plans. With regard to the EU-FD, harmonization of the approaches has been promoted and coordinated by the International Commission for the Protection of the Danube River (ICPDR). The EU-FD demands explicitly for adjustments of flood risk maps accounting for climate change, however, this has not been done in the current reporting cycle.

Also insurers and re-insurers have an interest in understanding the impact of climate change on the magnitude and frequency of extreme weather and flood events, in order to adapt their insurance policies to possibly changing conditions and thereby to curb trends in ever increasing losses and keep risks insurable (Lloyd's, 2014, Hattermann et al., 2014). Where the recurrence interval of a 100-year flood may be estimated in some river sections based on observations, the recurrence of a higher order flood, e.g. a 1000-year flood event may only be assessed using probabilistic methods in the absence of long-term observations. A common approach in the insurance sector to assess flood frequencies is therefore, for instance, stochastic flood modelling based on the distribution of historical data that involves estimating thousands of plausible flood events and their return periods (Mitchell-Wallace et al., 2017).

We apply a similar approach by generating 10,000-year (10 ka) time series of daily synthetic weather and discharge variables. Such time series include a large set of extreme events and thus provide the basis for the application of extreme value statistics to estimate the probabilistic occurrence of events while ideally reducing the uncertainties for events beyond the time scale of observed data. The novelty of this approach is that these time series are not only generated based on historical climate data but also for two future time slices using climate simulations from four bias-corrected Global Climate Model (GCM) – Regional Climate Model (RCM) combinations and two climate scenarios.

The Future Danube Model (FDM) allows for investigating the impacts of climate change along the entire risk modelling chain, from weather and climate events, floods, droughts, heatwaves, and storms to their corresponding hazards and risks and possible adaptation strategies. The FDM is developed in the framework of the OASIS + [1] and H2020_Insurance[2] projects, jointly together with end-users from the insurance industry and public sector. It enables, for example, the implementation of the WFD and EU-FD by providing a consistent river basin model to assess multiple hazards and risks in the entire Danube River basin with harmonised approaches for all riparian countries.

The purpose of this paper is to present and describe the model suite, its input data and results, with the latter focusing on flood events and their return periods in the Danube River basin upstream and around the city of Budapest (Hungary).

2. Methods and data

2.1. Model domain

The model domain of the FDM is the entire Danube River basin that is shared by 19 countries, is home to more than 81 million people, and covers an area of 801,000 km^2 (Fig. 1). Especially for the downstream part of the basin, information about climate-related extreme event risks under scenario conditions is currently scarce. To demonstrate the application of the FDM, we initially focus on changes of flood return periods in the upper part of the basin until Nagymaros upstream of the city of Budapest covering an area of 183,386 km^2.

2.2. Input and output data

The FDM integrates several data sources and passes information down to the subsequent modules as shown in Table 1. All model components use the E-OBS reanalysis data (Haylock et al., 2008) as meteorological reference. E-OBS represents a consistent observation dataset that was used in the IMPACT2C project to bias correct regional climate model runs of the EURO-CORDEX project (http://www.euro-cordex.net/) using quantile mapping (c.f. 2015; Wilcke et al., 2013; Gobiet et al., 2015), which are applied in this study for the scenario analysis (see Table A1 in the Appendix). The data are used as input to the climate module of the FDM and permeate through the entire model chain. The subsequent modules are calibrated using the E-OBS data and historical observations of flood events.

Fig. 2 displays the modules of the FDM and the main output, which is further described in the following sections.

2.3. The Future Danube Model

2.3.1. Weather and climate module

The Imperial College Weather Generator (IMAGE) is a new weather generator that captures both the point statistics and spatial-temporal autocorrelation of single and multiple variables (Sparks et al., 2017). IMAGE ingests observations, re-analysis or climate model results to capture the spatial-temporal statistics. In this application, IMAGE is used to produce daily weather time series of 10 k years representing historical and projected future climate based on Regional Climate Model (RCM) simulations driven by Global Climate Model (GCM) scenarios. 30 years of weather simulations from four different EURO-CORDEX GCM-RCM combinations (see Table A1 in the Appendix), representing the climate in the past (1970–1999) and in two future periods (2020–2049 and 2070–2099), are used to generate 10 k years of weather for each of the three periods and two climate scenarios. Simulations are chosen to properly represent the entire ensemble's spread and being as independent as possible.

The climate scenarios are based on the latest climate scenario generation of the IPCC (International Panel for Climate Change), the so called Representative Concentration Pathways (RCPs, van Vuuren et al., 2011). Two scenarios have been selected to represent possible climate projections: RCP4.5 constitutes a moderate scenario and RCP8.5 a high-end scenario with temperature increases around 2.5 °C (RCP4.5) and 3.5 °C (RCP8.5) until end of this century in the Danube area (Jacob et al., 2014). Present-day E-OBS weather data with a resolution of 0.25 degrees were used to bias-correct the RCM simulations. While statistical characteristics of the 10 k years are similar to those of their respective 30-year baseline periods, extreme events of higher recurrence interval are sampled and generated spatially and temporally consistent over the entire Danube River basin. All in all, 200 k years of weather data were generated by the IMAGE model based on 4 GCM-RCM combinations, 2 RCPs, 1 historical and 2 future periods, where each period consists of 10 k years. These weather simulations are the main input to the hydrological module in the FDM.

Return periods of extreme rainfall events in the mostly exposed subcatchments of the Danube River basin simulated with IMAGE show a very good fit with observations (E-OBS), see Fig. 3. An additional indirect validation of the generated information, based on observed flood extremes, was performed when the weather data were fed into the hydrological module to translate them into flood events.

[1] http://www.oasisdanube.eu/.
[2] https://h2020insurance.oasishub.co/.



Fig. 1. Map of the Danube River basin and four important gauge stations.

Table 1
Input and output data of each module. Output data is passed down into the next module.

Module	Input	Output
Weather & climate	• E-OBS reanalysis reference climate (1979–2008) • EURO-CORDEX regional climate change scenarios (RCP-4.5, RCP-8.5), ensemble of 4 models	• 10 ka daily temperature, precipitation, radiation for the reference period and 2 future climate periods with 2 scenarios
Hydrology/Hazard	• SRTM 90 m elevation • CORINE landcover • Harmonised World Soil Database • GLIMS glacier cover • GRDC discharge data for calibration	• 10 ka daily river reach discharge and water levels • water balance terms at subbasin and hydrotope level (runoff, soil moisture, etc.) • flood hazard maps (extent, inundation depth)
Risk	• EU census data (2011) • various building footprint data (Infas, Uni. of Groningen, EU Copernicus, OSM) • DFO historical flood observations • CORINE land cover • Urban land cover based on Sentinel-2 (remote sensing), 10 m resolution (focus areas) • DEM with 10 m resolution (focus areas) or 25 m resolution (large scale application)	• loss maps of residential buildings and commercial sector
Adaptation	• Flood loss/risk maps and Local information collected, e.g., through stakeholder engagement, including: - Specific adaptation decision criteria (e.g., protection level, risk aversion, cost-efficiency) - Technical description of adaptation measures (e.g., costs, location, risk reduction potential)	• Cost-benefit analysis of adaptive measures
Visualization	• Hazard and risk data of the basin or for smaller areas such as municipalities, districts, river sections, sub-regions • other spatial information such as population density, assets, roads and rivers, urban areas etc.	• Hazard and risk maps, graphs, statistics, streamlined to end-user needs

2.3.2. Hydrological module

The Soil and Water Integrated Model (SWIM) is an eco-hydrological model that has been developed at the Potsdam Institute for Climate Impact Research (Krysanova et al., 2005) to investigate impacts of changes in climate, land use, and water management (reservoirs and irrigation) on the catchment hydrology (including floods and droughts) and vegetation processes (e.g. crop yields) at the regional scale. SWIM has been applied in various flood related studies (Huang et al., 2013) also in collaboration with the German Insurance Association (Hattermann et al., 2014, 2016), and has taken part in model intercomparison exercises (Huang et al., 2016).

SWIM is a spatially semi-distributed model that generally operates at a daily time step, but which can simulate important runoff (e.g. infiltration) and discharge processes (river routing) on a sub-daily mode. In the FDM, the hydrological module creates the link between the weather/climate (IMAGE) and the risk modules. The SWIM model was set up for the entire Danube River basin with a spatially detailed resolution represented by 13,473 sub-basins (Fig. 4) and 190,000 hydrological response units (unique combinations of sub-basins, landuse, soil types and elevation zones). This high-resolution model enables us to zoom into any location of interest, such as small tributaries. The model was calibrated and validated to observed discharge in the reference period 1979–2008

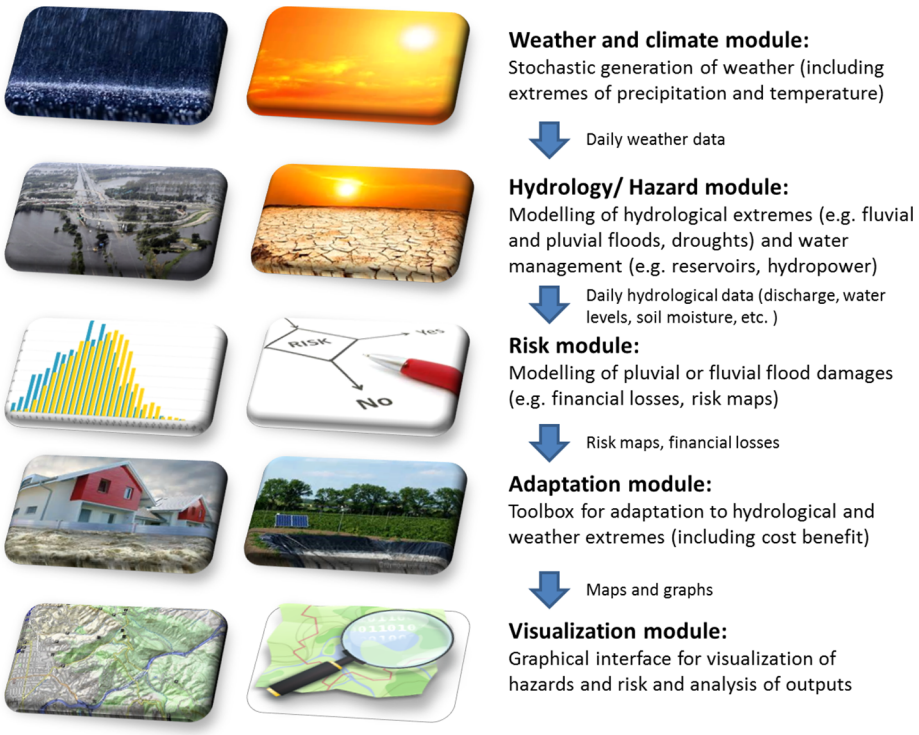


Fig. 2. The modules of the Future Danube Model (FDM).

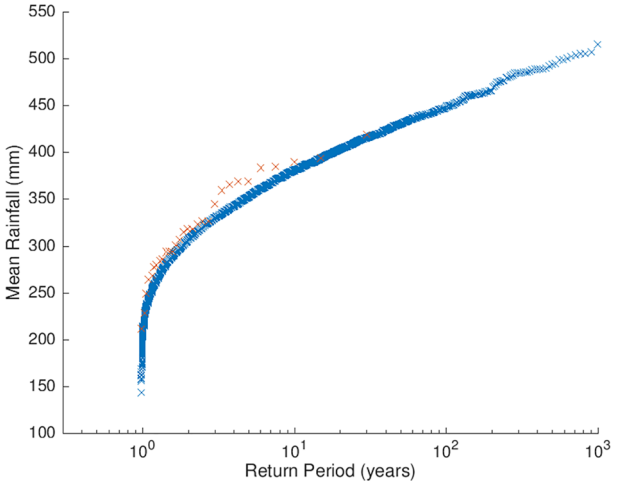


Fig. 3. E-OBS (red) and simulated daily rainfall extremes (blue) in the mostly exposed sub-catchments of the Danube basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at up to 50 gauging stations across the catchment. The evolutionary multi-objective optimisation algorithm SMS-EMOA (Beume et al., 2007) was employed to calibrate 13 parameters considering three objective functions, Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970) of daily discharge, water balance and the root mean square error of the flood peaks exceeding Q1 (discharge exceeded 1% of the time). The mean of the NSE for the 19 discharge gauge stations in the upper part of the Danube, where this article focusses on, is 0.68, the station with the poorest result has an NSE of 0.41, and the mean long-term discharge is bias 1.2%. After calibration, the 10 ka blocks of weather data generated by IMAGE are used as input to SWIM to simulate daily discharges and to investigate the impacts of climate change on hydrological parameters such as future flood and drought return periods and average seasonal or annual discharge patterns.

The ability of the hydrological model to reproduce daily flood events in the upper part of the Danube is illustrated in Fig. 5 for the main river and important tributaries. While small events and also the highest events are well reproduced, some of the medium events are seen to be slightly less accurate. The hydrological model so far does not consider dikes or polders, where no consistent information exists in most regions.

To complement SWIM in cases where floods may arise from highly localized extreme cloudburst events either on their own or in combination with fluvial floods, the hydrological module also comprises a pluvial flood model. The pluvial flood model, which creates an independent link between the weather/climate and the risk modules, is currently based on the 2D overland flow model embedded in the MIKE 21 modelling suite (MIKE Powered by DHI, 2018), which computes overland flows in response to precipitation input based on terrain data and a Digital Elevation Model (DEM). The precipitation input generally follows the standard of a Chicago Design Storm based on the parameters of an assumed Intensity-Duration-Frequency relationship, but the time series input can in principle take any form.

MIKE 21 is applied worldwide and is here used in a configuration similar to Kaspersen et al. (2017). In this approach, the pluvial flood model does not include an explicit representation of subsurface flows (e.g. the urban drainage system) which are replaced by a “conceptual” model, emulating to some extent the effect of, e.g., infiltration and urban drainage. In the simplest form the conceptual model removes surface water uniformly at a pixel level according to the slope and fraction of pervious vs. impervious surface within the pixel. For pervious surfaces, the corresponding fraction of infiltrated water is removed according to soil type, whereas for impervious surfaces water is reduced according to, e.g., assumed service level of the drainage system. In both instances, the infiltration/drainage is in the simplest case assumed to be homogenous across the modelled area. The conceptual model is generally informed by high-resolution remote sensing information (Kaspersen et al., 2015). Combined, this makes the model highly transferable and in principle ensures a similar performance across sites, which is a quality appreciated by the insurance community.

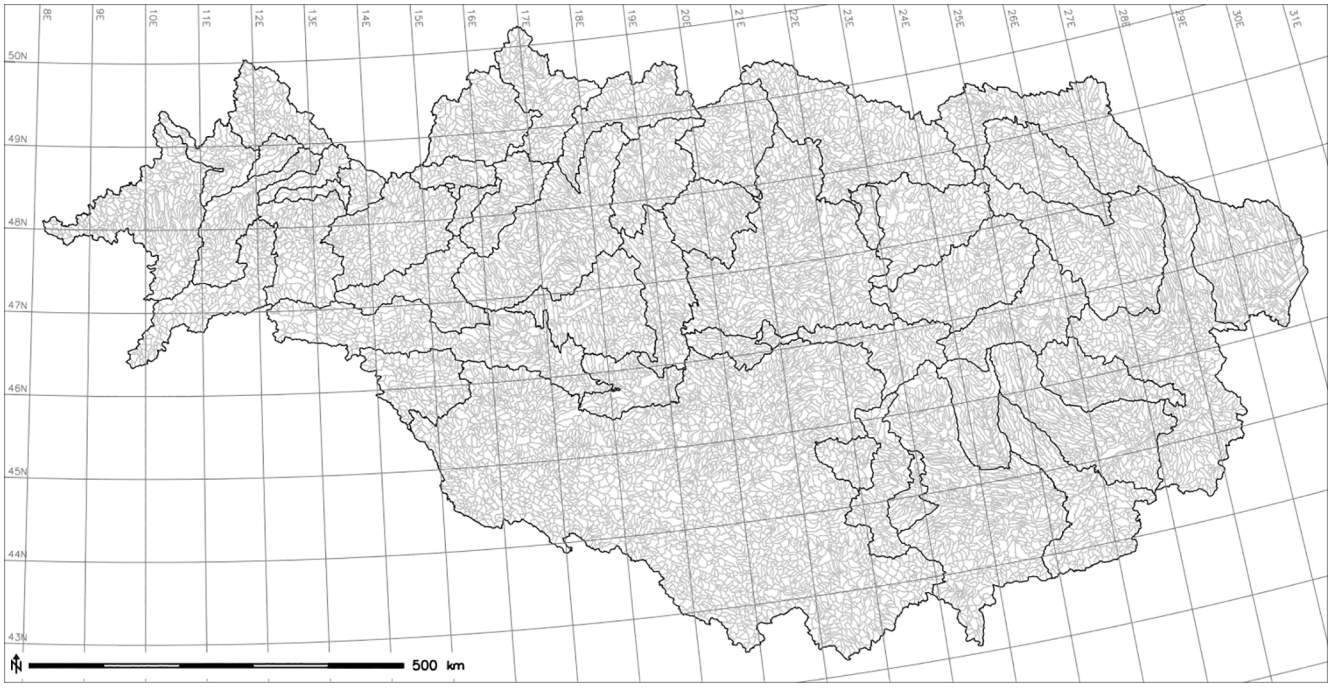


Fig. 4. Model sub-basin and calibration area discretisation.

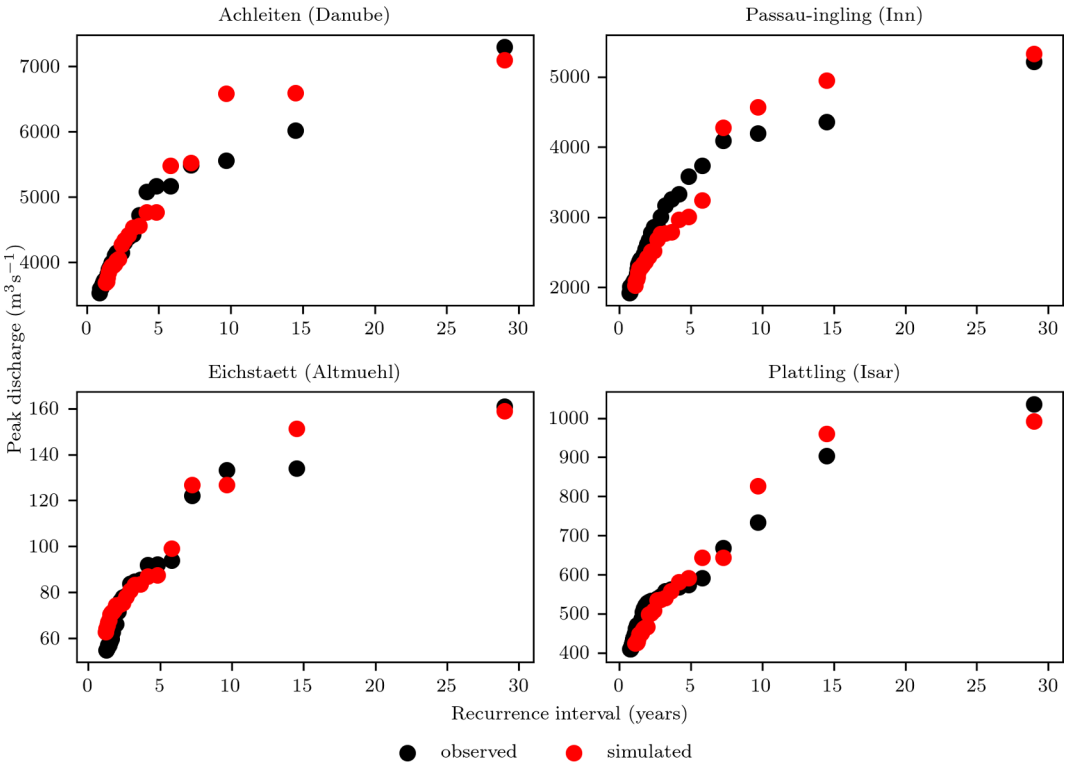


Fig. 5. Return periods of observed (black) and simulated (red) flood events. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The resolution of the model is defined by the horizontal (and vertical) resolution of the DEM, which in practice tends to lie between 5 and 25 m.

Output from the pluvial flood model (input to the risk module) optionally includes flood (inundation) depth, flood duration and flow speeds at the pixel level, e.g. see Fig. 11.

2.3.3. Risk module

The purpose of the risk module is to transform the hazard, in our example the streamflow data of flood events as simulated by the hydrological module, into inundation depths maps, to estimate flood damages, and to derive risk indicators as for instance loss exceedance probability curves or expected annual loss values. The transformation of hydrological flows into water levels and inundation maps uses non-

stationary 1D-hydrodynamic approaches and GIS techniques at larger scales, and coupled non-stationary 1D-, 2D hydrodynamic models (Falter et al., 2016) at regional scales, as for instance for the German part of the Danube basin, or for urban scales (Kaspersen et al., 2017). The flood inundation modelling for river networks considers the interactions of flood wave propagation as for instance superposition of the waves from different tributaries. The continuous long-term simulation of flood event sets allows taking spatial patterns of flood risk, i.e. spatially varying magnitude of flood hazards, into account (Falter et al., 2015).

Inundation depth is the key input variable to flood vulnerability models (Gerl et al., 2016). Even though the estimation of flood loss is very sensitive to the choice of the vulnerability model (Apel et al., 2009), the standard approach to loss estimation is based on highly simplified functions, which basically relate the damage for the element at risk to inundation depth. The FDM model suite currently includes the multi factorial flood loss model FLEMOps + r (Elmer et al., 2010) for residential buildings which uses multiple variables to explain flood loss including information about building types, building characteristics, and event return period. Given the modular structure of FDM, the model suite will be further extended: i) to include also vulnerability models for the commercial sector, and ii) to implement advanced methods for flood loss estimation and associated uncertainty (e.g. using Bayesian Networks, Schröter et al., 2014), which is an important basis for informed decision making in risk mitigation and adaptation planning.

2.3.4. Link to the OASIS Loss Modeling Framework

The resulting flood event sets and vulnerability functions provide flood hazard footprints and the vulnerability components which can be used as input to the Oasis Loss Modeling Framework (LMF, see Fig. A1). This is an open source platform for developing, deploying and executing catastrophe models that has been built in collaboration with the insurance industry to enable the “plug and play” of hazard and vulnerability modules (along with exposure and insurance policy terms) by way of a set of data standards that describe a model. These data standards are used as the input for a bespoke calculation kernel adhering to the demands and best practice standards within the insurance industry. They produce, e.g., a standard set of risk assessment output reports that provides ground-up loss data and financial damage (insured loss) of event scenarios (www.oasislmf.org).

This standardization of the risk assessment using OASIS LMF makes the FDM results directly accessible to the insurance industry, but also provides a standardized and transparent risk estimation for applications beyond.

2.3.5. Adaptation module

Well-planned adaptation measures can help prevent or reduce the adverse effects (economic losses, damage to infrastructure, lives lost) of weather related hazards that are likely to be exacerbated by climate change. Likewise, appropriate adaptation may allow communities to benefit from potential opportunities of climate change (IPCC, 2014). Robust adaptation decisions are often achieved by considering the benefits and costs, i.e. the potential reduction of climate risks or losses caused by their impacts vs. the costs incurred by installing these adaptive measures, such as flood protection or changed management strategies, balanced by the associated (deep) uncertainty (e.g., Hallegatte, 2009; Halsnæs et al., 2015; Wilby and Dessai, 2010).

In this context interaction with stakeholders is crucial for establishing which adaptation measures are to be considered, data needs, the local decision-making context, and realistic values with respect to costs and (co-)benefits (Kaspersen and Halsnæs, 2017). In the FDM, the adaptation module relies on a dedicated cost-benefit tool, which seamlessly integrates the output from the preceding modules (in particular the Risk Module) or similar kinds of hazard and risk information from other sources (Kaspersen and Halsnæs, 2017) with technical descriptions of the potential adaptation measures (e.g., costs of implementation) and other local information that is relevant in the decision-making context. The tool currently visualizes the cost and (co-) benefits of adaptation in terms of, e.g. adaptation cost curves (ECA, 2009) connecting data, risk information and existing knowledge.

2.3.6. The visualization module, data availability and web frontend

The visualization module serves as an interface to (potential) end-users. Internet-based open Geographic Information Systems (GIS) technology integrating OpenStreetMap data is used to visualize and graphically overlay and analyze the perils and other spatial information such as population density or assets. The approach enables user interaction with maps and other results using the default web browser and without having to install additional GIS software.

The results can be visualized for larger parts of the basin or for smaller areas such as municipalities, districts, river sections, sub-regions etc. Some results of the Hydrological and Meteorological and Climate modules will be available for the entire basin and its sub-regions ready for visualization and analysis, while more specific evaluations e.g. of flash floods in cities will only be there for selected stakeholders commissioning a specific investigation. A map server also allows users to integrate results in existing GIS solutions.

The data, models and information are made additionally available through the OASIS Hub, a global window to free and commercial environmental and risk data, tools and services (https://oasishub.co/). The Oasis HUB is technically an online portal and marketplace for the publishing and purchasing of environmental data, adaptation planning tools, models and services.

3. Selected results and discussion

The following results were selected in such a way that they provide an insight and an overview about data and information provided by the different modules, which may be of interest for end-users in the public and private sectors.

3.1. Flood hazard under climate change

Using the detailed resolution of the hydrological module, changes in the recurrence of the 100-year flood can be estimated for all sub-basins as given in Fig. 6 (top) for RCP-8.5 in 2020–2049. The hydrological module was driven by the 10 ka weather time series produced by the IMAGE weather generator for each of the time slices. Flood events were identified for each sub-basin using the Peak Over Threshold (POT) approach using the Q1 discharge as minimal exceedance value. At the ensemble median the present day 100-year flood is projected to occur more often in the catchment upstream of Budapest with some exceptions in the north-eastern parts. In the German part of the catchment, it would occur every 20–40 years and every 40–60 years in the Austrian and Hungarian part. Some river reaches in the Czech and Slovakian parts show decreases in the occurrence.

Also given is the ensemble agreement in the change signals of the scenario model runs driven by the four EURO-CORDEX models (Fig. 6 bottom). It is evident that most models agree on an increase in the frequency of the 100-year flood. In some smaller river reaches only 3 out of 4 models predict an increase in frequencies, while the decreases in the Slovakian and Czech parts are confirmed by 3 out of 4 models.

A detailed flood hazard analysis for the catchment at the gauging stations Achleiten (just downstream of the German border) and Nagymaros (just upstream of Budapest, see Fig. 1) is provided in Fig. 7, assessing potential changes in flood frequencies over the 21st century. The figures show flood frequencies for the reference and the two future periods under both RCP scenarios. Flood peaks corresponding to respective return periods increase in both future periods and both scenarios compared to the historical period. The increase of flood peaks is higher in the far future than in the near future. The differences between

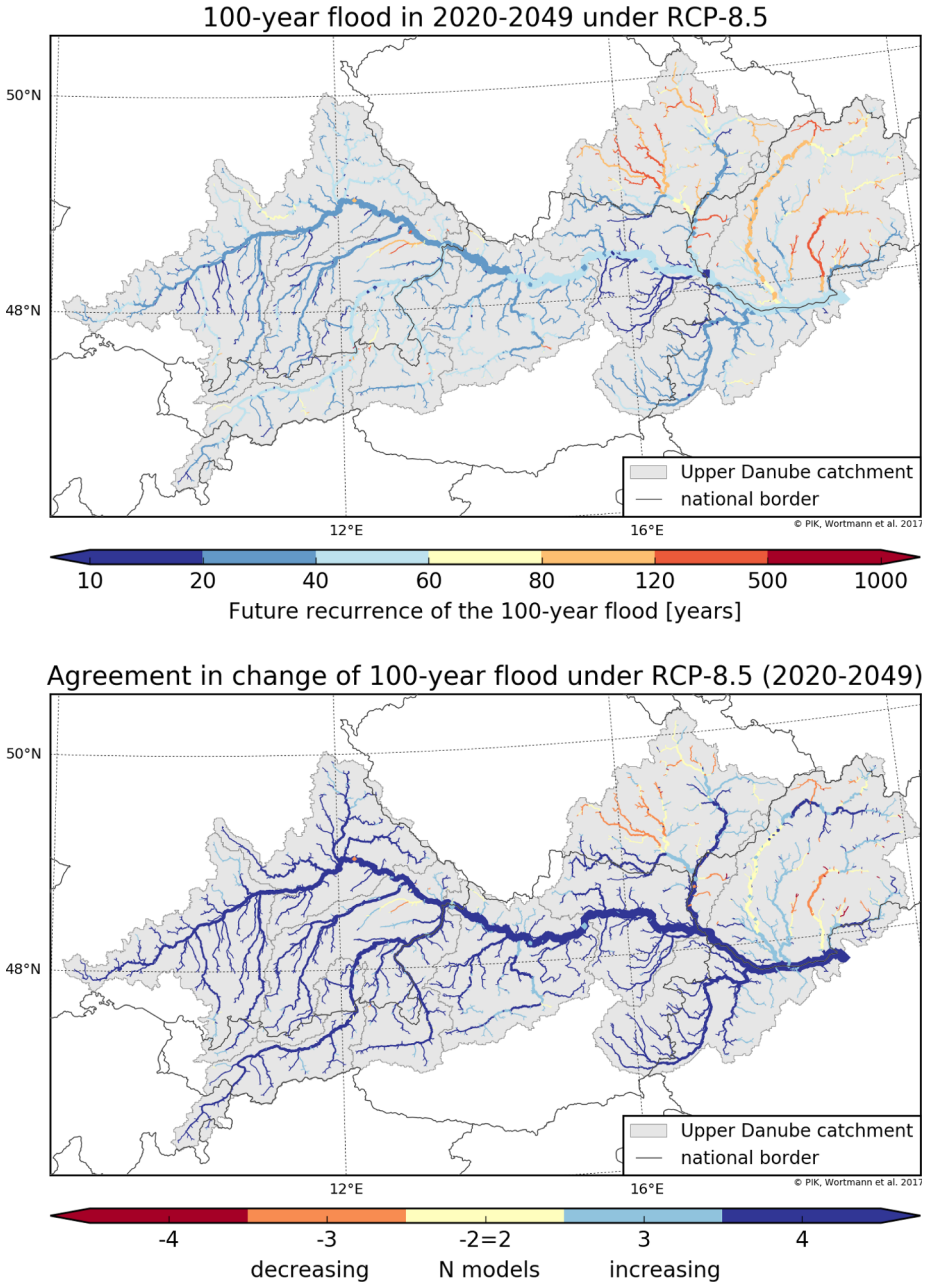


Fig. 6. Top: Recurrence of the present 100-year flood magnitude in the near future (2020–2049). Changes in ensemble median values are shown. 100-year flood occurs more frequently in blue shaded streams and less frequently in red shaded streams. Bottom: Number of projections agreeing in a positive or negative trend (out of the 4 EURO-CORDEX model runs fed into the hydrological model).

historical and future flood peaks increase with higher return periods. The projected increase of flood peaks is higher under RCP8.5 than in RCP4.5, especially in the far future. The underlying data are available for each of the 13,473 sub-basins.

3.2. Droughts and low flows under climate change

Besides floods, information on low flow conditions is of interest for example to water supply companies and the shipping industry. The projected impacts on the flow regime are illustrated in Fig. 8. While the annual mean discharge is increasing, we also see lower discharge in summer. This trend is more pronounced in the high end scenario. Winter and spring discharge is projected to increase under both scenarios and future climate periods.

3.3. Fluvial flood risk

Long term continuous simulations of hydrodynamic flood processes using the coupled 1D-2D flood model (Falter et al., 2016) have been conducted for the major river network (along 4150 km) of the German part of the Danube basin. The plausibility of the hydro-dynamic model set-up has been successfully checked using water level observations at various gauges and flood masks from historic events (1999, 2002 and 2006 floods) in the area.

The results of the hydro-dynamic models are maximum inundation depth information in cm above ground level on a 100 m grid, see Fig. 9 for an example detail, and maps of event return periods. Due to considerable computational costs, sample inundation maps are derived, so far, only for a time period of 100 years (from 10,000 years) for the historical period (1970–1990) and two RCPs (4.5 and 8.5) for the near

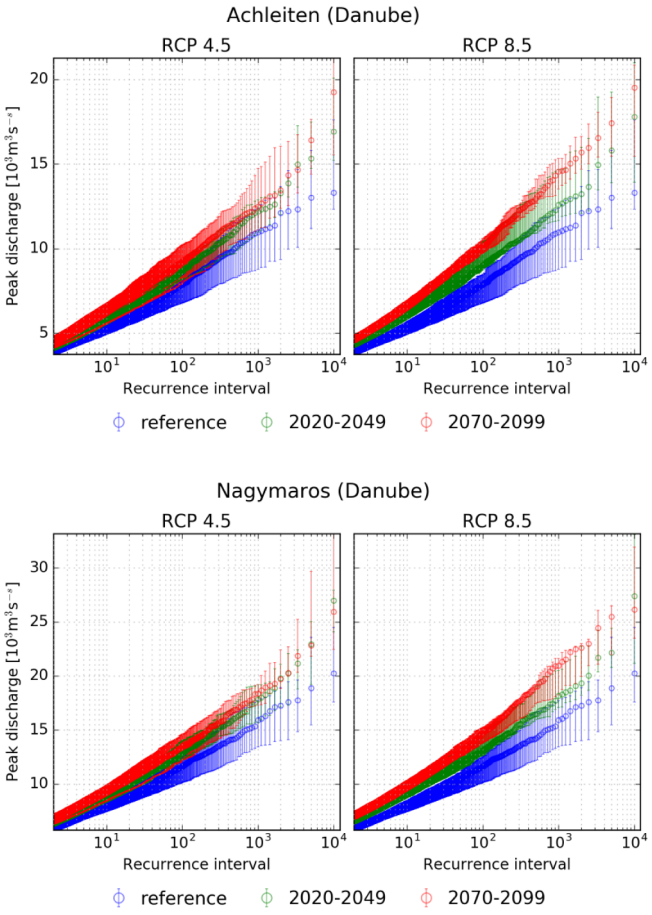


Fig. 7. Multi-model median (circles) and ensemble ranges (error bars) of flood recurrence intervals and their magnitudes for the medium emissions scenario RCP4.5 (left) and the high end scenario RCP8.5 (right) at the gauging station Achleiten (at the border Germany to Austria) and Nagymaros (just upstream of Budapest) over the 21st century.

future (2020–2049) and far future (2070–2099) for the four EURO-CORDEX models (Schröter et al., 2017a).

The inundation maps are used as input to the flood vulnerability model FLEMPps+r (Elmer et al., 2010). Besides flood inundation depth, this model uses information about building types, building quality and the return period of the flood event to estimate relative loss to residential buildings based on ATKIS land-use information. Economic loss is calculated using spatially disaggregated information on the residential building stock (Kleist et al., 2006, Wünsch et al., 2009). As an outcome, spatially detailed damage maps for the flood event set are obtained (Schröter et al., 2017b). These data can be further analysed and evaluated for the assessment of future flood risk under different scenarios and adaptation planning using for instance cost-benefit analyses.

As an example Fig. 10 shows the development of flood risk in terms of exceedance probability curves of residential flood loss in the German part of the Danube basin for the reference climate and time period, as well as for future time periods and climate projections based on the four CORDEX models under RCP4.5 and RCP8.5. The spread of loss estimates is due to the different CORDEX model inputs and increases for events with lower probability. This emphasises the need to consider a large sample of damaging flood events (i.e. propagate the stochastic event set along the flood risk chain) to provide robust risk estimates. While these results represent the aggregated perspective for the whole study region, these outputs can also be derived on any other spatial unit (e.g. districts, municipalities, sub-basins and also individual objects at risk or a selection of objects) according to the portfolio of an insurer or the demand of another end-user.

In perspective, the simulations can be extended to cover the full 10,000 years of simulations for the different climate models, RCPs and time periods. It is planned to further develop flood vulnerability modelling to use Bayesian networks as a probabilistic approach to flood loss estimation (Schröter et al., 2014; Wagenaar et al., 2018). All model components of the model suite are process based models which allow the quantitative analysis and evaluation of flood mitigation measures.

3.4. *Pluvial flood risk*

Based on the feedback from end-users, a rather new feature of the FDM is the 2D modelling of pluvial flooding in cities, which is currently being implemented for Budapest (see Fig. 11). The specific methodology used in the FDM has previously been tested in several European cities (Kaspersen et al., 2017). For increased accuracy, the pluvial flood model combines an urban remote sensing and flood modelling approach to simulate the occurrence and extent of flooding for a range of sub-daily design precipitation events under current and expected future

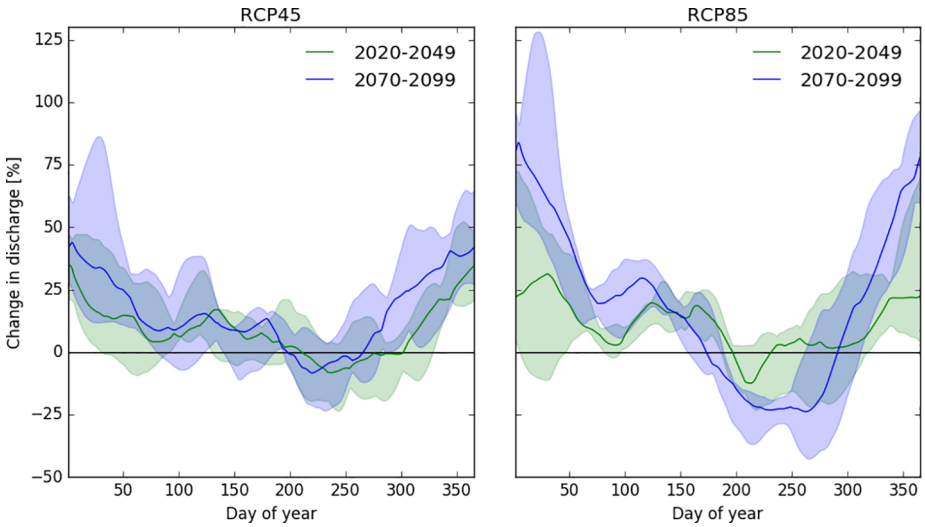


Fig. 8. Change in seasonal discharge in the Danube at Nagymaros. Relative change with regards to the reference period (1971–2000) is shown using the model ensemble median with min-max uncertainty range for both future periods.

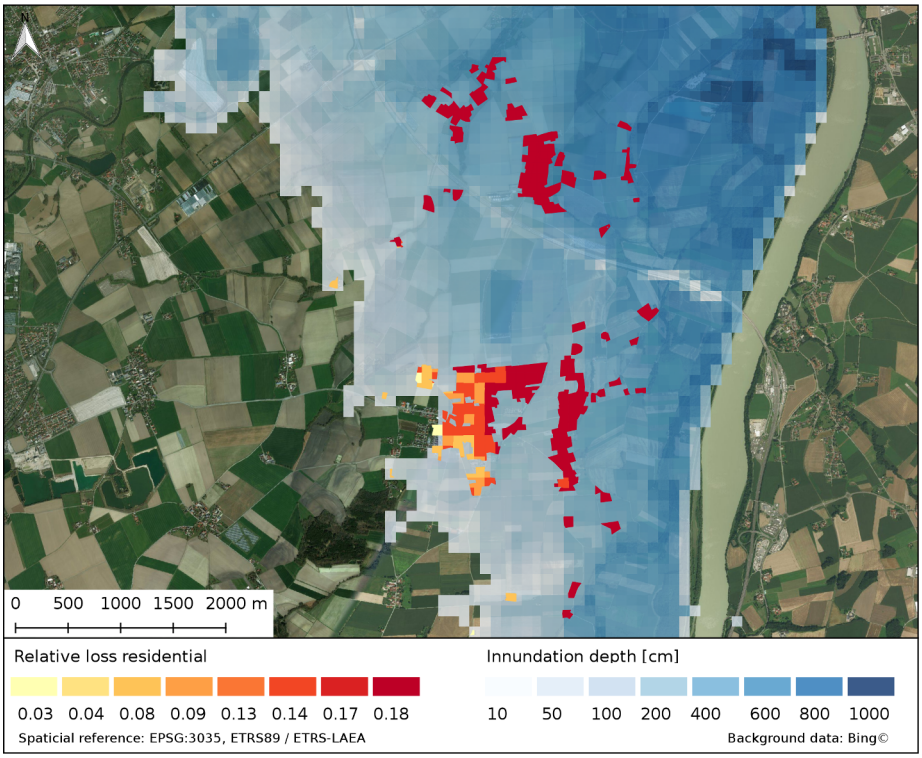


Fig. 9. Example output of the 2D flood model. In blue the inundation, in orange and red residential areas affected by the flood.

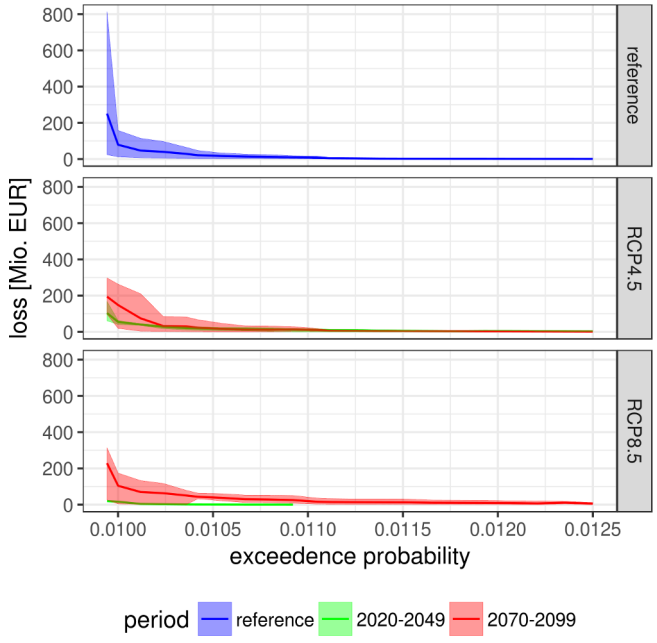


Fig. 10. Exceedance probability curves of residential flood loss in the German part of the Danube basin for different time periods and climate scenarios using 4 CORDEX models as climate drivers.

climate conditions provided by the weather and climate module. The effects of the urban drainage system in terms of mitigating flash floods are considered assuming a simplified conceptual drainage system model. This emulates the effect of urban drainage from impervious surfaces and infiltration from vegetated areas. In the case of Budapest the normal capacity of the urban drainage system varies geographically from what corresponds to a 1- or 2-year return level precipitation event up to a 10+ year return level event (for part of the main sewers).

Fig. 11 shows example results from Budapest based on a digital elevation model of 25 m resolution and urban land cover inferred from remotely sensed information. The map gives the inundation depth following a flash flood corresponding to a 2-year and a 100-year return level event under current climatic conditions. Similar maps were obtained for two RCP scenarios (RCP4.5 and RCP8.5) and varying land cover conditions, demonstrating an increased risk and severity of pluvial floods for future climatic conditions.

As in the case of the 2D fluvial flood model described above, the results of the pluvial flood model readily feeds into the risk module. In this way, for relevant cases it is possible to simultaneously evaluate the combined risk of river floods and pluvial floods, whereas in cases where it is less important to address this within a multi-hazard and multi-risk perspective, the risk assessment produced by means of the FDM suite proves to be robust and consistent whether fluvial or pluvial floods are considered jointly or separately.

In terms of evaluating the benefit of installing potential adaptation options, relevant measures explored by stakeholders may on request be added explicitly to the pluvial flood model, e.g., water retention areas or infiltration devices. Likewise, the pluvial flood model or results produced thereof could be hard- or soft-linked to drainage system models used by waste water companies, e.g., for increased accuracy.

4. Summary and conclusions

The results presented here only show an excerpt of the capabilities of the Future Danube Model (FDM). Based on a validated model for current climate conditions, projections of four bias-corrected EURO-CORDEX GCM-RCM combinations and two scenarios were used to show that the flood risk is likely to increase in future. The FDM is able to inform insurers and infrastructural stakeholders about the potential risk

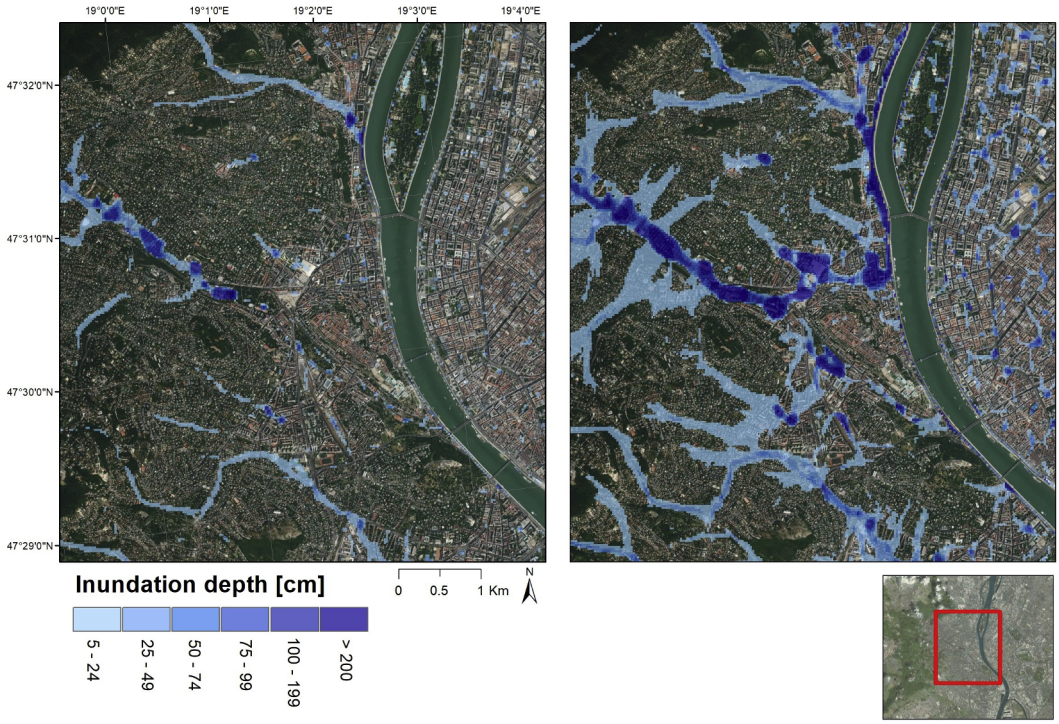


Fig. 11. Example for the simulation of pluvial flooding corresponding to a 2-year (left) and 100-year (right) event in the Center of Budapest under current climate conditions.

of higher order return periods. Due to the holistic and harmonised approach of simulating and integrating climate change and its impacts on various sectors in the entire Danube River basin, the FDM is a valuable tool for integrated and transboundary river basin planning and management, particularly with regard to European climate and water-related directives, climate risk estimation and climate proofing of adaptation measures.

An important aspect driving the development of the FDM is the close collaboration with stakeholders. User demands have shaped and will influence future developments. So far, the main aim of the FDM was to satisfy the demands of specific end-users mainly of the insurance sector by providing information related to climate change impacts on flood risks. The results produced with the FDM are in compliance with and will be used within the OASIS Loss Modeling Framework and will be made available using the OASIS Hub.

Conflicts of interests

None.

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Appendix

The Oasis Data Model represents a catastrophe model as:

- The Hazard Module: where an event affects an area with a severity. Uncertainty is represented here by a probability distribution of severity for the event/area combination
- The Vulnerability Module: where a given severity and vulnerability class (type of exposure) gives a damage factor. Again, uncertainty is represented by a probability distribution of damage for a given severity/vulnerability class combination.
- The Exposure Module: where an exposure is represented by an area identifier and a vulnerability class, along with an insured value.

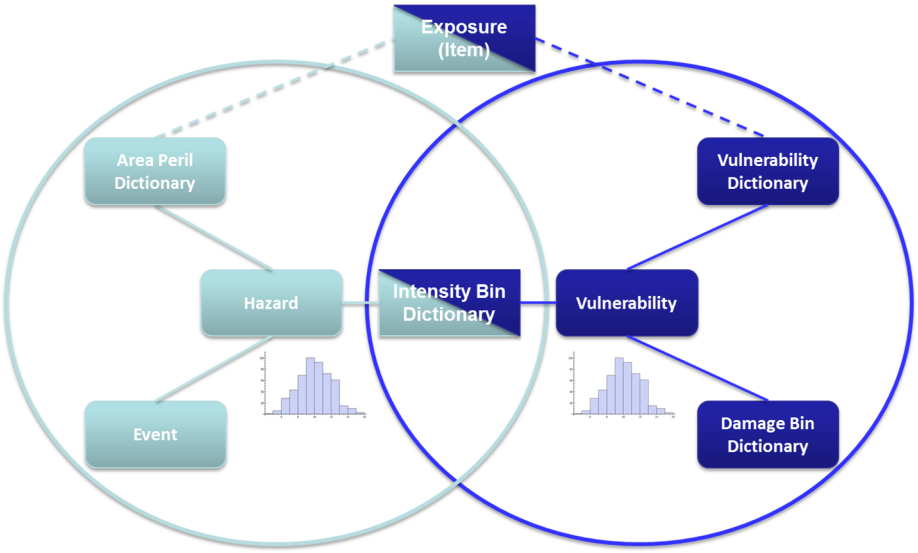


Fig. A1. Oasis Data Model.

Table A1
Bias-corrected CORDEX-EUR-11 simulations for RCP4.5 and RCP8.5 used in the study (Gobiet et al., 2015, GCM – Global Climate Model, RCM – Regional Climate Model).

	Institute	SMHI	MPI – CSC	KNMI
	RCM	RCA4	REMO2009	RACMO22E
GCM				
MOHC-HadGEM2-ES		X		
ICHEC-EC-EARTH		X		X
MPI-M-ESM-LR			X	

References

Apel, H., Aronica, G., Kreibich, H., Thieken, A., 2009. Flood risk analyses—how detailed do we need to be? Nat. Hazards 49 (1), 79–98.

Beume, N., Naujoks, B., Emmerich, M., 2007. SMS-EMOA: Multiobjective selection based on dominated hypervolume. Eur. J. Oper. Res. 181, 1653–1669. https://doi.org/10.1016/j.ejor.2006.08.008.

Cortekar, J., Bender, S., Brune, M., Groth, M., 2016. Why climate change adaptation in cities needs customised and flexible climate services. Clim. Serv. 4, 42–51.

Della-Marta, P.M., Haylock, M.R., Luterbacher, J., Wanner, H., 2007. Doubled length of western European summer heat waves since 1880. J. Geophys. Res. Atmos. 112.

Dong, B., Sutton, R.T., Shaffrey, L., 2017. Understanding the rapid summer warming and changes in temperature extremes since the mid-1990s over Western Europe. Clim. Dyn. 48, 1537–1554.

ECA, 2009. Shaping climate-resilient development: a framework for decision-making. Economics of Climate Adaptation (ECA) Working group, http://media.swissre.com/documents/rethinking_shaping_climate_resilent_development_en.pdf.

EEA, 2012. Climate change, impacts and vulnerability in Europe 2012. An indicator-based report. EEA Report No 12/2012.

Elmer, F., Thieken, A.H., Pech, I., Kreibich, H., 2010. Influence of flood frequency on residential building losses. Nat. Hazards Earth Syst. Sci. 10 (10), 2145–2159.

Falter, D., Schröter, K., Dung, N.V., Vorogushyn, S., Kreibich, H., Hundecha, Y., Apel, H., Merz, B., 2015. Spatially coherent flood risk assessment based on long-term continuous simulation with a coupled model chain. J. Hydrol. 524, 182–193.

Falter, D., Dung, N.V., Vorogushyn, S., Schröter, K., Hundecha, Y., Kreibich, H., Apel, H., Theisselmann, F., Merz, B., 2016. Continuous, large-scale simulation model for flood risk assessments: proof-of-concept: large-scale flood risk assessment model. J. Flood Risk Manage. 9 (1), 3–21.

Gerl, T., Kreibich, H., Franco, G., Marechal, D., Schröter, K., 2016. A review of flood loss models as basis for harmonization and benchmarking. PLoS ONE 11 (7), e0159791.

Gobiet, A., Suklitsch, M., Heinrich, G., 2015. The effect of empiricalstatistical correction of intensity-dependent model errors on the temperature climate change signal. Hydrol. Earth Syst. Sci. 19, 4055–4066.

Hallegatte, S., 2009. Strategies to adapt to an uncertain climate change. Global Environ. Change 19, 240–247.

Halsnæs, K., Kaspersen, P.S., Drews, M., 2015. Key drivers and economic consequences of high-end climate scenarios: uncertainties and risks. Climate Res. 64, 85–98.

Hattermann, F.F., Huang, S., Burghoff, O., Willems, W., Österle, H., Büchner, M., Kundzewicz, Z.W., 2014. Modelling flood damages under climate change conditions – a case study for Germany. Nat. Hazards Earth Syst. Sci. 14 (12), 3151–3168.

Hattermann, F.F., Huang, S., Burghoff, O., Hoffmann, P., Kundzewicz, Z.W., 2016. Brief Communication: An update of the article "Modelling flood damages under climate change conditions – a case study for Germany". Nat. Hazards Earth Syst. Sci. 16, 1617–1622.

Huang, S., Kumar, R., et al., 2016. Evaluation of an ensemble of regional hydrological models in 12 large-scale river basins worldwide. Clim. Change 1–17. https://doi.org/10.1007/s10584-016-1841-8.

Huang, S., Hattermann, F.F., Krysanova, V., Bronstert, A., 2013. Projections of climate change impacts on river flood conditions in Germany by combining three different RCMs with a regional eco-hydrological model. 3-4. Clim. Change 116, 631–663.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. J. Geophys. Res. 113.

Hoy, A., Hänsel, S., Skalak, P., Ustrnul, Z., Bochníček, O., 2017. The extreme European summer of 2015 in a long-term perspective. Int. J. Climatol. 37, 943–962 John Wiley & Sons.

IPCC, 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32.

Jacob, D., Petersen, J., Eggert, B., et al., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. Reg. Environ. Change 14, 563–578.

Kaspersen, P.S., Høegh Ravn, N., Arnbjerg-Nielsen, K., Madsen, H., Drews, M., 2017. Comparison of the impacts of urban development and climate change on exposing European cities to pluvial flooding. Hydrol. Earth Syst. Sci. 21, 1–17.

Kaspersen, P.S., Halsnæs, K., 2017. Integrated climate change risk assessment: A practical application for urban flooding during extreme precipitation. Clim. Serv. 6, 55–64.

Kaspersen, P.S., Fensholt, R., Drews, M., 2015. Using landsat vegetation indices to estimate impervious surface fractions for European cities. Remote Sens. 7, 8224–8249.

Kleist, L., Thieken, A.H., Köhler, P., Müller, M., Seifert, I., Borst, D., Werner, U., 2006. Estimation of the regional stock of residential buildings as a basis for a comparative risk assessment in Germany. Nat. Hazards Earth Syst. Sci. 6 (4), 541–552.

Kovács, S., Lovas, A., Gombás, K., 2016. Magyarország árvízvédelme az iktegrált vízgazdálkodásban a Tisza folyó példáján. Hidrológiai Közlöny 96 (4), 6–19.

Krysanova, V., Hattermann, F., Wechsung, F., 2005. Development of the ecohydrological model SWIM for regional impact studies and vulnerability assessment. Hydrol.

Process. 19, 763–783.
Lloyd's, 2014. Catastophy modeling and climate change.
MIKE Powered by DHI, 2018. https://www.mikepoweredbydhi.com/. Accessed 4-6-2018.
Mitchell-Wallace, K., Jones, M., Hillier, J., Foote, M., 2017. Natural Catastrophe Risk Management and Modelling: A Practitioner's Guide, 1 ed. Wiley-Blackwell.
Nash, J., Sutcliffe, J., 1970. River flow forecasting through conceptual models, Part 1 – a discussion of principles. J. Hydrol. 10, 282–290.
Petrow, T., Merz, B., 2009. Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. J. Hydrol. 371, 129–141.
Russo, S., Sillmann, J., Fischer, E.M., 2015. Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ. Res. Lett. 10.
Schröter, K., Kreibich, H., Vogel, K., Riggelsen, C., Scherbaum, F., Merz, B., 2014. How useful are complex flood damage models? Water Resour. Res. 50 (4), 3378–3395.
Schröter, K., Rivas Lopez, Maria del Rocio, Nguyen, V.D., Wortmann, M., Liersch, S., Hardwick, S., Hattermann, F.F., 2017a. Flood inundation depth maps Danube catchment. V. 0.1. GFZ Data Services. http://doi.org/10.5880/GFZ.5.4.2017.003.
Schröter, K., Rivas Lopez, Maria del Rocio, Nguyen, V.D., Wortmann, M., Liersch, S., Hardwick, S., Hattermann, F.F., 2017b. Residential flood loss maps Danube catchment. V. 0.1. GFZ Data Services. http://doi.org/10.5880/GFZ.5.4.2017.004.
Sparks, N.J., Hardwick, S.R., Schmid, M., Toumi, R., 2017. IMAGE: a multivariate multi-site stochastic weather generator for European weather and climate. Stoch. Environ. Res. Risk Assess. 1–14.
Swiss Re, 2014. Natural catastrophes and man-made disasters in 2014: convective and winter storms generate most losses. Sigma 2/2015. www.swissre.com/sigma.
van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S., Rose, S., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5–31.
Wagenaar, D., Lüdtke, S., Schröter, K., Bouwer, L.M., Kreibich, H., 2018. Regional and temporal transferability of multivariable flood damage models. Water Resour. Res. https://doi.org/10.1029/2017WR022233.
Wilby, R.L., Dessai, S., 2010. Robust adaptation to climate change. Weather 65, 180–185.
Wilcke, R., Mendlik, T., Gobiet, A., 2013. Multi-variable error correction of regional climate models. Clim. Change 120, 871–887.
Wünsch, A., Herrmann, U., Kreibich, H., Thieken, A., 2009. The role of disaggregation of asset values in flood loss estimation: a comparison of different modeling approaches at the Mulde river, Germany. Environ. Manage. 44 (3), 524–541.