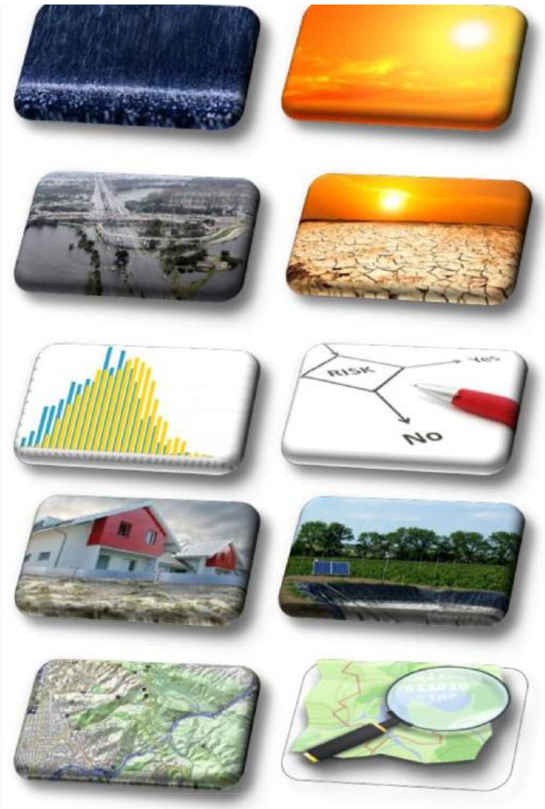
MODELLING SUITE OF FUTURE DANUBE

Complementary material to general info sheet

The modules of the Future Danube model have been developed by the partners and are linked in such a way that output from one module can be used standalone (such as heavy precipitation from the weather module) or fed into subsequent modules, e.g. into the hydrology module, to simulate flooding, and from there into the risk module, to simulate hydraulic processes and losses. This way, stakeholders can estimate risks from multi-perils, but also feed output from the modules into their own simulation tools, if needed, or vice versa. The graphical interface is a user-friendly web GIS interface allowing for data analysis and extraction.



Weather and climate module:
Stochastic generation of weather extremes under current and future conditions (precipitation, heat waves)

Hydrological module:
Modelling of hydrological extremes (floods, inundation, droughts) and water management (reservoirs, hydropower)

Risk module:
Modelling of flood damages in selected locations, to be extended to larger areas and other sectors

Adaptation module:
Toolbox for adaptation to hydrological and weather extremes

Visualization module:
Graphical interface for visualization of hazards and risk and analysis of outputs

The simulation of future weather and corresponding hydrological flood events, the hydraulic processes, risks and associated losses require a huge computational effort and resources and can be realised only with high-performance computing technology. For instance, the 10,000 years weather time series representing the recent and future periods alone require a storage volume of 1TB. These volumes are multiplied when simulating hydrologic and hydraulic processes.

Where the recurrence interval of a 100-year flood can be estimated in some river sections based on observations, the recurrence of a 1,000 or 10,000-year flood event can, due to an absence of observed data, only be assessed using statistical methods. A common practice to estimate flood risks and flood frequencies, applied by insurance companies, is to generate a synthetic weather or discharge time series of 10,000 years. Such a time series consists of 10,000 annual events, compared to only 100 observed events. It is therefore a statistically sounder method to estimate the probabilistic occurrence of events and reduces the uncertainties for events beyond the time scale of observed data.

The novel and up to now unique approach in OASIS+, to account for the impacts of climate changes in the risk modelling chain, is that the described method is not only applied to the recent but also to the future climate by using simulations of bias-corrected Regional Climate Models (RCMs).

IMAGE **Imperial College Weather Generator**	**Weather and climate module:** Stochastic generation of weather extremes under current and future conditions (precipitation, heat waves)
by Imperial College London	

More information: http://www.sp.ph.ic.ac.uk/~rtoumi/IMAGE.html

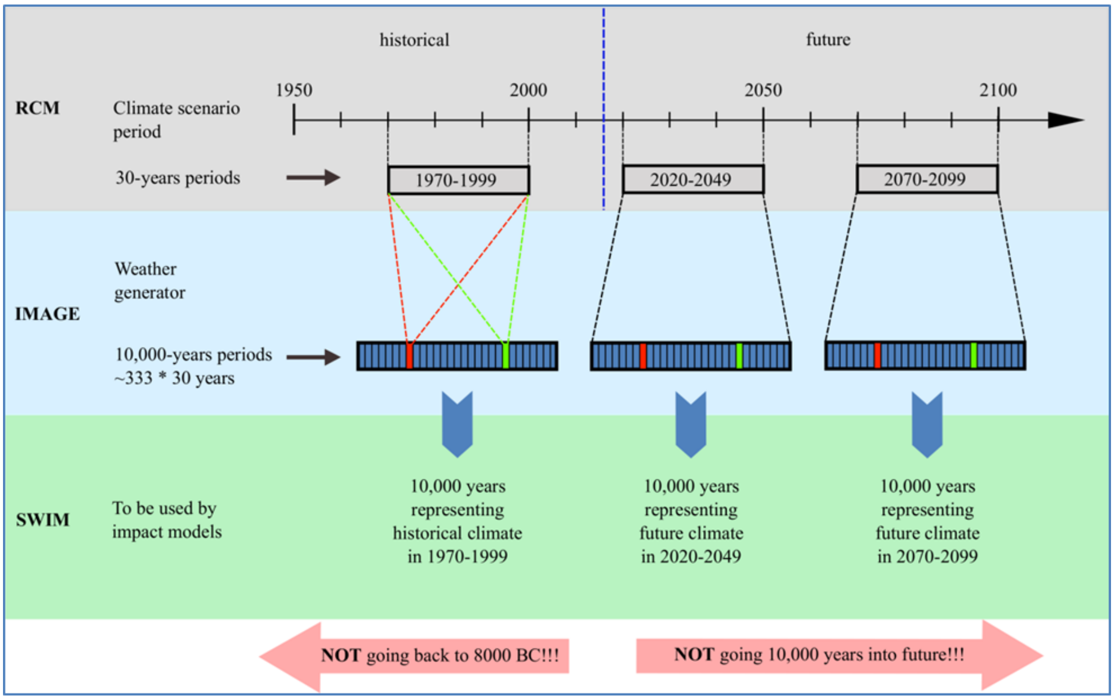
Purpose:

There is a need to explore extremes and out of sample events for risk assessments and broader understanding of climatology. One way to achieve this is to build a statistical model of weather variables. This has been done extensively for point observations using point probability distribution and auto-regression models, for example. More challenging is to build a statistical model. IMAGE (Imperial College Weather Generator) a new weather generator captures both the point statistics and spatial temporal correlation of single and multiple variables. IMAGE can be based on spatial observations, re-analysis or models to capture the spatial-temporal statistics. The simulation can then be run for thousands of years to generate footprints of very extreme events which are out of sample of the initial data but obey the same statistical rules.

In the Future Danube modelling process, future weather data are the most basic input required to assess future risks of hazards, such as pluvial and fluvial floods and droughts. This input is provided by IMAGE. On the one hand, these weather time series are directly analyzed to assess the likelihood of future changes in extremes, such as heavy precipitation or heatwaves. On the other hand, the data serve as input to a hydrological model.

Approach:

The Future Danube modelling suite follows a risk assessment approach that is commonly used in the insurance sector. At the example of flood damages, insurance companies are interested in flood magnitudes of various return intervals, such as a 100, 1 000, or 10 000 year flood. To produce this kind of information in a statistically sound way, weather and hydrological simulations are required consisting of very long periods (10 000 years) which are never available. The logic of this 10 000 years of data is explained on the below figure.



Therefore, the IMAGE weather generator produces daily (or sub-daily) weather time series of 10 000 years representing historical and projected future weather based on regional climate model (RCM) simulations. 30 years of weather simulations from each RCM, representing the climate in the past (1970-1999) and in two future periods (2020-2049 and 2070-2099), are used as basis to generate 10 000 years of weather for each of the three periods (see figure above). Statistical characteristics of the 10 000 years are similar to those of their respective 30 years' baseline period. These weather simulations form the main input for the hydrological module.

Already covered area of the Danube Region:

IMAGE output has been produced for the entire Danube Basin at a resolution of 0.25 degrees (1492 gridcells).

Plans for update:

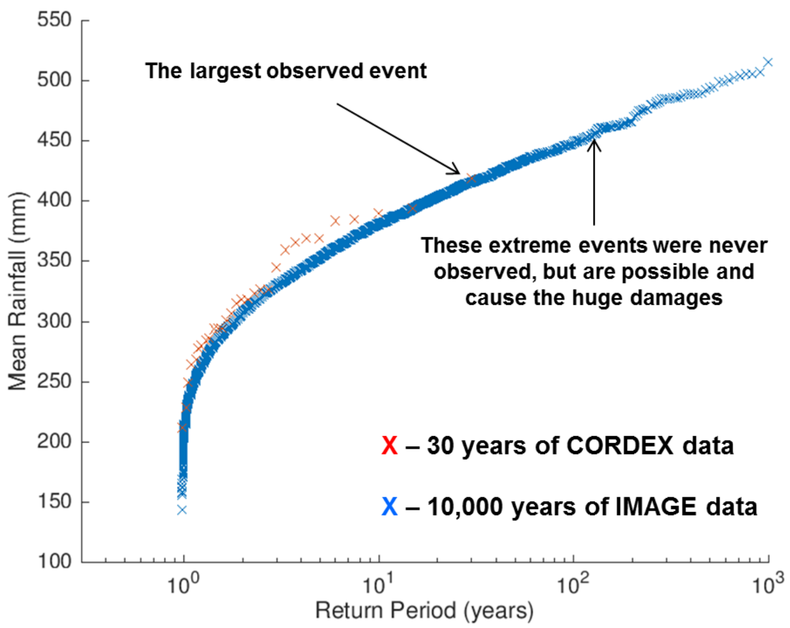
IMAGE is under continuous development, with a particular focus on improving the representation of spatial correlation between different regions. A new version of the model could be used for the Danube Basin in 2017.

Input data needs and current sources:

- present-day E-OBS weather data: http://www.ecad.eu/E-OBS/ and Haylock et al. 2008
- RCM projections from EURO-CORDEX: http://www.euro-cordex.net/

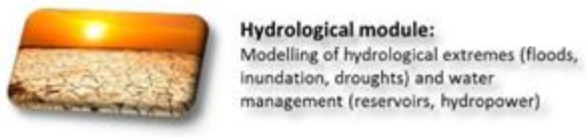
Few examples of output data:

- Realistic daily precipitation generated by IMAGE: figure below shows summer (JJA) precipitation for Upper Danube basin with more events than observed, the higher likelihood to spot rare (extreme) events



SWIM
Soil and Water Integrated Model

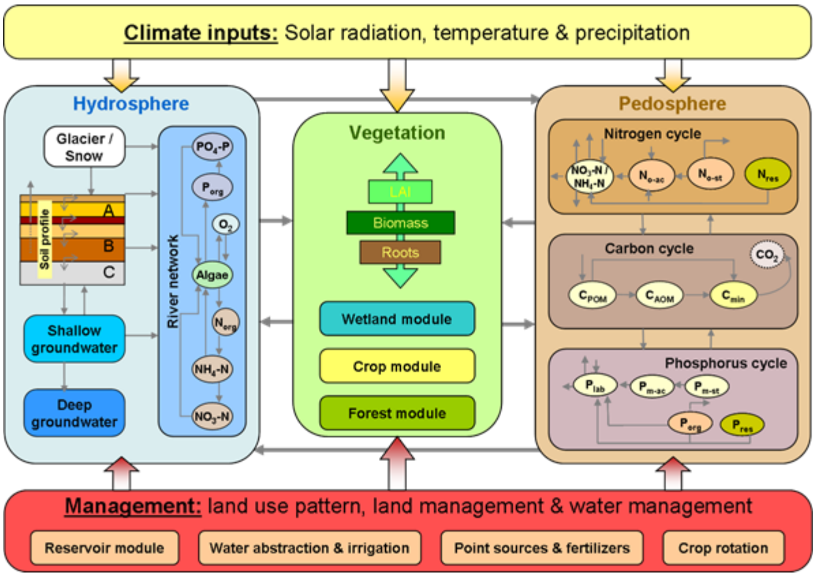
by PIK Potsdam



More information:
https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/models/swim

Purpose:

The Soil and Water Integrated Model (SWIM) is an eco-hydrological model that was developed at PIK Potsdam to investigate impacts of climate, land use, and water management (reservoirs and irrigation) changes on the catchment hydrology (including floods and droughts) and vegetation processes (e.g. crop yields) at the regional scale. See the structure of the SWIM model on the below figure.



It is a spatially semi-distributed model that operates at the daily time step. In the Future Danube modelling suite, the hydrological module creates the link between the weather/climate (IMAGE) and the risk modules. For this reason, a SWIM model was developed that covers the entire Danube River basin in a single application which is represented spatially very detailed by about 14 000 subbasins and 190 000 hydrological response units. This high-resolution model setup enables us to zoom into any location of interest, like small tributaries, to investigate the impacts of climate change on hydrological parameters such as future flood and drought occurrence, average seasonal or annual discharge patterns.

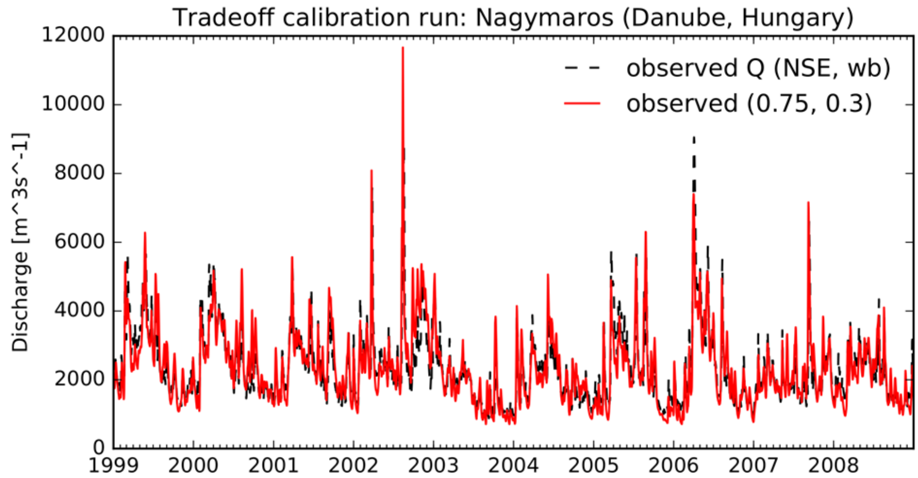
Approach:

SWIM uses the climate data provided by IMAGE to simulate future scenarios of daily discharges in the entire Danube river basin. In Future Danube modeling suite, the standard to calculate flood recurrence intervals is to simulate 10 000 years of daily discharge for each climate simulation (4 RCMs, 2 climate scenarios or Representative Concentration Pathways (RCPs), and two future time slices: 2020-2049 and 2070-2099). Future changes in flood and drought recurrence are assessed based on 10 000 years of historical weather simulations representing the historical period 1970-1999. The data of the hydrological module (daily discharges at each subbasin outlet) are transferred to the Future Danube risk module which generates risks and costs of flood events for different locations in the Danube River basin.

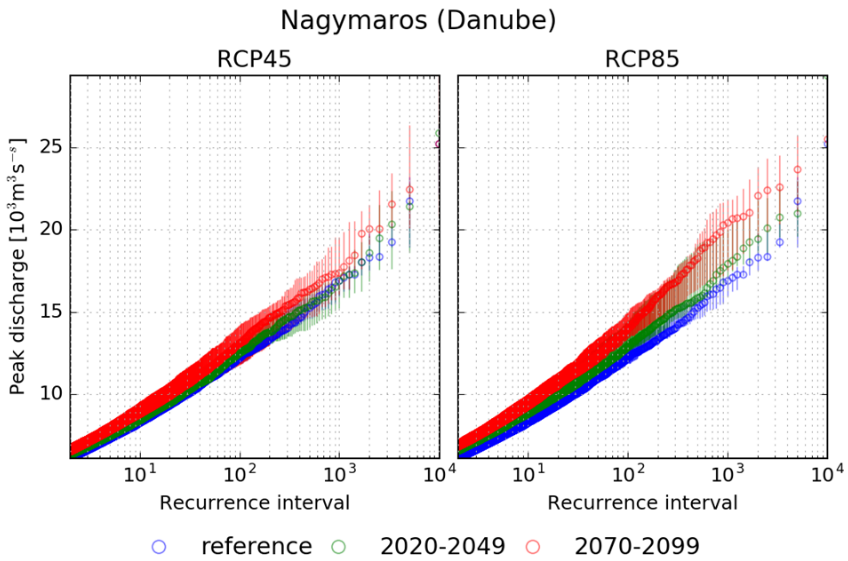
Already covered area of the Danube Region:
The SWIM model was setup to the entire Danube River basin in a single application which is represented spatially very detailed by about 14 000 subbasins and 190 000 hydrological response units.
Plans for update: Currently, the SWIM model is calibrated and validated up to the gauge Nagymaros, Hungary. The model will be calibrated to the entire Danube River basin in this phase of the project.
Input data needs and current sources: Spatial data: ▪ DEM (digital elevation model) in any spatial resolution to delineate the catchment and its subbasins. The SRTM 90m DEM was used: http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1 ▪ Land use/cover and soil maps in any resolution to identify hydrological response units (HRUs) within each subbasin. The Harmonized World Soil Database (HWSD) was used in this study: http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/ ▪ Soil properties to parameterize each soil type: number of layers, depth of layers, contents of sand, silt, and clay, bulk density, porosity, available water capacity, field capacity, organic carbon content, organic nitrogen content and saturated conductivity. Temporal data: ▪ Climate: precipitation, min./mean/max. air temperature, solar radiation, relative air humidity (minimal requirements: Precipitation, min. and max. air temperature) from either weather stations or gridded weather data. Present-day E-OBS weather data: http://www.ecad.eu/E-OBS/ (Haylock et al. 2008) were used for model calibration and validation. ▪ Discharge: observed river discharge data are required for calibration and validation. Discharge data provided by GRDC were used in this study: http://www.bafg.de/GRDC/EN/Home/homepage_node.html. Management data: ▪ Crop calendar: days of planting, harvest, fertilization for each HRU with managed crops. ▪ Reservoirs: inflow, outflow, ration between water level, volume, and reservoir area, dead and active storage capacity, monthly release rules, hydropower efficiency, capacity, and fall height etc. ▪ Irrigation: water uptake or plant requirements for each location within a subbasin, can be expressed either in mean monthly (12 values), monthly, or daily values.

Few examples of output data:

- SWIM was used to simulate the entire Danube river basin driven by the state of the art EOBS climate reanalysis dataset. Eight subcatchments until the gauge station Nagymaros (Danube, Hungary) were calibrated via a multi-objective, evolutionary algorithm to find suitable parameter trade-offs between average hydrology and flood conditions (see a subset of 10 years in figure below).



- The model was then driven by the 10,000-year synthetic climate data (provided by IMAGE, Imperial College London) to obtain a comprehensive set of flood recurrence intervals (see figure below) for the reference period (blue, 1980-2009), the near (green) and far future (red) under two standard climate change scenarios (RCP4.5 and RCP8.5). Results indicate the potential for large shifts in recurrence intervals, i.e. higher order floods may occur more frequently. For example, the present 1000-year flood at Nagymaros (estimated to have a peak discharge of ca. 16.5x10^3 m^{3}s^{-1}) would occur at a frequency of 600 years in the far future under the RCP4.5 scenario and every 250 years under the RCP8.5 scenario. The model is able to provide these assessments for all stream segments of the upper Danube basin with both a parameter and scenario uncertainty range.



Risk module	
by Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences	

More information:

- D. Falter, N.V. Dung, S. Vorogushyn, K. Schröter, Y. Hundecha, H. Kreibich, H. Apel, F. Theisselmann, B. Merz (2014) Continuous, Large-Scale Simulation Model for Flood Risk Assessments: Proof-of-Concept. *Journal of Flood Risk Management*, 9:3-21. http://onlinelibrary.wiley.com/doi/10.1111/jfr3.12105/abstract
- D. Falter, K. Schröter, N.V. Dung, S. Vorogushyn, H. Kreibich, Y. Hundecha, H. Apel, B. Merz (2015) Spatially Coherent Flood Risk Assessment Based on Long-Term Continuous Simulation with a Coupled Model Chain. *Journal of Hydrology*, 524:182-93. http://www.sciencedirect.com/science/article/pii/S002216941500133X
- H. Kreibich, A. Botto, B. Merz, K Schröter. (2016) Probabilistic, Multivariable Flood Loss Modeling on the Mesoscale with BT-FLEMO. *Risk Analysis*, online http://onlinelibrary.wiley.com/doi/10.1111/risa.12650/abstract
- K. Schröter, H. Kreibich, K. Vogel, C. Riggelsen, F. Scherbaum, B. Merz (2014) How Useful Are Complex Flood Damage Models? *Water Resources Research* 50: 3378–95. http://onlinelibrary.wiley.com/doi/10.1002/2013WR014396/abstract

Purpose:

Vulnerability, as the product of exposure and susceptibility, is a key factor of the flood risk equation. Even though the estimation of flood loss is very sensitive to the choice of the vulnerability model, and in addition is an important source of uncertainty in risk assessment, the standard approach to loss estimation is based on highly simplified functions which relate the damage for the element at risk to inundation depth. An important improvement in flood loss estimation can be achieved if additional factors are taken into consideration as for instance building types, flood experience, precaution etc., and additional flood intensity metrics. Further, the reliability of flood loss estimates can be increases if probabilistic modeling approaches are applied which inherently provide information about the uncertainty associated with loss estimates as an important basis for informed decision making.

Approach:

Probabilistic, multi-variable, damage functions for residential buildings and private households are implemented. These damage functions are prepared to be applicable across a range of spatial scales (local to regional) using European wide available data and/or local specific data.

Typical outputs of the Risk module are loss estimate within the inundated areas with quantitative information about the uncertainty associated with these results. The module can be linked to the hydrological module so that flood hazards under current and future climate conditions can be fed into the risk analysis of current and future risks.

The damage models use multiple variables to explain flood loss including information about buildings types, building characteristics, flood experience, precaution and other factors to characterize building resistance and flooding intensity. The model approach is based on Bayesian networks which enable the inference of the complete probability density of flood damage losses and hence inherently provide damage estimates with uncertainty bounds. This probabilistic approach enables the estimation of flood losses even with incomplete and particularly considering uncertain observations.

Inundation depth is a key input variable to flood loss models. The transformation of hydrological flows available from the Hydrological module are transformed into water levels and inundation depth maps using GIS techniques at larger scales or a non-stationary 2D hydrodynamic model at smaller scales.

Already covered area of the Danube Region:

German part of the Danube basin (upstream of gauge Achleiten in Austria)

Plans for update:

Loss model transfer to other riparian states using European data sources

Extension to other sectors (e.g. commercial)

Extension to other hydro-meteorological hazards (e.g. urban pluvial flooding)

Input data needs and current sources:

Spatial data:

- DEM (digital elevation model) in high spatial resolution (<10m) to derive river cross sections and topography for hydraulic simulations
- Building footprint area, building value, building type and quality as average values for municipalities and disaggregated to Landuse units as for instance ATKIS DLM (in Germany) or CORINE LULC in Europe
- Income and ownership structure (EU census data)
- Flood experience (Dartmouth flood observatory)

Few examples of output data:

- Flood intensity footprint maps (inundation depths) for German part of the Danube
- Flood loss maps for residential assets in the German part of the Danube
- Flood risk maps providing spatially distributed expected annual damage for the residential sector

Adaptation module	
by Technical University of Denmark (DTU)	

More information: Please contact Dr. Martin Drews, mard@dtu.dk.

- Halsnæs K., Kaspersen P.S., Drews M. (2015) Key drivers and economic consequences of high end climate scenarios: uncertainties and risks, Clim Res 64:85–98, http://www.int-res.com/abstracts/cr/v64/n1/p85-98/

Purpose:

Well-planned adaptation measures can help prevent or reduce the adverse effects (economic losses, damage to infrastructure, lives lost) of weather related hazards in the Danube that are highly likely to be exacerbated by climate change such as floods and droughts. Likewise, appropriate adaptation may allow populations to benefit from potential opportunities of climate change.

Decisions on adaptation as in the case of insurance are inherently based on knowledge about climate risks i.e. the probability of specific hazards and their expected impacts. Unlike insurance however which generally has a focus on medium to low probability events having significant to catastrophic impacts, adaptation may be applicable for a wider range of probabilities depending on the characteristics of the systems affected and the consequences caused by the impacts. The Future Danube multi-hazard, multi-risk model delivers fully probabilistic information spanning the whole range from frequent occurrences to the extremes and therefore serves as an ideal tool to underpin decisions on adaptation.

Robust adaptation decisions are generally obtained by considering the benefits and costs i.e. the potential reduction of risks or losses associated with a specific adaptation vs. the costs incurred by installing these adaptive measures e.g. flood protection, changed management strategies, etc.

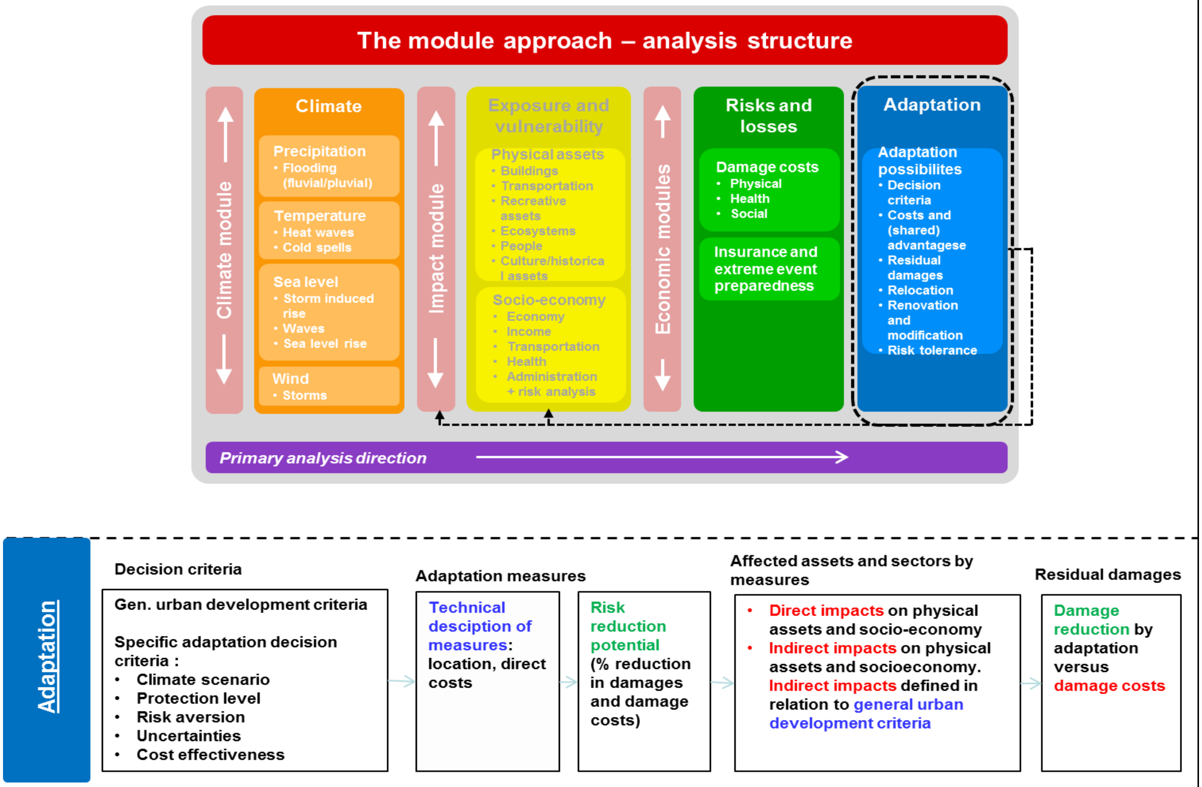
Approach:

An adaptation analysis is carried out using output from e.g. the preceding modules (weather and climate information through the hydrological module and the risk and damage module) together with case-specific information on, e.g. indirect or intangible damages (e.g. amenity values) co-assessed with stakeholders.

The adaptation assessment, which often takes the form of a cost-benefit analysis, will confront the costs (or risks) related to the impacts of a future climate scenario with "no adaptation" installed with the situation where adaptation is present i.e. the damages avoided by implementing relevant adaptation measures while taking into account the costs incurred by installing the adaptation(s). A schematic overview of the structure of the adaptation analysis is shown below. As indicated in the diagram the adaptation analysis may prompt for new e.g. hydrological model calculations to be carried out or additional factors to be included in the risk analysis.

Interaction with stakeholders will be crucial i.e. in order to establish which adaptation measures are to be considered, data needs, the local decision-making context, and realistic values with respect to costs and (co-)benefits.

The adaptation module will rely primarily on a dedicated cost-benefit tool (see below) however depending on the specific stakeholder framing, a suite of additional tools will be available.



Already covered area of the Danube Region:

-

Plans for update:

By applying the Adaptation module to different cases in the Danube region, the underlying methodology and tools will be further developed and refined to local conditions.

Input data needs and current sources:

Output from the Risk Module will be a primary source of input data. General input will depend closely on the type of hazard and risk (e.g. flood risk, shortage of water resources, heat stress) being considered, the considered adaptation options (e.g. flood risk protection, building codes, water storage, new technologies or management practices) and relevant decision-making criteria (e.g. imposed by the policy context, urban development criteria, cost-effectiveness and legal requirements).

Spatial data:

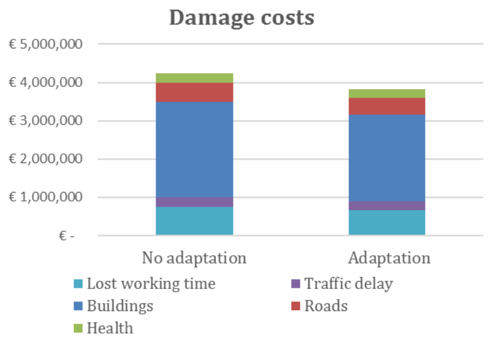
- Flood intensity footprint maps (inundation depths) (from Risk module)
- Flood loss maps (from Risk module)
- Flood risk maps e.g. expected annual damage for relevant sectors (from Risk module)
- Asset value maps (direct and indirect)

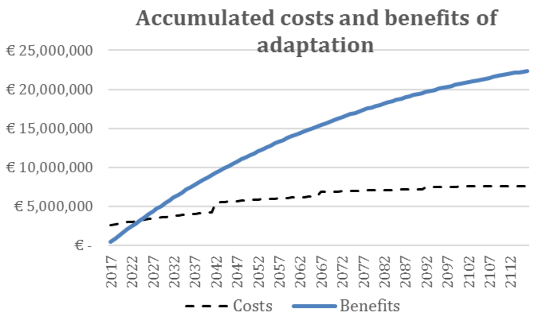
Management data:

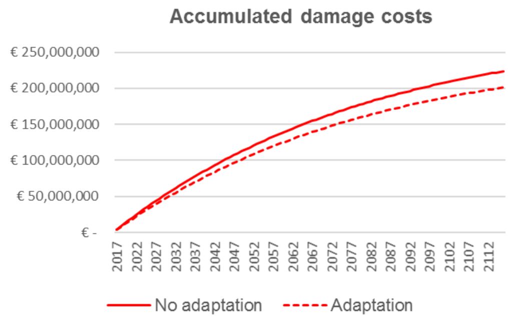
- Costs of adaptation measures (e.g. flood protection)
- Value of potential co-benefits, direct/indirect and tangible/intangible damages not spatially distributed

Few examples of output data:

The embedded suite of adaptation decision-support tools, including cost-benefit analyses, have previously been applied to a variety of different rural and urban cases. The figure below summarizes the results of cost-benefit analysis related to the installation of a nature-based solution mitigating urban pluvial floods. The upper left shows the estimated damage costs related to flooding, considering direct impacts such as damage to roads and buildings as well as indirect impacts i.e. working time lost, traffic delays and health. The upper right shows the accumulated costs and benefits of the considered adaptation over time (effectively visualizing the return-on-investment). The lower left similarly shows the accumulated damage costs over time, whereas the lower right summarizes the combined results of the cost-benefit analysis.

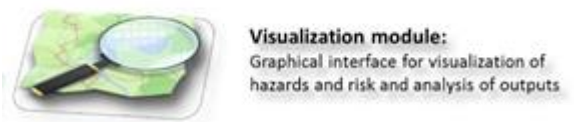






Cost-benefit summary (Net Present Value)

time period-->		25 year		50 year		100 year
Adaptation cost	€	4.276.751	€	6.273.886	€	7.642.003
Benefit	€	9.018.864	€	15.269.485	€	22.372.589
Benefit-cost ratio		2,11		2,43		2,93
Net benefit	€	4.742.113	€	8.995.600	€	14.730.587
Annual net benefit	€	189.685	€	179.912	€	147.306
Payback period (years)				8		
Payback time (year)				2024		

<table>
<tr><td>Visualization module
by PIK Potsdam</td><td>
</td></tr>
<tr><td colspan="2">More information:
-</td></tr>
<tr><td colspan="2">Purpose:
Visualization of results of the modelling suite for stakeholder engagement and product delivery.</td></tr>
<tr><td colspan="2">Approach:
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 tool is already under construction and data uploading is possible.
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, in a pilot this will be done for the Municipality of Budapest.</td></tr>
<tr><td colspan="2">Already covered area of the Danube Region:
All of the Danube river basin but so far with a focus on the upper part of the basin until Budapest.</td></tr>
<tr><td colspan="2">Plans for update:
So far, the module is in a prototype stage and will be continuously extended to cover all available results.</td></tr>
<tr><td colspan="2">Input data needs and current sources:
▪ research results in the form of spatio-temporal data</td></tr>
<tr><td colspan="2">Few examples of output data:
▪ visualization of flood recurrence intervals at selected stations
▪ model results of historic flood extents in the entire basin</td></tr>
</table>

References

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. Journal of Geophysical Research: Atmospheres, 113.

In case of interest for cooperation or for more information please visit the Oasis Danube website at http://oasisdanube.eu/ and contact:

- Miklós Gyalai-Korpos, PANNON Pro Innovations Ltd., miklos.gyalai@ppis.hu
- Fred Hattermann, Potsdam Institute for Climate Impact Research, hattermann@pik-potsdam.de
- Tracy Irvine, Imperial College London, t.irvine@imperial.ac.uk

---

The Oasis+ initiative and its activities in the Danube Region are supported by

- Oasis Future Danube with support from the EU's, EIT Climate-KIC, Europe's largest public-private innovation partnership focused on climate innovation to mitigate and adapt to climate change.
- O+D: Oasis+Danube Loss Modelling Programme selected under the Technical Assistance Facility for Danube Region Projects (TAF-DRP). Project preparation supported by the EUSDR´s Technical Assistance Facility for Danube Region Projects.
- H2020 Insurance Project, starting Spring 2017.

eit Climate-KIC

TAF-DRP

Members of the Oasis+ consortium:

ARIA TECHNOLOGIES | cea | BUDAPEST | Budapest Sewage Works Pte Ltd.

BUDAPEST WATERWORKS | TU Delft | Deltares | GFZ Helmholtz-Zentrum Potsdam

Imperial College London | OASIS Loss Modelling Framework Ltd | OASIS PALM TREE | ONF International

PIK | PPIS PANNON PRO INNOVATIONS | BetterPoints | DTU

Oasis LMF has 44 global reinsurance and insurance members.