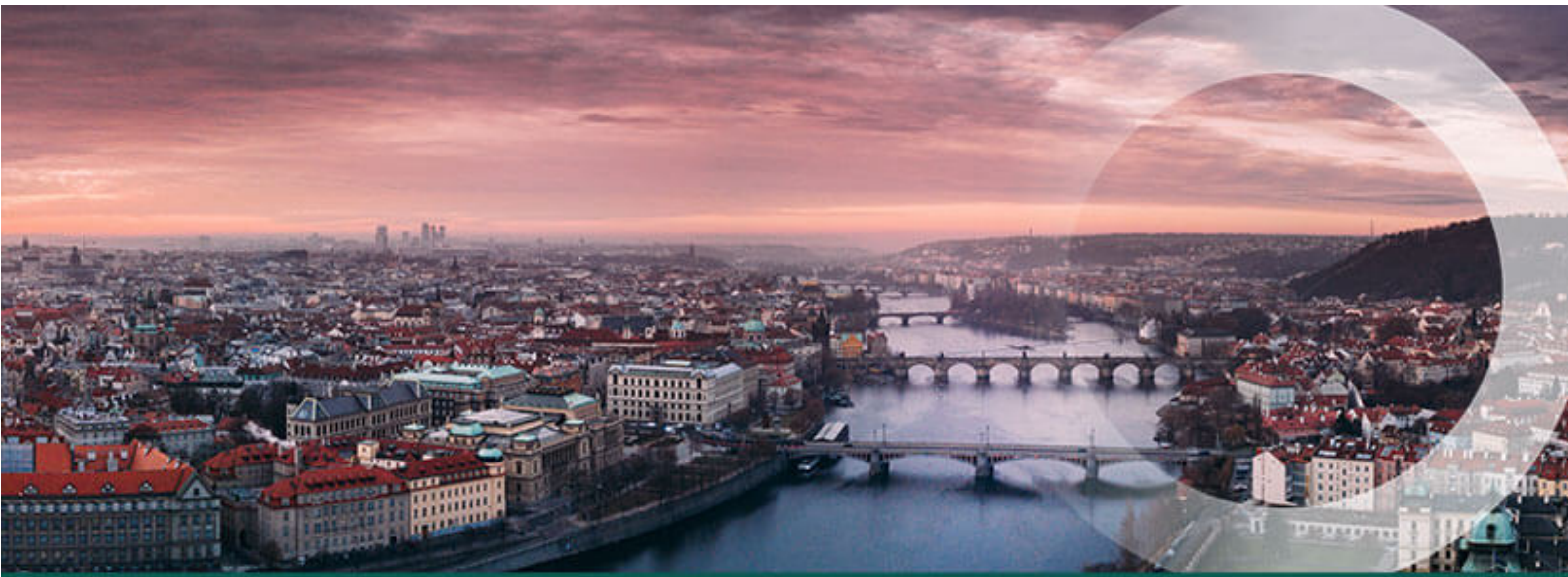

Horizon2020 Insurance

Oasis Innovation Hub for Catastrophe and Climate Extremes Risk Assessment

The Oasis-LMF-compliant Future Danube Model on the Oasis-Hub

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Executive summary

The Future Danube Model (FDM) is a catastrophe model compliant with both insurance industry standards and climate science best practices. In its core it provides risk and damage information for fluvial flooding for the entire Danube Basin and pluvial flooding for selected cities in the Danube Basin for the past, present and future. A unique feature is the use of climate change scenarios to provide risk information for the present (2006-2035) and two future climate periods (2020-2049, 2070-2099), allowing analyses of risk with regards to the baseline period (1970-1999). The model was co-designed and co-validated in collaboration by the Potsdam Institute of Climate Impact Research (PIK), the German Centre for Geoscience (GFZ) and the Technical University of Denmark (DTU) with partners from the insurance industry.

The model is implemented in the Oasis Loss Modelling Framework (LMF), an open source catastrophe modelling platform that seeks to open up the catastrophe modelling community and is driven by the needs of the (re)insurance industry. This document describes the model components, their representation in the LMF and the data needed to run the model with an insurance portfolio. It closes with a presentation of the sample data available on the OasisHub, the main delivery platform for the model to end users.

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1 The Future Danube Model (FDM)

The Future Danube Model (FDM) is a high-resolution, multi-risk catastrophe model for the Danube Basin with a focus on fluvial and pluvial flood risk under climate change. The model domain (see Figure 1) encompasses the following countries (percent of territorial coverage, only those with significant shares are listed):

- Hungary 100%
- Romania 97%
- Austria 96%
- Germany 16%
- Slovakia 96%
- Serbia 92%
- Slovenia 81%
- Bosnia and Herzegovina 74%
- Croatia 62%
- Montenegro 51%
- Bulgaria 43%
- Moldova 35%
- Czech Republic 27%

High-resolution pluvial flood risk assessments will be made available for four selected cities (Budapest, Hungary; Bratislava, Slovakia; Novi Sad, Serbia; Vienna, Austria) but will also be available for other cities upon request.

The FDM consists of a chain of several components that represent self-contained scientific modelling tools (Figure 2). The hazard driving data is provided by an observation dataset (EOBS, Haylock et al., 2008; and ECA&D, Klein-Tank et al., 2002) as well as climate model output (EURO-CORDEX, Jacob et al., 2014). These data sets are available from the Copernicus Climate Data Store. These drive the hydrological and hydrodynamic models to produce event footprints, which are then turned into loss estimates by the last component at building scale.

The following sections briefly describe the approach to include impacts of climate change and the model components (for the fluvial and pluvial cases) with references to the scientific literature. Then the implementation into the OASIS Loss Modelling

Framework (Oasis-LMF) is described with details on how to use the model with a custom insurance portfolio and open-source software tools.

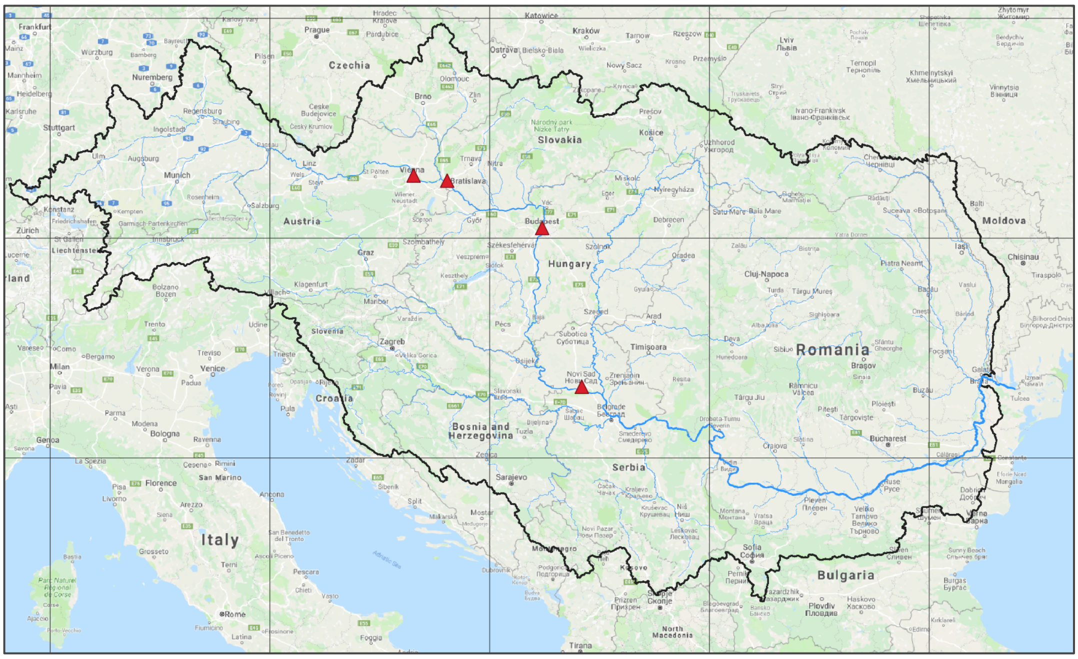

Figure 1: Model domain including the selected cities with already existing pluvial model results (red triangles).

1.1 Climate change scenarios

A unique feature of the FDM is the ability to not only assess risk based on historical driving data (as is traditionally done) but also climate model simulations pertaining to the current and future climate periods. By that approach, changes in risks induced by a changing climate are accounted for. Results of a representative ensemble comprised by four global and regional climate model combinations from the EURO-CORDEX initiative (Jacob et al., 2014) for the reference, the current and two future climate periods and for two climate change scenarios were used (Table 1). The ensemble approach allows for a quantification of uncertainty in the change signal (i.e. compared to reference period) arising from the climate models. For the fluvial flood modelling, the climate model results were bias-adjusted to the gridded EOBS historical observational dataset (Haylock et al., 2008) by the quantile mapping approach to ensure that the results have the same distribution as the observational data. For the pluvial flood modelling, climate model output for the modelled cities were bias-adjusted directly to site-specific observations from the ECA&D historical observational dataset (Klein Tank et al., 2002), which the gridded EOBS data is derived from.

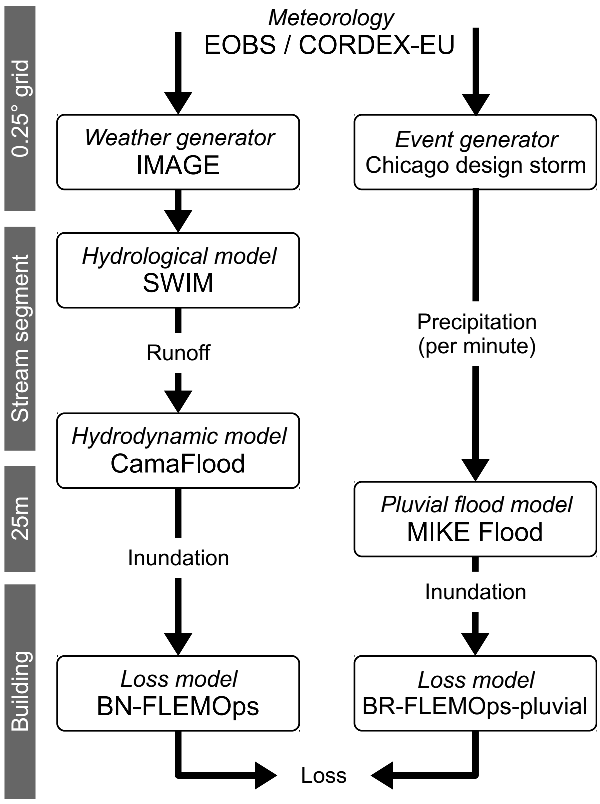

Figure 2: The model chain of the Future Danube Model from the meteorological driving data to the loss generation for both fluvial (left) and pluvial (right) flooding. The resolution of each component is shown in the bars on the left.

The two climate change scenarios (RCP-4.5 and 8.5) were chosen to encompass the currently most likely development of greenhouse gas emissions over the 21st century. This includes a business-as-usual assumption in RCP-8.5, i.e. unabated growth in emissions with global surface temperatures of around 5˚C, and moderately curbed emission that will stabilise global surface temperature between 2-3˚C in the RCP-4.5 scenario.

Table 1: Overview of climate model combinations (global–regional climate model) where abbreviations relate to the modelling institutes: Irish centre for high end computing (ICHEC), Dutch Meteorological Institute (KNMI), Swedish Meteorological Institute (SMHI), Met Office Hadley Centre (MOHC), Max Planck Institute for Meteorology (MPI). Results for four periods and two Representative Consecration Pathway (RCP) scenarios (Meinshausen et al., 2011) were used.

Climate models	Climate periods	Scenarios
ICHEC-KNMI	Reference (1970-1999)	
ICHEC-SMHI	Current (2006-2035)	RCP-4.5
MOHC-SMHI	Near future (2020-2049)	RCP-8.5
MPI-MPI	Far future (2070-2099)	

1.2 Fluvial flood hazard

The fluvial flood hazard footprints are created by a three-level model chain consisting of a stochastic, multi-variate, multi-site weather generator (IMAGE), a high-resolution, semi-distributed hydrological model (SWIM) and an intermediate-complexity, semi-distributed hydrodynamic model (CamaFlood) (Figure 2). The driving (climate) and static input data is given in Table 2. The observational EOBS driving data is used to calibrate and validate both models using observed discharge as well as extents and other hydrodynamic modelling results of past flood events. The other data is mainly used for the setup of the models.

Table 2: Input data to the SWIM and CamaFlood model.

Variable	Source	Reference
Climate (daily)	E-OBS, WATCH (radiation only); EURO-CORDEX, 0.25°	Haylock et al. (2008), Weedon et al. (2011), Jacob et al. (2014)
Elevation	EU-DEM v1.1, 25m	EEA (2016)
Land cover	CORINEv18 2012, 100m; GLIMS (glaciers); OpenStreetMap (lakes, residential and industrial areas)	EEA (2016a), OSM (2019a), GLIMS and NSIDC (2018)
Soils	HWSD, 1km	FAO et al. (2012)
River network	OpenStreetMap	OSM (2019a)
Lakes, reservoirs	OpenStreetMap	OSM (2019a)

The IMAGE weather generator (Sparks et al. 2017) is used to create 10'000-year (10ka) daily meteorological event sets for four variables and all 0.25° grid cells (n=1494) from the 30-year chunks of EOBS and EURO-CORDEX climate data, ensuring the distribution as well as the spatial and temporal correlation of the training data is preserved, The resultant 10ka event sets (for each climate model combination x climate period x scenario one, i.e. 28 in total; see Table 1) have the same characteristics (mean, distribution) but include more extreme events to produce flood events with reoccurrence intervals of up to 10'000 years.

The hydrological model SWIM (Krysanova et al., 1998; Hattermann et al., 2005) is driven by the 10ka meteorological event sets to estimate river discharge at 13641 stream segments within the model domain, i.e. all creeks, streams and rivers with catchment areas larger than 50km^2. The model simulates all major hydrological processes from snow, overland flow, soil percolation and groundwater flow. The model was calibrated to observed discharge at 44 gauging stations by a multi-objective, evolutionary algorithm (SMS-EMOA; Beume et al., 2007) that is optimising the Nash-Sutcliffe Efficiency (NSE), the bias in water balance and the agreement (RMSE) between observed and simulated Gumbel distribution estimates for annual maximum discharge of reoccurrence probabilities of 2-10'000 years. An example of the results of SWIM for two climate periods (reference and current) and the highest 5000 peaks (i.e. reoccurrence greater than 2 years) for the Danube segment at Budapest, Hungary, is shown in Figure 3. The same is available for all 13641 stream segments and all four climate periods. A map of future reoccurrence intervals for the historical (reference) 100-year peak discharge is given in Figure 4.

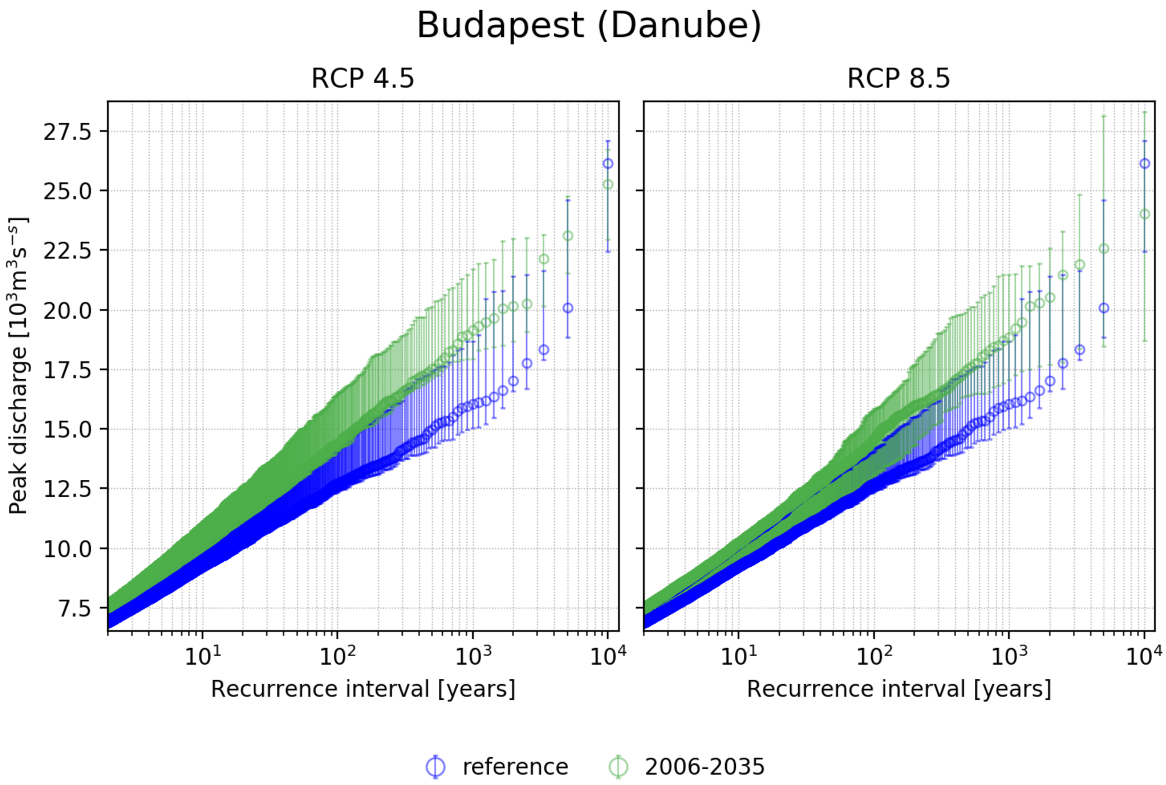

Figure 3: Peak discharge reoccurrence at Budapest, Hungary, i.e. all peaks with a reoccurrence interval greater than 2 years for the reference period (1970-1999) and the current climate period under the RCP-8.5 scenario. Error bars relate to the min. and max. of runs driven by the climate model ensemble, with the circles indicating the median.

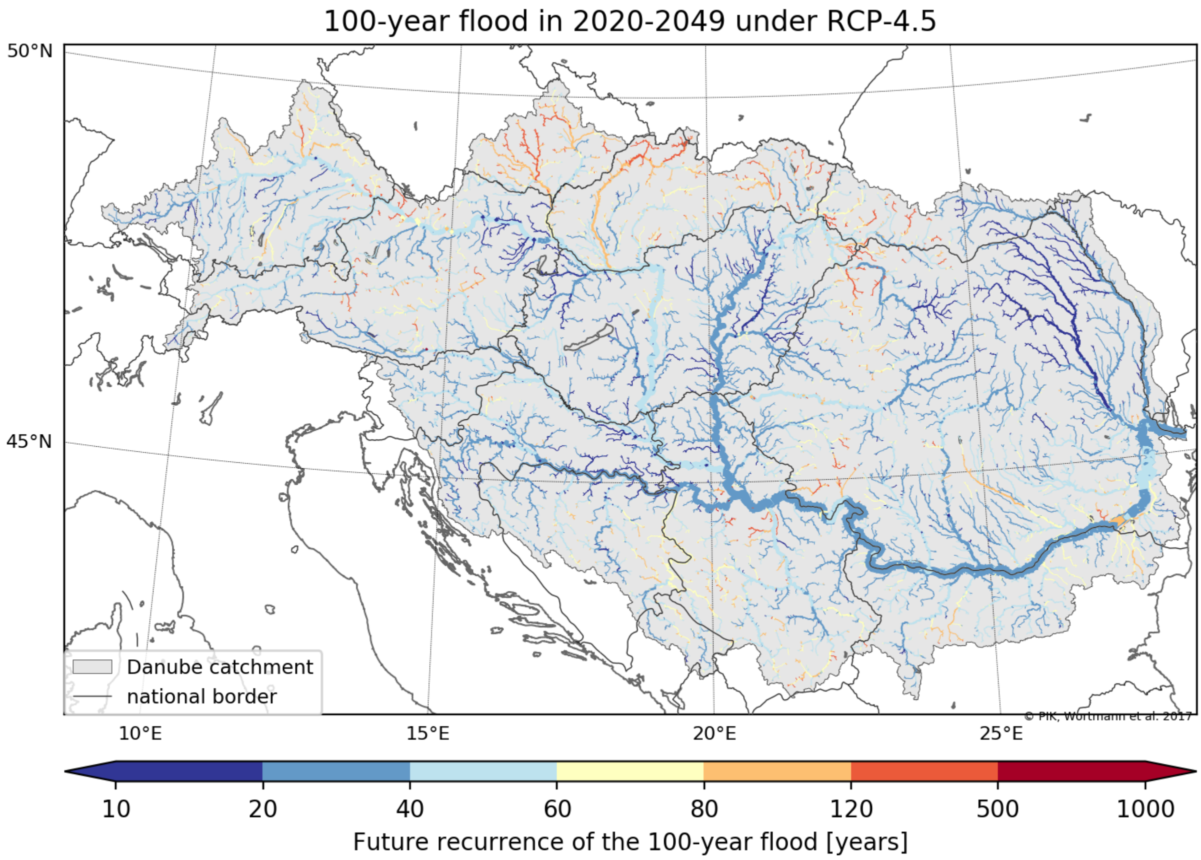

Figure 4: Map of reoccurrence intervals of the historical 100-year peak discharge in the Danube Basin.

The daily runoff generated by SWIM is used as driving data to the semi-distributed hydrodynamic model CamaFlood (Yamazaki et al., 2011; 2014). It implements a simple difference approximation of the shallow water equations (local inertia form) to route runoff through the 13641 river segments (or subbasins). Water level is inferred by a simple width-depth river geometry assumption and floodplain profile for each segment when discharge exceeds the channel capacity. While river width is inferred from Open Street Map riverbank outlines, the depth is adjusted according to the mean annual maximum discharge (no flood protection assumption) or the peak discharge of the protection level provided by the FLOPROS database (Scussolini et al., 2016). The results are daily water levels at each river segment that is used to construct daily or 7-day maximum flood footprints, such as the example shown in Figure 5. The flood footprint event set provided in the OasisLMF implementation includes ca. 350'000 events per period and scenario.

Figure 5: Flood footprint estimated by CamaFlood for a ca. 100km reach of the Danube River (Bavaria, Germany). The footprint corresponds to a ca. 100-year flood without flood protection.

1.3 Pluvial flood hazard

The methodology for creating the pluvial flood hazard footprints for select cities is as follows:

Since direct output from the abovementioned IMAGE weather generator (Sparks et al., 2017) is unsuited for modelling cloud burst events at the grid point level, simulated precipitation data for the same four climate models used as input to IMAGE, for each of the 30-periods (1970-1999, 2006-2035, 2020-2049, and 2070-2099) and for both RCP scenarios are extracted from EURO-CORDEX (Jacob et al., 2014) and processed. For each location (city), the nearest nine grid cells are extracted and pooled, provided they are shown to belong to the same statistical distribution.

City-specific daily observational data used to bias-correct the climate model output are extracted from ECA&D dataset (Klein Tank et al., 2002), which forms the basis for the gridded EOBS data.

Using the random cascade micro-canonical disaggregation approach originally formulated by Olsson (1998), the time series of daily model and observation data are temporally downscaled to 1-minute rainfall bins based on in-situ high-resolution rainfall data provided by collaborators in, e.g., Budapest and Novi Sad. These bins are subsequently re-aggregated appropriately and based on this a full set of Intensity-Duration-Frequency (IDF) curves are produced for each location and for all time-periods.

Based on the IDF's created (and validated vs. official sources, if possible), a limited series of heavy to extreme cloud burst events (Chicago Design Storms) of varying intensity is created and feed into an urban-scale MIKE FLOOD (Mike by DHI, 2019) model to assess the corresponding extent of urban pluvial flooding. This model uses the same digital elevation map as used for the fluvial flood modelling, but imposes a dedicated urban land cover parameterization based on a remote sensing analysis (Kaspersen et al., 2015) to distinguish between impervious and non-impervious surface fractions at the grid point level. The run-off from impervious surfaces is assumed to enter the urban drainage system at a fixed rate, which is set based on local information on the capacity of the system provided by local drainage engineers, i.e., corresponding to for example a 2-year rainfall event. Run-off from non-impervious (green) is infiltrated into soils based on the specified soil characteristics and the digital elevation map. A more detailed description of the MIKE FLOOD model setup may be found in Kaspersen et al. (2017).

Finally, OASIS-LMF compliant event sets are created, including pluvial flood hazard footprints, by generating long series of cloud burst events based on the same extreme value distributions used to construct the IDF's. Pluvial flood maps corresponding to non-modelled events are generated by interpolating between the pluvial flood maps produced in the preceding step by MIKE FLOOD. Table 3 and Figure 6 summarizes the input data used for the pluvial flood modelling and shows an example of pluvial flood maps produced for Budapest.

Table 3: Input data to the pluvial flood modelling.

Variable	Source	Reference
Climate (daily)	ECA&D; EURO-CORDEX, 0.25°	Klein Tank et al. (2002), Jacob et al. (2014)
High-resolution rainfall (minute)	Time series of in-situ data acquired by personal communication	NA
Elevation	EU-DEM v1.1, 25m	EEA (2016)
Urban Land cover	SENTINEL -2	https://sentinel.esa.int/web/sentinel/sentinel-data-access
Soil water infiltration	US Department of Agriculture	USDA (2016)

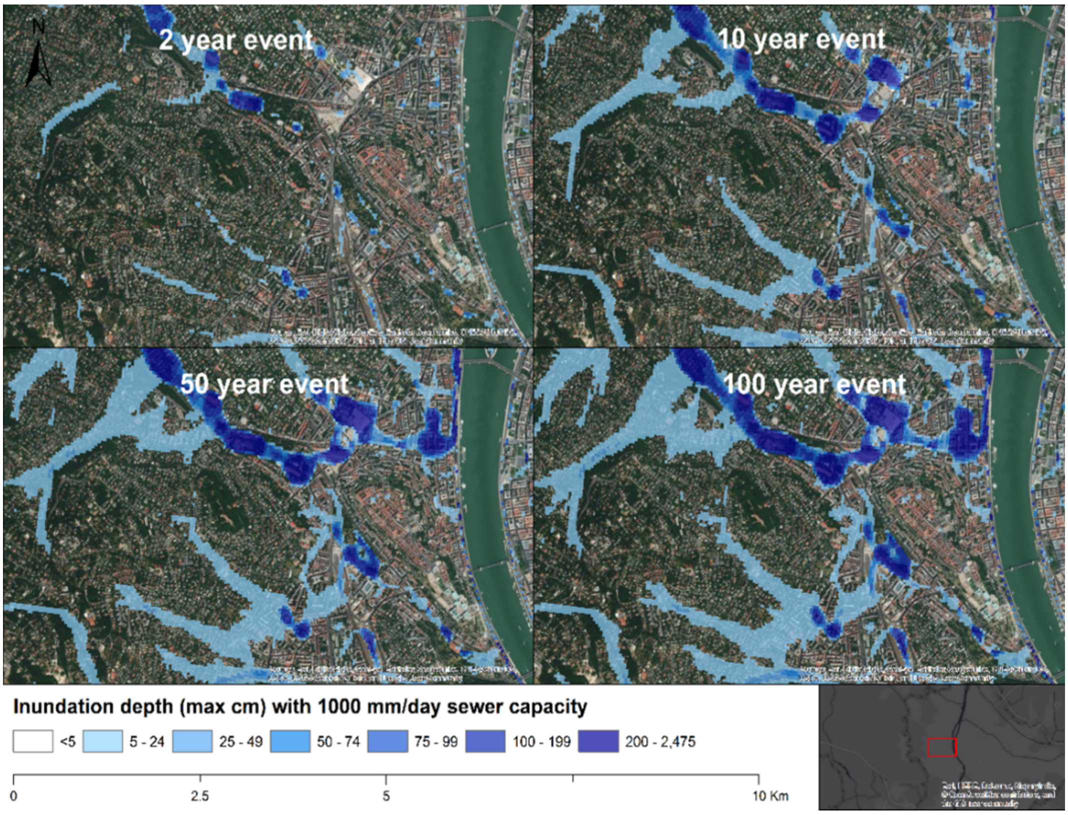

Figure 6: Examples of pluvial flood maps for Budapest for a present-day climate.

1.4 Fluvial flood vulnerability

Flood vulnerability models use flood intensity characteristics as for instance inundation depth or inundation duration to estimate flood damage for affected objects. FDM contains vulnerability models for the private and commercial sectors with specific implementations for fluvial and pluvial flood types (pluvial only for residential buildings).

1.4.1 Private Sector

The Bayesian Network - Flood Loss Estimation MOdel for the private sector BN-FLEMOps was developed to estimate the damage to residential buildings from fluvial floods. BN-FLEMOps is a probabilistic multi-variable flood loss model or vulnerability function respectively. The model outputs are probability distributions for relative loss given observations of the different input variables. The model can be applied in various locations and on different scales.

The structure of the Bayesian network (Figure 7) is derived from empirical post-event survey data conducted after flood events in Germany (2002 - 2013). This probabilistic multi-variable model includes the following variables for the prediction of relative flood loss for residential buildings:

Table 4: Model variables of BN-FLEMOps

Variables	Description
wd	Water depth of the inundated areas in centimetre
d	Duration of the flood event in hours
rp	Statistical return period of the flood event in years
fe	Flood experience of the local population (number of floods in the past 25 years)
bt	Building type (category of construction type)
ba	Building footprint area in square meter
pre	Precaution (score for the number of precautionary measures taken)
rbloss	Relative building loss between zero (no loss) and one (complete loss)

These variables are connected in a directed acyclic graph (DAG) that defines the structure of the Bayesian network. The network consists of parent- and child nodes. Each node has a "node probability table" that carries probability information for every class of every variable. Child nodes carry the combined or conditional probability of its parent nodes. One of the advantages of the Bayesian network is the possibility to run the model with incomplete input data. BN-FLEMOps can still predict flood loss even if for example the variable flood experience is not available. When input data for a child node is directly available the parent nodes information become superfluous. BN-FLEMOps is fully implemented in the OASIS-LMF to calculate ground up loss to residential buildings. An example of a ground-up loss estimation for the entire German Danube basin is shown in Figure 8.

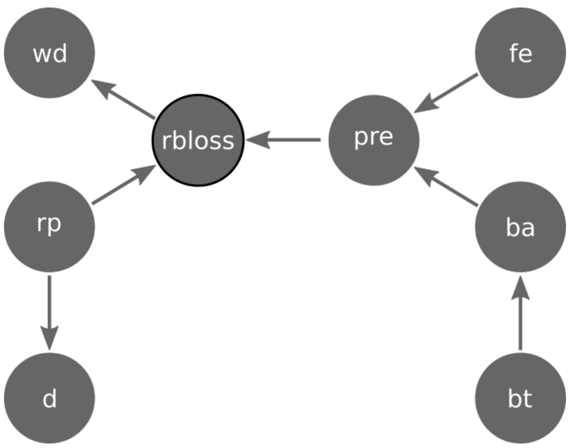

Figure 7: Network structure of the fluvial flood loss model BN-FLEMOps. See Table 4 for a description of the nodes.

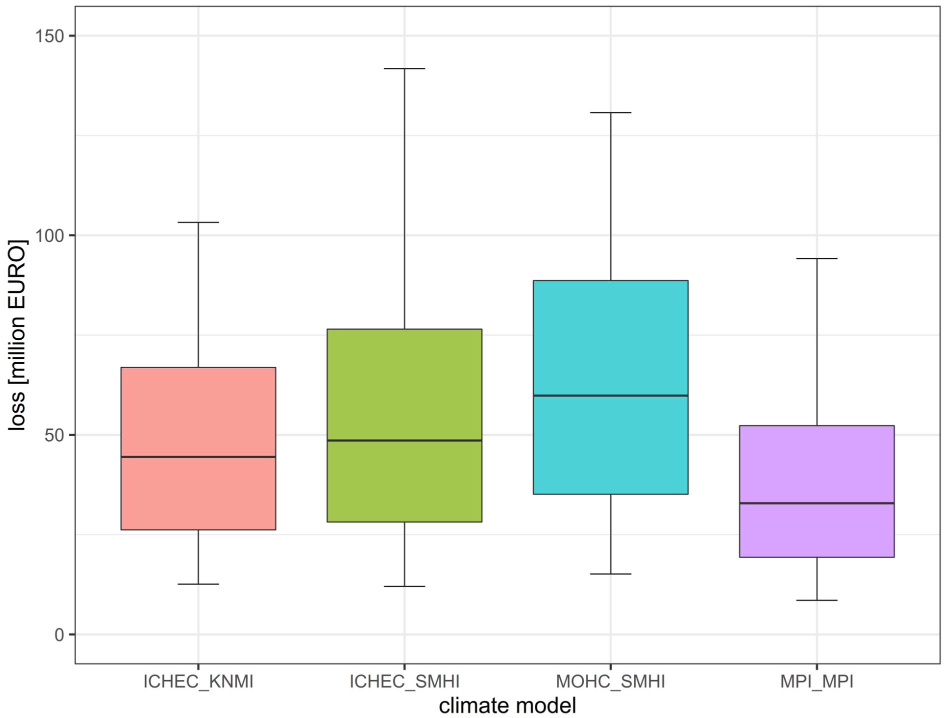

Figure 8: Ground up flood loss estimation for a 100-year flood event in the German Danube Basin based on four climate model data sets (see Table 1) for the reference period 1970-1999.

1.4.2 Commercial Sector

The **B**ayesian **N**etwork - **F**lood **L**oss **E**stimation **MO**del for the commercial sector **BN-FLEMO**cs was developed to describe the vulnerability of commercial buildings to damage from fluvial floods. BN-FLEMOcs is a probabilistic multi-variable flood loss model or vulnerability function respectively. The model outputs are probability distributions for relative loss given observations of the different input variables. The structure of the Bayesian network (Figure 9) is derived from empirical post-event survey data conducted after flood events in Germany (2002 – 2013). The full implementation and documentation of BN-FLEMOcs in the OASIS-LMF is not yet finalized and will be included in a later release of the FDM.

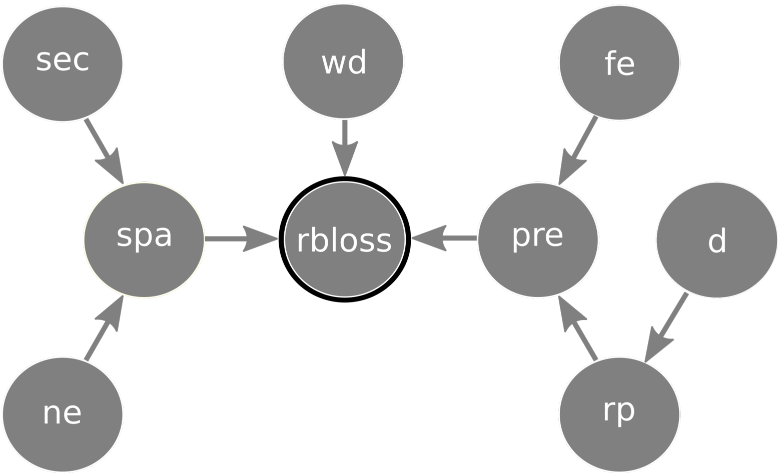

Figure 9: Network structure of the fluvial flood loss model BN-FLEMOcs

1.5 Pluvial flood vulnerability

The pluvial flood loss model has the same probabilistic properties like the fluvial model. It follows a probabilistic, multi-variable approach for the estimation of loss in the private sector and can be transferred in location and scale. Also, predictions are possible with incomplete data.

Table 5: Model variables of BR-FLEMOps-*pluvial*

Variables	Description
wd	Water depth of the inundated areas in centimetre
d	Duration of the flood event in hours
con	Contamination of the flood water (yes/no)
hs	Household size, number of persons living in the household
bt	Building type (category of construction type)
pre	Precaution (knowlage about the hazard)
dam	Damage (yes/no), to distinguish loss and zero-loss cases
rbloss	Relative building loss between zero (no loss) and one (complete loss)

The structure of the pluvial flood loss model (Figure 10) was derived from an empirical survey data base like the fluvial model. The damaging processes and loss influencing parameters of pluvial floods differ from those of fluvial floods. Many so called "Zero-loss" cases occur, which is mathematically represented in the Bayesian model by a zero-inflated beta regression.

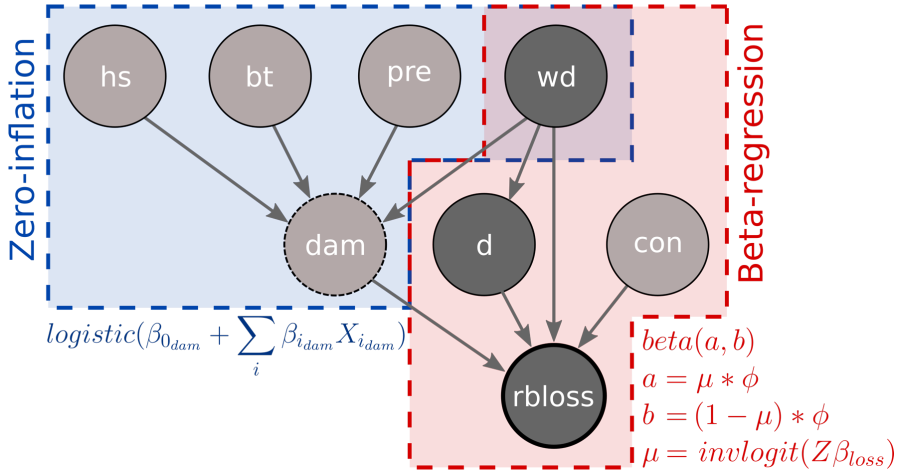

Figure 10: Structure of the Bayesian zero-inflated beta regression model for pluvial flood loss (BR-FLEMOps-*pluvial*). See Table 5 for a description of nodes.

The pluvial flood loss model has been equally implemented in the OASIS lmf table format and first results for the case study of Budapest have been created. The loss estimation can be performed on an object sharp level and provide loss figures for past events as well as scenarios. BR-FLEMOps-*pluvial* is fully implemented in the OASIS-FDM to calculate ground up loss to residential buildings.

2 Model data

2.1 Oasis LMF

The Oasis Loss Modelling Framework provides an open source platform for developing, deploying and executing catastrophe models. It uses a full simulation engine and makes no restrictions on the modelling approach. Figure 11 shows the main components of the model setup and components. They are packaged in a standard format and the components can be from any source, such as model vendors, academic and research groups. The platform provides:

- A platform for running catastrophe models, including a web based user interface and an API for integration with other systems (Oasis Loss Modelling Framework)
- Core components for executing catastrophe models at scale and standard data formats for hazard and vulnerability (Oasis ktools)
- Toolkit for developing, testing and deploying catastrophe models (Oasis Model Development Toolkit)

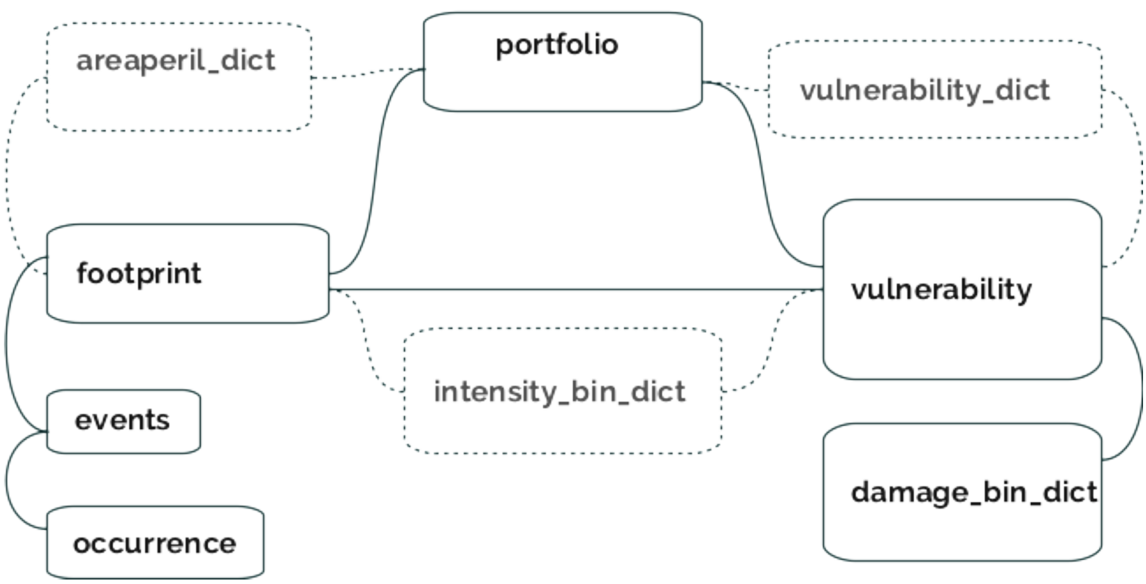

Figure 11: Structure of the OasisLMF framework. Solid boxed names correspond (except. portfolio) to ktools input files, while dashed boxes refer to ancillary files.

2.2 File structure

Full documentation on the file structure of an Oasis LMF model can be found here https://github.com/OasisLMF/ktools/blob/develop/docs/md/DataConversionComponents.md . The files provided by the FDM can be found below (names without extension, maybe .csv or .bin):

- input:
    - *events* (copy of any event option from the *static* directory)
    - occurrence
- static:
    - damage_bin_dict
    - events_1970_1999
    - events_2006_2035
    - events_rcp4.5_2020_2049
    - events_rcp4.5_2070_2099
    - events_rcp8.5_2020_2049
    - events_rcp8.5_2070_2099
    - footprint
    - *intensity_bin_dict.csv* (intensity ID mapping not read by ktoos)
    - vulnerability

The event options (provided in the static directory and copied to the input directory as *events*) allow the assessment of the various time periods and climate change scenarios described in Section 1.1 (Table 1).

2.3 Lookup Service

The Oasis LMF lookup service is responsible for mapping a set of exposure data presented by the user to the hazard footprint and vulnerability data specific to the model. This is usually done in two steps:

1. Area Peril Lookup: This section uses some location data In the exposure data (say, latitude and longitude) and maps each exposure to some spatial component in the hazard footprint file, represented by the Area Peril ID

2. Vulnerability Lookup: This section maps some combination of attributes In the exposure data (say, building type, building age, building height, etc.) to a specific vulnerability function In the vulnerability file.

The Future Danube Model follows this process in the main, using latitude and longitude to map into a grid representing Area Peril IDs and some combination of in place precautionary measures, flood experience and building area map to a specific vulnerability function. The model here differs from a standard deployment only in that the flood experience measure used in the vulnerability lookup is derived from the area peril id, based on a mapping file provided by GFZ. This is because the typical user will not typically have flood experience metrics in the exposure data but it Is a major driver of the vulnerability function to be used in the model.

3 Data on the OasisHub

A dataset was created on the OasisHub marketplace (https://oasishub.co/dataset/future-danube-model), including this report of the model, as shown in Figure 12. It includes sample data which gives potential customers a chance to inspect the format of it and the compatibility with their infrastructure. The file format is equivalent to the actual model files, but only 10 events (rather than 350'000) per period and scenario are included and the vulnerability is truncated.

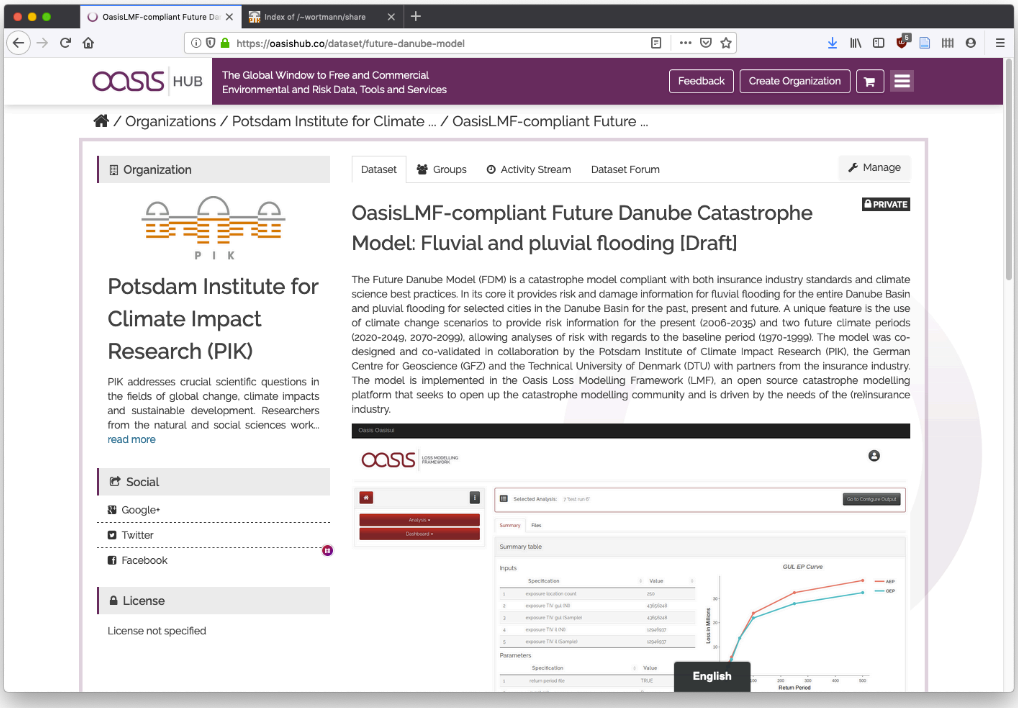

Figure 12: Screenshot of the dataset page on the OasisHUB.

A dedicated server is also setup to include the entire model files and the necessary software installed to simulate an exemplary portfolio (see Figure 13 and Figure 14). Access to this test instance may be requested.

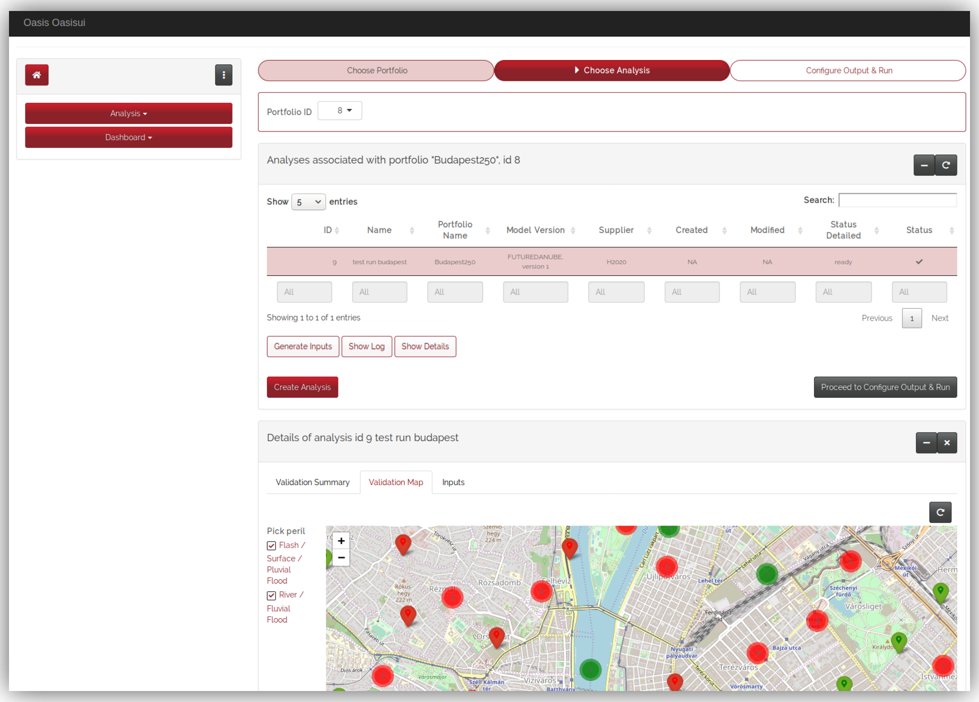

Figure 13: Screenshot of the user interface portfolio page for the exemplary model setup.

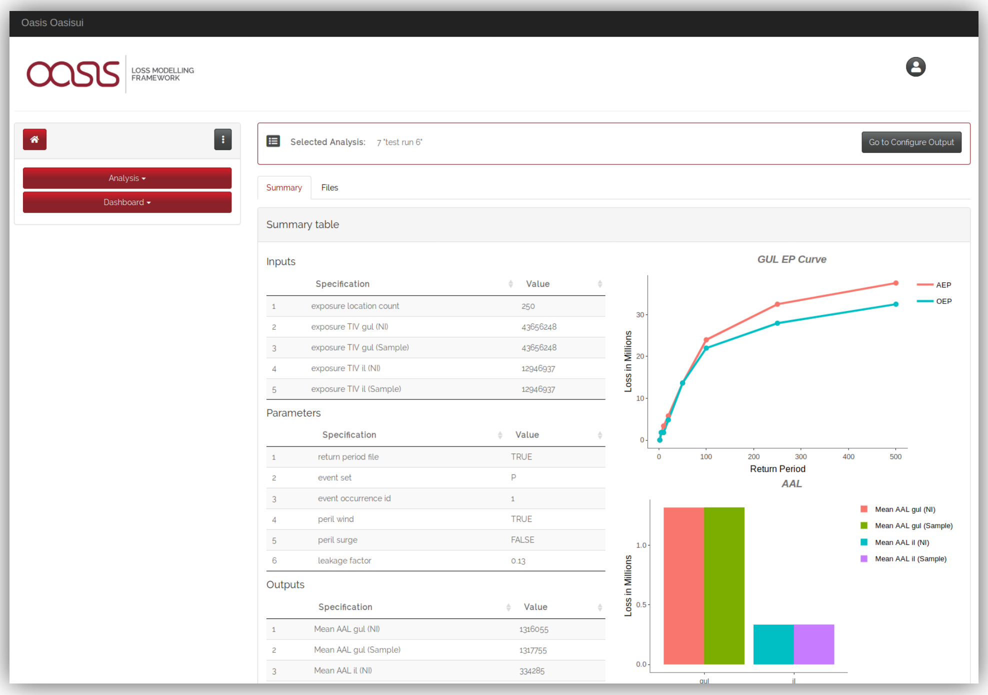

Figure 14: Screenshot of the user interface analysis and result page.

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