# GIS-based approach to estimate direct economic damages of fluvial flooding under various future scenarios: A case study of the Neckar river basin (Germany)

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**Abstract**
*Fluvial floods can cause significant damages to inundated assets. The frequency and magnitude of fluvial floods are related to precipitation amounts, which are expected to change throughout the 21st century due to global warming. Alongside the hazard characteristics of fluvial flooding, flood damage potentials depend on flood exposure and flood vulnerability, which are also subject to change due to socio-economic development. In the context of continuously evolving damage-causing factors, methods to assess future changes in flood damage potential are increasingly asked for by decision-makers in flood risk management. This thesis project addresses this need by a) providing a GIS-based assessment framework, suitable to quantitatively estimate direct economic damages due to potential fluvial flooding under various future scenarios, and b) by testing the developed assessment framework in a case study in the Neckar river basin, which is located in the federal states of Baden-Wuerttemberg and Hesse in southern Germany. The developed framework is based on the findings of a scoping study on existing GIS-based flood damage assessment approaches. To account for uncertainties surrounding these future projections, a qualitative confidence estimation is introduced to reflect on the strength of knowledge underlying the framework-based flood damage assessment. The case study prognoses a significant increase in average annual flood damages in the study area throughout the 21st century. The increase in flood damage is primarily related to changes in flood exposure and flood vulnerability and to a smaller extent due to climate-related changes in the flood hazard.*



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## Executive summary

Fluvial floods can cause significant damages to assets within the floodplain. The occurrence and magnitude of fluvial floods are related to precipitation amounts, which are expected to change throughout the 21st century due to global warming. Alongside these hazard characteristics of fluvial flooding, flood damage potentials depend on flood exposure and flood vulnerability, which are also subject to change due to socio-economic development. In the context of continuously evolving flood hazard characteristics, flood exposure and flood vulnerability, methods to assess future changes in flood damage potential become increasingly relevant. This thesis project addresses this need by a) providing a GIS-based assessment framework, suitable to quantitatively estimate direct economic damages due to potential fluvial flooding under various future scenarios, and b) by testing the developed assessment framework in a case study in the Neckar river basin, which is located in the federal states of Baden-Wuerttemberg and Hesse in southern Germany.

The developed framework is based on the findings of a previously performed scoping study. In the scoping study, 48 peer-reviewed articles on existing GIS-based flood damage assessment approaches were selected and systematically analysed. The findings of the scoping study underline that economic flood damages are most commonly assessed using stage-damage functions, which allow for flood damage estimates for different asset types under various inundation depths.

Informed by the outcomes of the scoping study, the developed flood damage assessment framework consists of a flood component and a damage component, which in combination can be used to assess flood damages for various flood scenarios under today's and future conditions. The flood component comprises flood simulations using the hydrologic and hydraulic simulation software packages HEC-RAS and HEC-GeoRAS in combination with GIS. The damage component of the assessment framework entails the estimation of flood exposure based on land use patterns and flood vulnerability in the form of stage-damage functions and potential maximum damages to the different land use types.

The estimation of future flood damages in the case study is based on simulated changes in the flood hazard due to discharge changes under RCP2.8, RCP8.5 and on a standard climate-change-factor, and an extrapolation of past changes in flood exposure and flood vulnerability using the MOLUSCE GIS extension and historical change rates.

The case study prognoses a significant increase in average annual flood damages in the study area throughout the 21st century. The increase in flood damage is primarily related to changes in flood exposure and flood vulnerability and to a smaller extent due to climate-related changes in the flood hazard. The disagreement between the projections based on the RCPs in comparison to the climate-change-factor projections is related to uncertainties regarding future precipitation patterns and adequate means to transfer projected rainfall data into flood discharges.

To account for uncertainties surrounding these future projections, a qualitative confidence estimation is introduced to reflect on the strength of knowledge underlying the framework-based flood damage assessment.

The main value of this thesis project is the systematic review of existing GIS-based flood damage analysis approaches and the subsequent development of a state-of-the-art assessment framework. Practitioners in flood risk management can benefit from the comprehensive overview on the most commonly used GIS-based flood damage assessment methods. Practitioners can use the developed framework in study areas of various scopes, while the level of detail of such framework-based assessments can be easily adjusted based on the study purpose, existing expertise and available resources. The performed case study exemplifies how the use of the flood damage assessment framework might look like in practice.

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## List of abbreviations

| | |
|---|---|
| AAL | Average Annual Damages |
| AAS | Asian Air Survey |
| BW | Baden-Wuerttemberg (Federal state) |
| CLC | CORINE Land Cover |
| DEM | Digital Elevation Model |
| DHI | Institute for Water and Environment |
| EAD | Expected Annual Damages |
| ESRI | Environmental Systems Research Institute |
| EU-DEM | Digital Elevation Model of the European Union |
| GCM | Global Climate Model |
| GDP | Gross Domestic Product |
| GERICS | Climate Service Center Germany |
| GMST | Global Mean Surface Temperature |
| GIS | Geographic Information Systems |
| HQ | Return period of a flood event |
| IKoNE | Integrating Conception Neckar River Basin |
| IPCC | Intergovernmental Panel on Climate Change |
| JRC | Joint Research Centre |
| KLIWA | Climate Change and Consequences for Water Management |
| LAEA | Lambert Azimuthal Equal Area Projection |
| LUBW | State Institute for the Environment, Climate Protection & the Energy Sector BW |
| MOLUSCE | Modules for Land Use Change Simulations |
| PIK | Potsdam Institute for Climate Impact Research |
| PWC | PricewaterhouseCoopers |
| RCP | Representative Concentration Pathway |
| RCM | Regional Climate Model |
| RSP | Return Period Shift Method |
| SoK | Strength of Knowledge |
| SRES | Special Report on Emissions Scenarios |
| UM BWL | Ministry for the Environment, Climate Protection and Energy Sector BW |
| USACE | United States Army Corps of Engineers |
| USDA | Agriculture Research Service |
| UTM | Universal Transverse Mercator |
| WM BW | State Ministry of BW for Economic Affairs, Labour and Housing Construction |

# 1. Introduction

Climate change is expected to alter the magnitude and frequency of climate-related hazards such as fluvial flooding, which results in changed flood damage potential. While climate change is primarily affecting flood hazard characteristics, socio-economic developments can impact the level of flood exposure and flood vulnerability, which is also directly linked to the flood damage potential. Flood damage assessments are increasingly asked for by decision-makers in flood risk management and particularly relevant in the context of changing flood, exposure and vulnerability characteristics (Merz, Thieken & Kreibich 2011). Flood damage assessments, which take changing risk levels into account, can make a valuable contribution to long-term risk-based land use planning and structural climate change adaptation.

This thesis project addresses the existing research need for adequate flood damage estimation methods considering dynamic damage-causing factors by **a)** providing a GIS-based assessment framework, suitable to quantitatively estimate direct economic damages due to potential fluvial flooding under various future scenarios, and **b)** by testing the developed assessment framework in a case study in the Neckar river basin, which is located in the federal states of Baden-Wuerttemberg and Hesse in southern Germany.

The following two research questions guide the thesis project:

a) *How can future changes in average annual fluvial flood damages be assessed and compared to today's average annual flood damages?*

*b) How will the average annual direct economic flood damages in the Neckar river basin change throughout the 21st century, based on various future scenarios?*

The two research questions are answered through three main thesis components. The first component comprises a scoping study, in which existing flood damage assessment approaches are systematically reviewed and evaluated. The scoping study as well as the other thesis components, are solely focused on flood damage assessment approaches using Geographic information systems (GIS) to delimit the vast variety of resources to a feasible level. GIS is widely used to assess damages due to the spatial implication of flood risk. GIS is capable and highly efficient in processing huge amounts of spatial and non-spatial data, which is vital for flood damage assessments in large study areas (Komolafe, Herath & Avtar 2018b).

In the second part of the thesis, a flood damage assessment framework is developed and presented based on the findings of the scoping study. The last major thesis component comprises the case study, in which the developed flood damage assessment framework is applied and tested in the context of the Neckar river basin.

# 2. Scoping study

A scoping study was performed to suit the primary aim of this thesis, namely, to compile a GIS-based assessment framework, suitable to quantitatively estimate direct economic damages due to potential fluvial flooding under various future scenarios.

## 2.1 Purpose and structure of the scoping study

The scoping study is required to grasp and evaluate existing scientific concepts and approaches in GIS-based flood damage assessment to identify state-of-the-art practices. The gained knowledge from the scoping study forms the basis for the development of a damage assessment framework, which is suitable to fulfil the second aim of this thesis, namely, to apply the compiled flood damage assessment framework in the context of the Neckar river basin.

Elsevier's abstract and citation database *Scopus***,** which comprises the worldwide biggest pool of peer-reviewed scientific articles, was consulted for the scoping study (Elsevier 2020). Thematically relevant keywords, in combination with Boolean operators, were used to select significant articles from the database, which correspond to GIS-based flood damage assessments in river basins. The applied Scopus search string can be seen in appendix I.

In January 2020, when the scoping study was performed, Scopus delivered 165 preliminary hits, using the search string shown in appendix I (Elsevier 2020). Out of these 165 articles, the ones with actual relevance for the thesis topic were selected for the scoping study. A refined article selection was necessary, since many articles had no thematic relevance for the thesis project, even though they fulfilled the selection criteria of the search string. The refined selection of relevant articles was based on a criteria-based review of all 165 titles, abstracts and keywords. After the refined selection was performed, 48 relevant articles remained for the scoping study. An overview of the selected articles can be found in the reference list. The used criteria for selecting and evaluating articles, as well as for compiling the damage assessment framework, are described in detail in the subsequent section.

## 2.2 Criteria for the scoping study and the framework development

The developed damage assessment framework is tied to a set of requirements to suit the purpose of the thesis project. These framework requirements have implications for the article selection in the scoping study, since the framework development is informed by the outcome of the scoping study. The underlying framework requirements are reflected in the Scopus search string, which was used for the article selection. Additional criteria were used to refine the selection of articles for the scoping study.

### 2.2.1 Criteria to be fulfilled by the damage assessment framework

The following criteria are to be fulfilled by an assessment framework to satisfy the aim of this thesis project.

- **The assessment framework should be state-of-the-art**
  *Reasoning*: Progressive methodological improvements in GIS-based flood and damage assessment have taken place in recent years. To make a valuable contribution to the scientific field, the developed damage assessment framework has to be informed by these recent changes to account for the ongoing developments in geospatial analysis.
  *Implementation*: The Scopus search string was limited to articles that were published after 2012. It was assumed that articles older than 2013 might not be state-of-the-art anymore.

- **The assessment framework should be based on GIS software**
  *Reasoning*: Due to the spatial implication of flood risk, GIS is a valuable tool for flood damage assessments. GIS is capable and highly efficient in processing huge amounts of spatial and non-spatial data, which are relevant for flood damage assessments in large study areas (Komolafe, Herath & Avtar 2018b).
  *Implementation*: This criterion is reflected in the Scopus search string. Existing flood assessment approaches which were not based on GIS were automatically excluded from the scoping study. This criterion was further considered when developing the methodology of the assessment framework for the case study of this thesis project.

- **The assessment framework should be applicable in the context of river basins**
  *Reasoning*: This criterion has to be fulfilled by an assessment framework to be applicable in the case study of this thesis project, since the study area comprises the basin of the Neckar river. When analysing fluvial floods, it is a common approach to focus on river basins as encapsulated drainage systems. While the assessment framework should be applicable for river basins, its use does not have to be limited to such mesoscale study scopes.

*Implementation*: This criterion is reflected in the Scopus search string. Existing flood assessment approaches which did not fulfil this criterion were automatically excluded from the scoping study.

- **The assessment framework should be compatible with future scenarios to assess future flood damages**
  *Reasoning*: This criterion has to be fulfilled to allow estimates of future flood damages, and thus to suit the purpose of this thesis.
  *Implementation*: Existing flood damage assessment approaches without an explicit focus on future changes in flood damage levels were not excluded from the scoping study to broaden the scope and to retrieve a sufficient number of articles for the scoping study. However, the criterion was considered when developing the methodology of the assessment framework, which is applied in the case study of this thesis project.

- **The assessment framework output should support the estimation of direct economic flood damages**
  *Reasoning*: Direct economic damages were chosen as essential aspect of risk in this thesis project due to the relative ease to quantify and compare economic damage values. While other damage categories exist, it is common to focus on direct economic losses (Albano, Crăciun, Mancusi, Sole & Ozunu 2017).
  *Implementation*: Existing flood damage assessment approaches which did not fulfil this criterion were not excluded from the scoping study to broaden the scope and to retrieve a sufficient number of articles for the scoping study. However, the criterion was considered when developing the methodology of the assessment framework, which is applied in the case study of this thesis project.

- **The assessment framework should be based on input data which is publicly available**
  *Reasoning*: Availability and free accessibility of input data have to be ensured. Otherwise, the assessment framework would not be applicable in the case study, and its usefulness to a broader professional audience would be limited.
  *Implementation*: Existing flood damage assessment approaches which did not fulfil this criterion were not excluded from the scoping study to broaden the scope and to retrieve a sufficient number of articles for the scoping study. However, the criterion was considered

when developing the methodology of the assessment framework, which is applied in the case study of this thesis project.

### 2.2.2 Criteria for the refined article selection for the scoping study

The following criteria were used to refine the preliminary Scopus article selection to exclude articles with no actual relevance for the thesis topic. The criteria were checked against the information provided in titles, abstracts and keywords.

- **Direct link to flood or damage assessment**

  *Reasoning*: Many irrelevant articles fulfilled the selection requirements of the Scopus search string due to the "right" combination of keywords in their title, abstract or keywords. Other topics than flood and damage assessment such as water quality assessment or sediment analysis were studied in some selected studies instead. Some studies pursued a qualitative analysis approach and only used GIS to map survey results.

  *Implementation*: Articles without direct link to GIS-based flood modelling or flood damage assessment were neglected. Articles which only studied past flood events, without relevant implications to the present or the future, were also excluded.

- **Availability of articles**

  *Reasoning*: Scopus considers peer-reviewed articles, which are not necessarily accessible via any of the article databases featured by Lund University. Articles in other languages are also featured.

  *Implementation*: Only articles which were accessible via available article networks and databases were selected. Articles written in other languages than English or German were also excluded. This criterion was of minor practical relevance. Only five articles with actual relevance to the thesis topic did not fulfil the availability requirements.

## 2.3 Results of the scoping study

The findings of the scoping study are described in the following. Not every single method, which was identified, is explained in detail. Instead, a general overview of the reviewed literature is given. The most common assessment components, as well as perceived similarities and differences between the studies, are depicted.

It was found that almost all GIS-based flood damage assessment approaches can be divided into two main components. The first component addresses flood modelling (hazard assessment), while the second component comprises damage modelling (exposure and vulnerability assessment). In combination, these two assessment components allow the estimation of expected damages under given flood scenarios (Komolafe, Herath, Avtar & Vuillaume 2019; Kobayashi, Takara, Sano, Tsumori, Sekii 2016). The main characteristics of these two assessment components are described in the following.

### 2.3.1 Flood modelling

Flood modelling is required to delineate and characterise potential flood events within a particular study area. Hydrologic and hydraulic simulation software is usually used in combination with GIS to model characteristics of hypothetical or historical flood events (Scorzini, Radice & Molinari 2018; Saini, Kaushik & Jangra 2016).

#### 2.3.1.1 Flood simulation software

Several different hydrologic and hydraulic simulation programmes and software packages were applied in the analysed studies. Some studies worked with multiple simulation programmes, while others were limited to a single simulation software. GIS was commonly combined with the primary flood simulation software to geo-visualise and process spatial flood data (Mahmood, Rahman & Shaw 2019).

By far, the most often used simulation software was HEC-RAS in combination with HEC-GeoRAS from the United States Army Corps of Engineers (USACE). More than $^1/_3$ of the reviewed studies made use of this software (Zúñiga & Novelo-Casanov 2019; Mihu-Pintilie, Cîmpianu, Stoleriu, Pérez & Paveluc 2019; Tarigan, Zevri, Iskandar & Indrawan 2017).

The simulation software packages MIKE FLOOD and MIKE 11 by the Danish Institute for Water and Environment (DHI), SWAT by the USDA Agriculture Research Service, and the Flo-2D model by Flow-2D Software Inc. were also applied in several reviewed studies. SWAT software was only used in combination with other simulation tools (Komolafe, Herath & Avtar 2018a; Cham & Mitani 2015; Qiao, Huang, Chen & Li 2018).

The mentioned hydrologic and hydraulic simulation tools were used to model fluvial, pluvial or coastal flood events (Jamali et al. 2018). In most cases, flood simulations were based on discharge, rainfall or stormwater data. Two studies considered flooding due to snowmelt (Qiao, Huang, Chen & Chen 2019; Qiao, Huang, Chen & Li 2018).

Regardless of which type of flood was modelled, and which software was used, most of the reviewed flood simulations were able to determine the inundation area and respective flood depths. Some studies also determined the expected flow velocity and flood duration (Bormudoi, Huy, Hazarika & Samarakoon 2013; Gergel'ová, Kuzevičová, Kuzevič & Sabolová 2013). In the reviewed studies, it was distinguished between one-dimensional (1D), two-dimensional (2D) and 1D-2D hydraulic modelling. One-dimensional hydraulic modelling is used for fluvial flood modelling, based on the assumption that water solely flows from upstream to downstream. Two-dimensional hydraulic modelling is more reliable to accurately represent river flows and floods in topographically complex environments; however, more detailed and comprehensive input data is required. Coupled 1D-2D hydraulic modelling aims to combine the advantages of both 1D and 2D modelling. While advantages and drawbacks of these modelling techniques were identified in the reviewed articles, all three modelling types seem to be generally adequate to model floods for flood damage assessments (Nga, Takara & Cam Van 2018; Kobayashi et al. 2016; Ahmadisharaf, Kalyanapu & Chung 2015).

A small number of reviewed studies pursued a statistical, survey-based or index-based approach to determine flood characteristics instead of engaging in software-based hydrologic and hydraulic modelling (Ettinger et al. 2016; Waghwala & Agnihotri 2019; Brown, Daigneault & Gawith 2017).

### 2.3.1.2 Flood scenarios

When simulating hazards such as floods, it is common to consider several design floods, respectively different flood scenarios, to account for the natural variability in terms of flood frequency and magnitude (Nga et al. 2018; Yu, Hall, Cheng & Evans 2013).

Another possibility is the simulation of a certain event, such as a historical flood. Out of the reviewed articles, ten studies focused on a specific historical event. A small number of studies considered a baseline scenario such as a historical flood and compared it to alternative scenarios based on adaptation measures or climate change (Brown et al. 2017; Cham & Mitani 2015; Ronco et al. 2014).

More than half of the reviewed studies applied return periods, also known as recurrence intervals, to build different flood scenarios. A return period can be defined as the estimated average time between the occurrence of two floods of similar magnitude (Mahmood et al. 2019; Tarigan, Hanie, Khair & Iskandar 2018; Muhadi & Abdullah 2015).

Between two and 11 different return periods were used in the analysed studies, while it is common to include a minimum of three different return periods (Karamouz, Zahmatkesh, Goharian & Nazif 2015; Morita 2018). A minimum of three different return periods is required when average annual losses are to be estimated (Nga et al. 2018). Return periods between 2-years and 1000-years were considered in the assessed papers, while 10-years, 50-years and 100-years were by far the most frequently applied recurrence intervals (Pathak, Bhandari, Kalra & Ahmad 2016; Gusyev et al. 2015). Floods for all kinds of return periods can be simulated using previously described hydrologic and hydraulic simulation software.

### 2.3.1.3 Flood frequency analysis

To determine different flood return periods, one has to estimate the occurrence frequencies and the corresponding flood magnitudes. Various statistical methods can be applied to estimate the frequency of river discharge or rainfall levels based on historical flood records. The determination of the most popular frequency analysis method was hindered by the fact that several studies did not specify their approach. Some studies only modelled historical floods with known discharge and rainfall levels, making frequency analysis redundant (Komolafe et al. 2019; Waghwala & Agnihotri 2019; Scorzini et al. 2018).

Where frequency analysis was performed, Gumbel distributions and Weibull distributions were the preferred statistical methods (Gusyev et al. 2015; Soliman, El Tahan, Taher & Khadr 2015). Several studies also used Pearson type III, lognormal or generalised extreme value (GEV) distributions in combination with Gumbel or Weibull to estimate flood frequencies (Faghih, Mirzaei, Adamowski, Lee & El-Shafie 2017; Eslamian 2014).

The most common approach was to adopt existing flood frequencies based on expert judgment, instead of using any of the above-mentioned statistical methods (Arrighi et al. 2018; Schmid-Breton et al. 2018; Aksoy, Ozgur Kirca, Burgan & Kellecioglu 2016; Ahmadisharaf et al. 2015).

### 2.3.1.4 Flood validation

Most studies emphasised the need to validate the accuracy of modelled floods. A prominent validation approach in the reviewed studies was comparing modelled floods with similar historical flood events in terms of flood extent and flood depth (Mahmood et al. 2019; Yu et al. 2013). Based on the comparison between modelled floods and historical flood events, flood models can be calibrated and refined if necessary (Zúñiga, Novelo-Casanova 2019; Karamouz et al. 2015). In cases where flood extent and flood depths of historical floods were not fully available, some flood models were validated against historical watermarks and historical flood information in news reports. Validation through surveys and interviews in the study area was also repeatedly applied (Komolafe et al. 2019; Saini et al. 2016).

### 2.3.2 Damage modelling

Damage modelling is required to estimate flood impacts on whatever is valued in an assessment. It has to be determined which damage categories of floods should be considered in the assessment. Flood damage can be divided into tangible and intangible damages and further subdivided into direct or indirect tangible and intangible damages (Albano et al. 2017; Cham & Mitani 2015; Morita 2014).

Direct tangible damages are monetary quantifiable and refer to adverse physical impacts on assets. Indirect tangible damages are monetary quantifiable and refer to follow up losses due to disruption of critical infrastructure. Direct intangible damages are not monetary quantifiable and refer to physical harm on people. Indirect intangible damages are not monetary quantifiable and refer to psychosocial harm on people. While all mentioned damage categories are relevant, not all categories are always considered in flood damage assessments. The selection of considered damage categories is linked to the determination of what is valued in an assessment (e.g. people, environment or physical assets). It is also linked to how damages are quantified (e.g. loss of life, number of people affected or monetary losses) as well as which damaging causes are considered (Albano et al. 2017; Cham & Mitani 2015; Morita 2014).

#### 2.3.2.1 Damage quantification

Out of the 48 studies, 15 studies were limited to flood modelling and did not quantify flood damages (Acosta, De Leon, Hollite, Logronio & James 2017; Faghih et al. 2017; Karamouz et al. 2015). Out of the remaining studies, $^{2}/_{3}$ were restricted to direct tangible damages, expressed in monetary terms. A few studies managed to integrate indirect and intangible damages alongside direct tangible damages (Arrighi et al. 2018; Nga et al. 2018; Trovato & Giuffrida 2018). A small number of studies applied ordinal damage classes to assess the risk seriousness instead of quantifying actual damages (Ettinger et al. 2016; Ronco et al. 2014). Reason for the focus on direct tangible damages seems to be the relative ease to accurately measure and quantify direct economic losses (Albano et al. 2017; Vozinaki, Karatzas, Sibetheros & Varouchakis 2015; Foudi, Osés-Eraso & Tamayo 2015).

Economic losses can be either quantified per individual scenario (disaggregated) or can be aggregated as average annual losses (AAL). Both approaches were identified in the reviewed studies. Average annual losses, also called expected annual damages (EAD), can be expressed as the sum of all considered damage scenarios, multiplied by their respective flood frequency (Lawrence, Pindilli & Hogan 2019; Foudi et al. 2015; Yu et al. 2013).

#### 2.3.2.2 Damage causation

In the reviewed articles, different damage-causing flood characteristics were discussed with a primary focus on direct tangible damages. The most commonly considered flood characteristics, which influence damages, are flood extent, flood depth, flood velocity and flood duration. One study, with a focus on flood damages in agriculture, emphasised the relevance of time and season of flood occurrence (Vozinaki et al. 2015). In the analysed studies, flood extent and flood depth were by far the most often used flood characteristics. Only one study quantified flood damages based on flood extent without considering flood depth (Tarigan et al. 2017). While many articles highlighted the theoretical relevance of flood velocity and flood duration, most studies were restricted to flood extent and flood depth when assessing flood damages. This is rooted in the relative ease to determine reasonably accurate damage estimates based on extent and inundation depth of floods (Komolafe et al. 2019; Mohammadi, Nazariha & Mehrdadi 2014).

Most reviewed flood damage assessment approaches, using extent and depth, were based on stage-damage functions. Stage-damage functions describe the linkage between flood depths and corresponding monetary damages of exposed assets, which arise due to inundation. Exposed assets are commonly grouped and assigned with group-specific stage-damage functions. Potential maximum damages of exposed assets are to be known to apply such loss functions. Flood depth determines the share of the potential maximum damage per area of an inundated asset (Arrighi et al. 2018; Vozinaki et al. 2015).

In the reviewed articles, it was distinguished between synthetic and empirical stage-damage functions. Empirical stage-damage functions are based on historical damage records of past flood events, which can be extrapolated to the present. Synthetic stage-damage functions are based on expert judgment using hypothetical what-if questions. Both types of stage-damage functions were commonly applied in the reviewed articles (Komolafe et al. 2018b; Neubert, Naumann, Hennersdorf & Nikolowski 2016; Vozinaki et al. 2015; Foudi et al. 2015). Some studies adopted already existing stage-damage functions instead of constructing their own loss functions. It was repeatedly emphasised that stage-damage functions pose a major source of uncertainty in flood damage assessment due to their context specificity, limited spatial transferability and difficult validatability. The inherent uncertainties in damage modelling seem to be significantly larger than the flood modelling uncertainties (Scorzini et al. 2018; Albano et al. 2017; Vozinaki et al. 2015; Morita 2014).

### 2.3.2.3 Damaged assets

Since the majority of the reviewed studies focused on direct tangible damages, land use categories were the most commonly considered assets. A small number of studies included impacts on people and the environment, which corresponded to difficulties to adequately quantify expected damages (Trovato & Giuffrida 2018; Saini et al. 2016).

Agriculture, residential areas and commercial sites were the most frequently considered land use categories in the reviewed articles. Most studies grouped the flood-affected areas into land use categories and assigned these asset groups with group-specific stage-damage functions as described above. Land use categories were either determined through analysing satellite imagery using remote sensing techniques or by simply adopting already existing land use and land cover data (Lawrence et al. 2019; Nga et al. 2018; Arrighi et al. 2018). A large variety of applied data and processing techniques was perceived in the literature review. Large variety was also observed in terms of spatial resolution, which ranged from 1 m cell size up to 30 km cell size. In most cases, the spatial resolution of land use data was adjusted to the spatial resolution of the digital elevation model (DEM) used in the respective flood model. Spatial resolution was further related to the size of the study area (Komolafe et al. 2019; Arrighi et al. 2018; Scorzini et al. 2018).

The CORINE land cover data (CLC) by the European Copernicus Land Monitoring Service was used in three studies and is thus the most frequently used prefabricated land use dataset (Schmid-Breton et al. 2018; Albano et al. 2017; Ronco et al. 2014).

It was emphasised that all considered spatial data, no matter if flood or damage data, have to be projected to the same geographic coordinate system (Neubert et al. 2016). Among the reviewed studies which specified the used geographic coordinate system for geospatial flood and damage data, the Universal Transverse Mercator projection (UTM) based on WGS84 geodetic datum was most prominent (Rincón, Khan & Armenakis 2018; Kobayashi et al. 2016; Karamouz et al. 2015). Most studies pursued a grid-based approach for both flood and damage data instead of a vector-based approach due to the better processability of continuous spatial data in raster format (Komolafe et al. 2018b; Jamali et al. 2018; Neubert et al. 2016). Parcel-level data on land use and properties was scarcely used (Lawrence et al. 2019).

### 2.3.2.4 Damage validation

Equal to modelled floods, modelled damages should be validated against reported damage data to assess the accuracy of the applied damage model (Komolafe et al. 2018a; Cham & Mitani 2015). Similar validation techniques as for flood model validation, such as surveys, interviews and the analysis of old news reports, were applied for damage validation. Many reviewed studies reported challenges in validating modelled flood damages due to lacking reference data. While the need for validation was broadly acknowledged, many studies failed to validate their damage model due to limited availability of historical data (Arrighi et al. 2018; Komolafe et al. 2018a; Neubert et al. 2016). It was mentioned that when complete validation is not possible, other means of verification should be sought (Vozinaki et al. 2015).

## 2.3.3 Future projections

Out of the 48 reviewed articles in the scoping study, ten articles considered climate change in their assessments, out of which five engaged in both, flood modelling and damage modelling (Komolafe et al. 2018b; Brown et al. 2017; Neubert et al. 2016; Morita 2014; Yu et al. 2013).

The methodology of these climate-related flood damage assessment studies is similar to the non-climate related studies in terms of the interplay of the two components flood modelling and damage modelling. What differs is the input data. To conclude on future changes in expected flood damages, flood and damage modelling was done for both, today's conditions as well as expected future conditions. Damages, estimated for future states, can then be compared to today's baseline damages (Komolafe et al. 2018b; Brown et al. 2017; Neubert et al. 2016; Morita 2014; Yu et al. 2013).

### 2.3.3.1 Flood projections

In terms of flood modelling, two generic approaches, aiming for an integration of climate change, were identified in the reviewed literature. The first approach is based on statistical downscaling of discharge and rainfall data from general circulation models (GCMs) to regional climate models (RCMs). Climate projections based on GCMs are characterised by coarse spatial resolution and poor performance in regional contexts. While RCMs can improve the resolution and performance of climate projections in regional settings, statistical downscaling comes along with significant uncertainties (Arunyanart, Limsiri & Uchaipichart 2017; Karamouz et al. 2015). Based on RCMs, expected future rainfall and discharge levels can be estimated for different climate scenarios. Based on such estimated future rainfall and discharge levels, one can model future floods, using the above-described simulation software (Komolafe et al. 2018b; Neubert et al. 2016; Yu et al. 2013).

The second identified flood modelling approach is based on a return period shift method (RSP). Instead of estimating future rainfall and discharge levels for different climate scenarios, the RSP method estimates future shifts in the average recurrence interval of constant rainfall or discharge levels based on climate projections (Brown et al. 2017; Morita 2014).

The reviewed projections are primarily based on the representative concentration pathways (RCPs) or the special report on emission scenarios (SRES). Both modelling approaches of future floods, as well as the corresponding climate scenarios, entail significant uncertainties (Komolafe et al. 2018b; Brown et al. 2017; Neubert et al. 2016; Morita 2014; Yu et al. 2013).

#### 2.3.3.2 Damage projections

Since projections of future flood damage go several decades into the future, it is common to consider non-climate related dynamic factors. In terms of damage modelling, several variables can be projected to future states. Land use is one variable which is continuously developing and thus changing the exposure of assets to future flood events. Developing land use is also influencing rainfall runoff with direct impact on flood likelihood and magnitude. Some studies integrated projections of future land use in their flood damage assessment (Neubert et al. 2016; Morita 2014; Yu et al. 2013). Other studies worked with static land use conditions for future states (Komolafe et al. 2018b; Yu et al. 2013).

While most reviewed studies primarily focused on future spatial changes in land use, it is also possible to consider future changes in economic land use values and consequently expected future maximum damages per asset (Neubert et al. 2016; Morita 2014). Such aspects can be considered through the use of changed stage-damage functions. Some studies considered potential future flood adaptation measures in their damage assessments (Neubert et al. 2016; Morita 2014).

While projecting all potentially relevant dynamic variables makes flood damage assessments more realistic, it also leads to increased uncertainties in the overall damage projection. Keeping several variables constant can reduce the uncertainties in the projected outcomes; however, it requires a different interpretation of the results. No matter which approach is pursued, it is crucial to reflect on the analytical sacrifices when discussing the assessment findings.

### 2.3.3.3 Validation of projections

Validation of future flood and damage projections is challenging due to absent verification data. Most studies validated their models against historical records to account for model accuracy under today's conditions. Validation of future projection was mostly not possible, resulting in significant uncertainties in the projected outcomes. Most studies were forced to solely trust in the quality of the projected input data (Komolafe et al. 2018b; Morita 2014; Yu et al. 2013).

## 3. Damage assessment framework

In this section, the structure and methodology of the developed damage assessment framework are described. The methodological choices are based on the outcomes of the previously described scoping study. A similar heading structure is applied as in the results of the scoping study to facilitate the read. In this section, the framework is described in isolation from the case study to lay the focus on the general structure and basic methodological choices underlying the framework. The description of the framework components, as well as the data requirements, is deliberately kept broad since explicit methodological choices are highly context-specific. The framework description grasps the general construct of the framework and covers recommended approaches and favoured alternatives. In the case study description, the application of the framework, as well as the required input data, are described in more detail, which gives a better understanding of how the framework might be used.

## 3.1 General framework structure

The developed framework consists of two main components. The first component addresses fluvial flood modelling (hazard assessment), while the second component comprises damage modelling (impact assessment). The damage modelling is subdivided into exposure and vulnerability. In combination, the two assessment components allow the estimation of expected direct tangible flood damages for various scenarios. The input data on flood and damage characteristics determine whether the simulated damages represent past, current or future conditions. The output of the framework can include flood and damage maps as well as expected damage costs for various scenarios and AAL. A schematic representation of the flood damage assessment approach can be seen in figure 1. Alongside the assessment framework description, the concept of strength of knowledge (SoK) is introduced. This concept shall be used in combination with the framework to qualitatively reflect on the quality of data inputs and outputs of the framework to assess the overall credibility and inherent uncertainty of the assessment results.

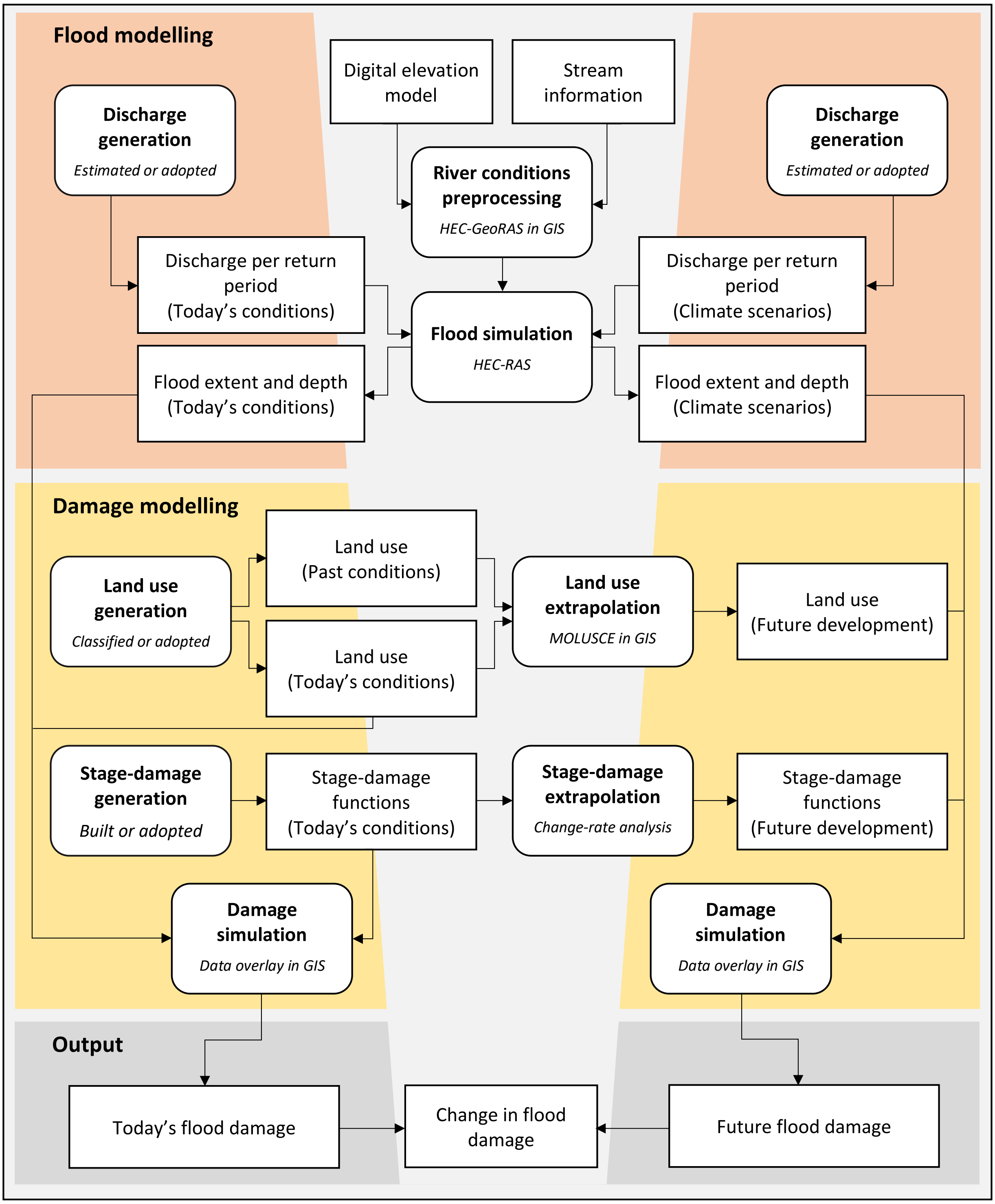


*Figure 1: Schematic damage assessment flow (own representation)*

## 3.2 Assessment methodology and validation

The characteristics of the two framework components are described in the following. A brief description of the validation approach is also given and is concretised in the case study section.

### 3.2.1 Flood modelling

The flood modelling component of the framework is based on a combination of GIS and hydrologic and hydraulic simulation software. The damage assessment framework is based on stage-damage functions, which is why flood extents and flood depths are the flood characteristics of interest in the flood modelling.

#### 3.2.1.1 Flood simulation software

HEC-RAS 5.0.7 and HEC-GeoRAS 10.2 from the United States Army Corps of Engineers (USACE) is favoured for one-dimensional flood modelling based on estimated flood discharges ($m^3/s$). The HEC-software packages are freely available and compatible with ArcGIS software by the Environmental Systems Research Institute (ESRI). Using the two HEC-software packages, it is possible to simulate flood extents and depths for various return periods. This methodological choice is backed by the findings from the scoping study and in line with the defined evaluation criteria described in section 2.2.1 (Mihu-Pintilie et al. 2019; Nga et al. 2018).

#### 3.2.1.2 Flood scenarios

The flood scenarios in the framework are based on different flood discharges ($m^3/s$) per return period. While all kinds of scenarios can be used in the framework, it is recommended to include estimated discharges for 10-year, 50-year and 100-year floods. The focus on these three most commonly used return periods allows the assessment of AAL while keeping the modelling expenses low. The restriction to these three scenarios is backed by the outcome of the scoping study and does not violate the defined evaluation criteria (Karamouz et al. 2018; Nga et al. 2018; Pathak et al. 2016).

#### 3.2.1.3 Flood frequency analysis

Where flood discharge frequency data of high quality is available, it is recommended to make use of it instead of engaging in statistical extreme value estimation. Adopting information on frequency and magnitude from official institutions matches the most frequently applied approach in the scoping study and is in line with the defined evaluation criteria (Arrighi et al. 2018; Schmid-Breton et al. 2018). In cases where frequency data are not available, it is recommended to use an ensemble of the above described statistical extreme value distribution methods (Faghih et al. 2017; Eslamian 2014).

### 3.2.1.4 Flood validation

Simulated floods need to be compared to existing flood data on past events or other flood simulations in the study area with similar conditions. Remotely sensed data of past flood extents or raster and vector data from other flood simulations are commonly used for comparison. Such verification can be used to calibrate and validate the simulated floods. Calibration is done in HEC-RAS by varying Manning's roughness coefficient to better align the simulated flood extents and depths with the verification data. Manning's roughness coefficient is used to represent the friction applied to river flow and is a vital parameter for water flow simulations in open channels.

This validation method is backed by the findings from the scoping study and in line with the defined evaluation criteria (Mahmood et al. 2019). Where high-quality data are not available, it is recommended to apply other available validation means as described in the findings of the scoping study (Komolafe et al. 2019; Zúñiga, Novelo-Casanova 2019).

## 3.2.2 Damage modelling

The damage modelling component of the framework is based on land use data to assess the flood exposure and on stage-damage functions to determine flood vulnerability in relation to flood depth.

### 3.2.2.1 Damage quantification

The damage assessment framework is restricted to direct tangible damages, due to the relative ease to quantify and compare economic damages. This methodological choice facilitates the comparison of results and helps to limit the uncertainties to a minimum. Estimated damages are expressed in the national currency. The estimated damage can be expressed as costs per individual scenario or as AAL. This approach is backed by the findings from the scoping study and in line with the defined evaluation criteria (Lawrence et al. 2019; Foudi et al. 2015; Yu et al. 2013).

Damages are quantified by overlaying the simulated floods with the exposed assets to determine the monetary damages of the flooded assets based on the flood vulnerability of these assets in relation to flood depth. The flood vulnerability determines the fraction of the potential maximum damage under a given flood depth.

#### 3.2.2.2 Damage modelling: Vulnerability

The assessment framework is based on stage-damage functions, which is the standard method to determine the flood vulnerability of exposed assets and to estimate direct economic flood damages. Since developing stage-damage functions requires a lot of data, time and expertise and is subject to significant uncertainties, it is suggested to make use of existing and publicly available stage-damage functions, which have been tested and validated, instead of engaging in the development of such loss functions. This can help to minimise potential sources of error. This methodological choice is backed by the findings from the scoping study and in line with the defined evaluation criteria (Scorzini et al. 2018; Vozinaki et al. 2015). Spatial context compatibility is essential when adopting existing stage-damage functions. In cases where no adequate and validated stage-damage functions exist, an empirical loss function approach is preferred over a synthetical approach due to the presumed higher validity (Komolafe et al. 2018b; Neubert et al. 2016).

#### 3.2.2.3 Damage modelling: Exposure

Since the damage assessment framework is used to quantify direct economic flood damages, only the exposure of physical asset categories is of interest. The use of validated and publicly available land use datasets instead of generating new land use data is favourable to minimise potential sources of error and to save resources. In areas where such land use data are not available or outdated, remote sensing can be used to generate land use data from satellite imagery (Lawrence et al. 2019; Arrighi et al. 2018). A raster-based approach is preferred over vector data. The Universal Transverse Mercator projection (UTM) based on WGS84 geodetic datum is recommended for the use of the framework. Depending on the location of the study area other projections might also be suitable, e.g. Lambert Azimuthal Equal Area projection (LAEA) based on ETRS89 geodetic datum for studies within Central Europe, as in the case study. These methodological choices are backed by the findings from the scoping study and in line with the defined evaluation criteria (Jamali et al. 2018; Komolafe et al. 2018b; Rinćon et al. 2018).

#### 3.2.2.4 Damage validation

While access to flood damage data is often limited, it is essential to validate the accuracy of a damage model against reliable references. Where a complete validation is not possible, a partial validation, based on a sub-sample of the produced data, is recommended. Since available validation means can vary greatly from study to study, a general validation technique is not specified in this damage assessment framework. This approach is backed by the findings from the scoping study and in line with the defined evaluation criteria (Arrighi et al. 2018; Vozinaki et al. 2015).

### 3.2.3 Future projections

Data for future flood extent and depths, land use changes, and changes in the loss functions and potential maximum damage can be projected in the framework to make estimates about future conditions. Potential flood adaptation measures are not primarily considered but can be added to the framework if relevant and applicable. This approach is backed by the findings from the scoping study and in line with the defined evaluation criteria (Brown et al. 2017; Morita 2014; Yu et al. 2013).

When comparing the estimated future flood damages with the damages under today's conditions, it is possible to vary the number of projected variables. One can analyse how flood damages are expected to change when only hazard data is projected compared to the damage estimation based on projected hazard, exposure and vulnerability data.

#### 3.2.3.1 Flood projections

Future precipitation scenario data from GCMs, which have been downscaled to RCMs, can be used in the framework. Based on the downscaled precipitation data, future flood discharges can be estimated for 10-year, 50-year and 100-year floods – either based on regionalised discharge estimation models or runoff-modelling and extreme value statistics. The required precipitation data can be retrieved from publicly available databases.

While many different climate scenarios are applicable in the framework, it is recommended to use the RCPs since these pathways are more recent scenarios than the also often used scenarios encompassed by the SRES. This choice is backed by the findings from the scoping study and in line with the defined evaluation criteria (Komolafe et al. 2018b; Brown et al. 2017).

#### 3.2.3.2 Damage projections

In addition to projections on future flood extent and depths, expected future changes in exposure and vulnerability, respectively in land use and stage-damage as well as potential maximum damages, are considered in the damage assessment framework. Future land use, stage-damage functions and potential maximum damages are estimated based on historical trends and change rates, which can be extrapolated to the future.

Future land use can be simulated based on two land use raster datasets from different years in the past using the freely available GIS-extension *Modules for Land Use Change Simulations* (MOLUSCE) from the Asia Air Survey (AAS) and NextGIS (NextGIS 2013). Future stage-damage functions can be estimated based on past growth rates of the relevant variables of the loss functions.

The projection of these two variables is backed by the findings from the scoping study and in line with the defined evaluation criteria (Neubert et al. 2016; Morita 2014; Yu et al. 2013).

#### 3.2.3.3 Validation of projections

Validation of future flood and damage projections is challenging due to absent empirical verification data. Projected data can be compared to projected data from other studies to achieve some form of accuracy assessment. The high quality of the projected input data is vital. This difficulty to verify projected data is reflected in the findings of the scoping study (Komolafe et al. 2018b; Neubert et al. 2016; Morita 2014).

## 3.3 Strength of knowledge

The concept of SoK is primarily used in risk science to qualitatively label the strength of knowledge, which motivates key assumptions and methodological choices regarding the assignment of probabilities. The use of SoK arises from the reflection that numbers alone often fail to display a complete picture of a situation (Askeland, Flage & Aven 2017; Berner & Flage 2014; Flage & Aven 2009). Pure numbers can suggest a high level of precision and certainty, which might not be supported by underlying methodological assumptions and simplifications.

Following the examples of Askeland, Flage & Aven (2017) and Bani-Mustafa, Zeng, Zio & Vasseur (2019), key variables were defined to reflect on the SoK to the here presented flood damage assessment framework.

| Strength of knowledge estimation | |
|---|---|
| **Flood component** | |
| ***SoK Flood simulation*** | |
| **Confidence in the inputs** | |
| Expert agreement on validity of used precipitation data | S |
| Context specificity of used precipitation data | S |
| Suitability of used flood discharge computation method | S |
| Consideration of all relevant aspects for flood discharge estimation | MS |
| Timeliness of computed flood discharge data | MS |
| **Confidence in the outputs** | |
| Level of detail of modelled floods in terms of spatial resolution | MS |
| Validation agreement of modelled floods with reference data | M |
| **Damage component** | |
| ***SoK Exposure*** | |
| **Confidence in the inputs** | |
| Suitability of applied land use classification method | S |
| Consideration of all relevant aspects for land use classification | MS |
| Timeliness of used land use data | M |
| **Confidence in the outputs** | |
| Level of detail of land use in terms of spatial resolution | MW |
| Land use classification validation agreement with reference data | MS |
| ***SoK Vulnerability*** | |
| **Confidence in the inputs** | |
| Timeliness of considered stage-damage data | MS |
| Context specificity of used loss functions | M |
| Context specificity of used data to estimate potential maximum damages | MS |
| Consideration of all relevant factors for maximum damage estimation | M |
| **Confidence in the outputs** | |
| Level of detail of loss functions in terms of depth-damage sensitivity | MS |
| Validation agreement of applied loss functions with reference data | MS |
| Validation agreement of potential maximum damage with reference data | M |
| **Strength of knowledge legend:** | |
| Strong knowledge | S |
| Moderately-strong knowledge | MS |
| Moderate knowledge | M |
| Moderately-weak knowledge | MW |
| Weak knowledge | W |

*Figure 2: SoK-estimation with arbitrary values (own representation)*

Such an SoK-estimation is recommended to be used to reflect on the strength of knowledge of the most relevant data inputs and outputs of the different framework components and thus to conclude on the confidence underlying the framework assessment results. The SoK is determined on an ordinal scale from *weak* to *strong* for 19 key variables regarding the estimation of the flood hazard, flood exposure and flood vulnerability.

An overview of the SoK-estimation, including the individual components, is given in figure 2. Arbitrary values were applied in the example in figure 2 to elucidate the confidence estimation. To achieve high trustworthiness of an assessment, it is vital to have strong knowledge about the quality and reliability of the individual assessment components. High ordinal values in the SoK-estimation are consequently favourable. The SoK can be assessed for each scenario that is considered in a flood damage assessment using the presented assessment framework. The assignment of the SoK-level, corresponding to the qualitative scale from weak to strong, is based on the confidence of the assessor, justified through reasoning and verification of the modelling results.

The individual variables are deliberately not aggregated to an overall confidence-value due to the ordinal nature of this qualitative confidence estimation. Such an aggregation of the individual variables is left up to decision-makers in flood risk management.

## 4. Case study

In this section, the application of the flood damage assessment framework in the Neckar river basin is described. The main stream of the Neckar river, as well as the surrounding areas located within the floodplains, are subject to the analysis in the case study. Tributaries of the Neckar river and other streams are not considered in the analysis, as they exceed the scope of this research project.

### 4.1 Study area

The Neckar river basin is located in southern Germany, mostly in the federal state of Baden-Wuerttemberg and partly in the federal state of Hesse. The river basin comprises an area of almost 14 000 $km^2$ (LUBW 2020a). The Neckar river, which is 362 km long, arises at 705 m altitude and flows from south to north. At 88 m altitude, it flows out into the Rhine river. Several big municipalities, such as the state capital Stuttgart are located along the Neckar river banks (LUBW 2020a). The Neckar river flows through the biggest economic centre of Germany with great relevance for the German and European industry (WM BW 2020). The Neckar river, including its main tributaries and relevant gauging stations, can be seen in figure 3.

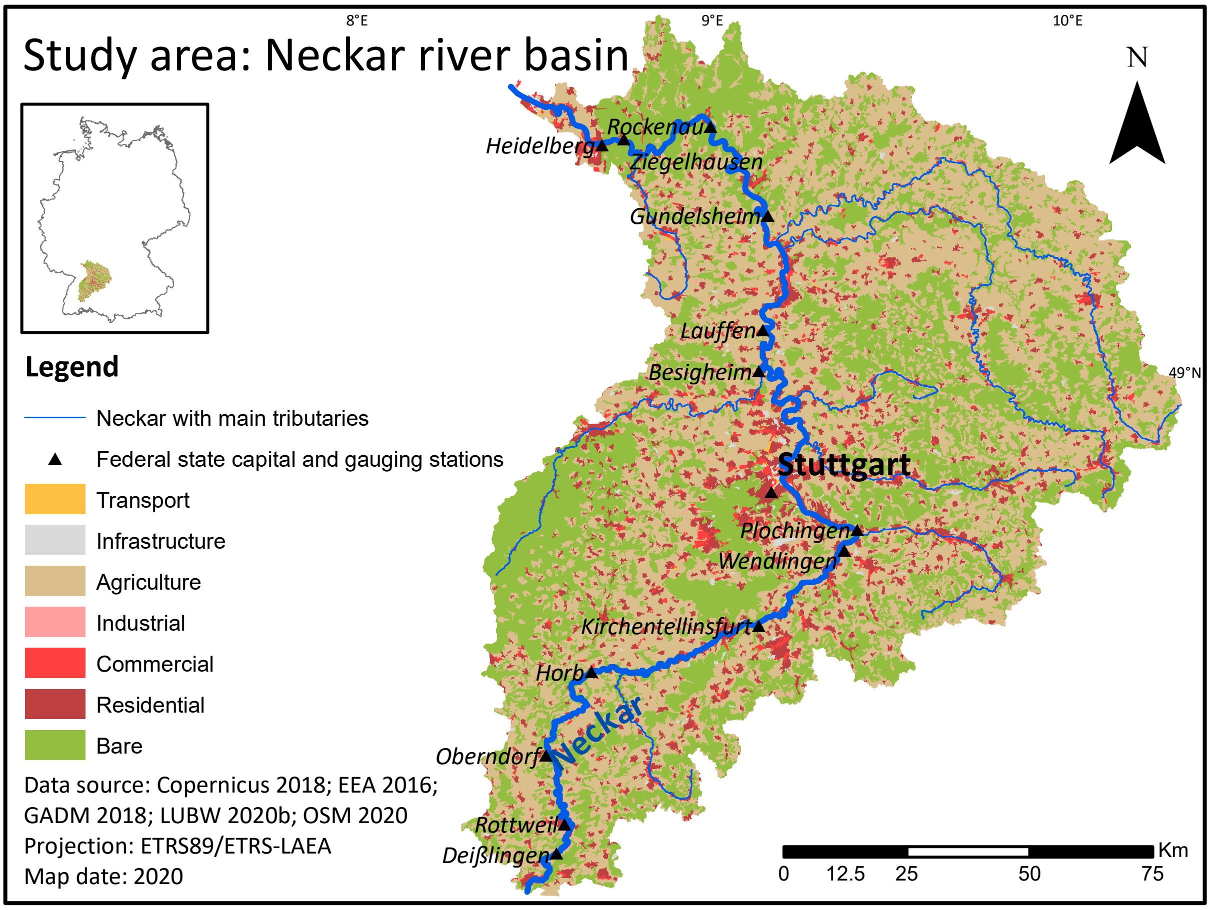


*Figure 3: Study area: Neckar river basin showing today's land use (own representation)*

## 4.2 Materials and methods

In the following, it is described how the individual assessment steps of the flood damage assessment framework were applied and which data were used. Regarding the geospatial analysis, not every single geoprocessing tool and process is named and described in detail. The general workflow of the geospatial analysis is described instead.

### 4.2.1 Flood modelling

In this section, the applied materials and methods for the flood modelling of the Neckar river under today's conditions are described. The output of the flood modelling are vector layers showing flood extents and raster layers showing flood depth per raster cell.

#### 4.2.1.1 Flood simulation software

For the flood simulation, the relevant Neckar river characteristics, namely river centreline, river banks, streamflow, river cross-sections, reach lengths as well as the 3D river geometry were digitised and pre-processed in ArcGIS Desktop 10.5.1 using the HEC-GeoRAS 10.2 GIS-extension. The European digital elevation model EU-DEM v1.1 from the European Union's earth observation programme Copernicus was used to generate the 3D river geometry (Copernicus 2016). The EU-DEM has a spatial resolution of 25 m and is thus the digital elevation surface model with the highest spatial resolution that is freely available for the study area.

The digitised river characteristics were further processed in HEC-RAS 5.0.7, where the reach lengths were completed, and Manning's roughness values were assigned to the different river sections. Estimated flood discharge values were assigned to 15 gauging stations along the river. After the steady flow flood simulation was run in HEC-RAS based on a mixed flow regime, the results were exported to ArcGIS and post-processed and validated using the HEC-GeoRAS GIS-extension.

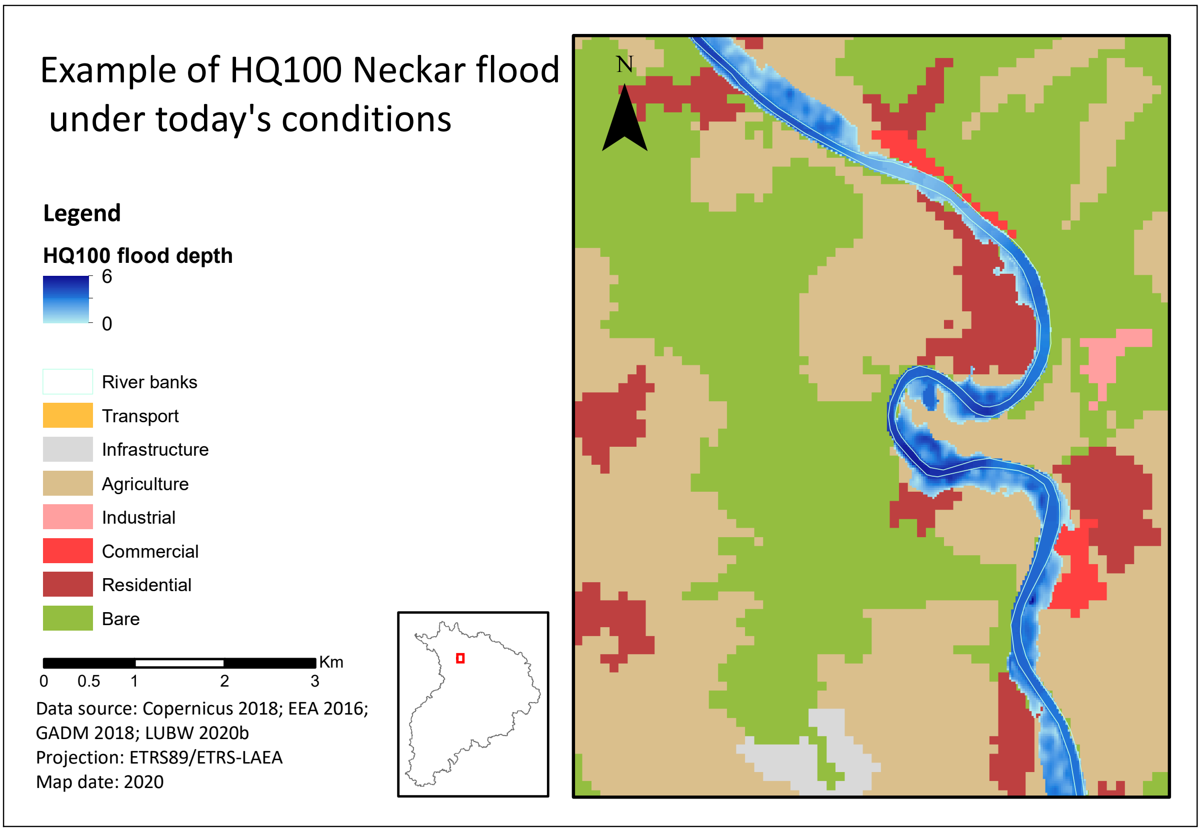


*Figure 4: Example section of the simulated 100-year flood under today's conditions (own representation)*

Figure 4 shows a small section of the simulated 100-year flood, including the extent and inundation depth under today's conditions. The river banks (light blue lines) show the water extent under normal river flow conditions.

### 4.2.1.2 Flood scenarios and frequencies

Validated data on today's flood discharges for a 10-year, 50-year and 100-year flood (HQ10, HQ50 and HQ100) at 14 critical gauging stations along the Neckar river were retrieved from the public database of the regional state office LUBW in Baden-Wuerttemberg. No frequency analysis was required for these values since the discharges were already estimated and validated for the three return periods by the LUBW (LUBW 2020a; LUBW 2015). No discharge data were available for the source of the Neckar river. An additional proxy gauging station at the river's source was introduced and assigned with discharge values 50% smaller than the discharges at the first official gauging station in downstream direction. This had to be done to simulate flood discharges between the river's source and the first official gauging station. In HEC-RAS, the discharge values for the three return periods were assigned to the 15 locations of the gauging stations along the Neckar river. An overview of the gauging stations and the respective flood discharges under today's conditions is given in figure 5.

| | Today's conditions | | |
|---|---|---|---|
| **Gauging station** | **HQ10** | **HQ50** | **HQ100** |
| Dummy station (Neckar's source) | 7 | 11 | 12 |
| Deißlingen | *22* | *32* | *37* |
| Rottweil | *158* | *228* | *259* |
| Oberndorf | *207* | *304* | *348* |
| Horb | *345* | *488* | *550* |
| Kirchentellinsfurt | *500* | *715* | *808* |
| Wendlingen (Weir) | *605* | *861* | *974* |
| Wendlingen (Waste water treatment plant) | *638* | *903* | *1018* |
| Plochingen | *720* | *1016* | *1145* |
| Besigheim | *1196* | *1672* | *1874* |
| Lauffen | *1209* | *1679* | *1877* |
| Gundelsheim | *1695* | *2339* | *2612* |
| Rockenau | *1768* | *2402* | *2665* |
| Ziegelhausen | *1875* | *2529* | *2796* |
| Heidelberg | *1885* | *2542* | *2811* |

*Figure 5: Gauging stations and flood discharges ($m^3/s$) under today's conditions (own representation). Data: LUBW 2020a*

### 4.2.1.3 Flood validation

Validated vector data on flood extents for a 10-year, 50-year and 100-year flood return period are freely available for the Neckar river basin (LUBW 2020b). The HEC-RAS flood simulation was calibrated against the validated flood extents by the LUBW. The best agreement between the simulated flood extents and the reference extents was achieved using n = 0.001 for Manning's roughness coefficient. The simulated floods are perceived to be sufficiently precise, considering that the simulation had to be based on a relatively coarse digital surface model of 25 m spatial resolution, while the simulation of the LUBW was based on a commercial digital surface model with 1 m spatial resolution (UM BWL 2012). While the simulated flood extents are partly smaller than the reference extents, overall, the performed flood simulation tends to slightly overestimate the areal flood extents compared to the reference data by the LUBW. On average, the simulated floodplains are 10% larger than the floodplains provided by the LUBW. For the 100-year flood the extent of the floodplain is overestimated by 1.5%, for the 50-year flood by 7.8% and for the 10-year flood by even 21,8%. It is assumed that the smaller the floodplain, the higher the relevance of the spatial resolution of the DEM. This would explain the relatively high deviation from the reference data in the simulated 10-year floodplain.

Since no better alignment could be achieved and due to the lack of freely available elevation data of higher spatial resolution than 25 m, it was decided to work with the simulated floods applying a roughness coefficient of n = 0.001. Reference flood depth data exists but is not freely available to be used for flood depth validation.

#### 4.2.1.4 Strength of knowledge

Since the flood discharge for today's conditions are readily available and validated by the official agency in the study area, the expert agreement on precipitation data validity as well as the context specificity of this data is perceived to be strong. The same applies to the discharge computation method, since the discharge values are based on a regionalised discharge computation model, which is specifically tailored to the study area (LUBW 2015). The confidence in the consideration of all relevant aspects for the flood discharge estimation is moderately-strong since the available discharge data is restricted to 14 gauging stations, which can only be an approximation of all relevant dynamics in flood discharge along the Neckar river. The timeliness of the data is moderately-strong since most discharge values were last updated in 2013.

Considering the size of the study area, the level of detail of the modelled floods is judged to be moderately strong, even though a higher spatial resolution than 25 m would be favourable. The validation agreement between modelled floods and reference data is moderate.

### 4.2.2 Damage modelling

In this section, the applied materials and methods for the damage modelling of the Neckar river under today's conditions are described.

#### 4.2.2.1 Damage quantification

The flood damages were quantified based on the individual flood scenarios as well as in form of the AAL under today's conditions. The damages are expressed in EURO.

The simulated floods and the used land use dataset were overlaid in GIS to identify the flood affected assets and the corresponding inundation depths. Using the applied stage-damage functions, the flood damages for the flood-affected areas were estimated in relation to flood depth. The flood depths determine the fraction of the potential maximum damage of the inundated assets.

#### 4.2.2.2 Damage modelling: Vulnerability

To determine the flood vulnerability of exposed assets in relation to flood depth, stage-damage functions were adopted from the Joint Research Centre (JRC) of the European Commission (Huizinga, de Moel & Szewczyk 2017). The applied stage-damage functions are based on the following land use categories: agriculture, commerce, industry, infrastructure, residential areas and transport. The loss functions consist of two components: the actual stage-damage functions and the estimated maximum flood damage per land use category. When combined together, the two components can be used to estimate monetary flood damages per flooded $m^2$. The used functions were developed on a European level while the maximum flood damage values are adjusted to German conditions. The stage-damage functions were developed based on historical flood records (Huizinga, de Moel & Szewczyk 2017). The shape of the stage-damage functions can be seen in figure 6. The functions cover flood depths between zero and six meters using nine stage data points (Huizinga, de Moel & Szewczyk 2017).

In the study by Huizinga, de Moel & Szewczyk (2017), the maximum flood damages are based on estimated construction costs, harmonised to the 2010 price level. For agriculture the maximum flood damage refers to loss in output due to destroyed yields, based on the value added per hectare of agriculture area (Huizinga, de Moel & Szewczyk 2017). For commercial, industrial and residential areas the maximum flood damage is based on the GDP per capita, adjusted with non-linear power law functions and scaled to $m^2$ (Huizinga, de Moel & Szewczyk 2017). Germany's maximum damage in infrastructure and transport is based on an estimated

European average damage value, multiplied by Germany's GDP per capita and divided by the average European GDP per capita (Huizinga, de Moel & Szewczyk 2017).

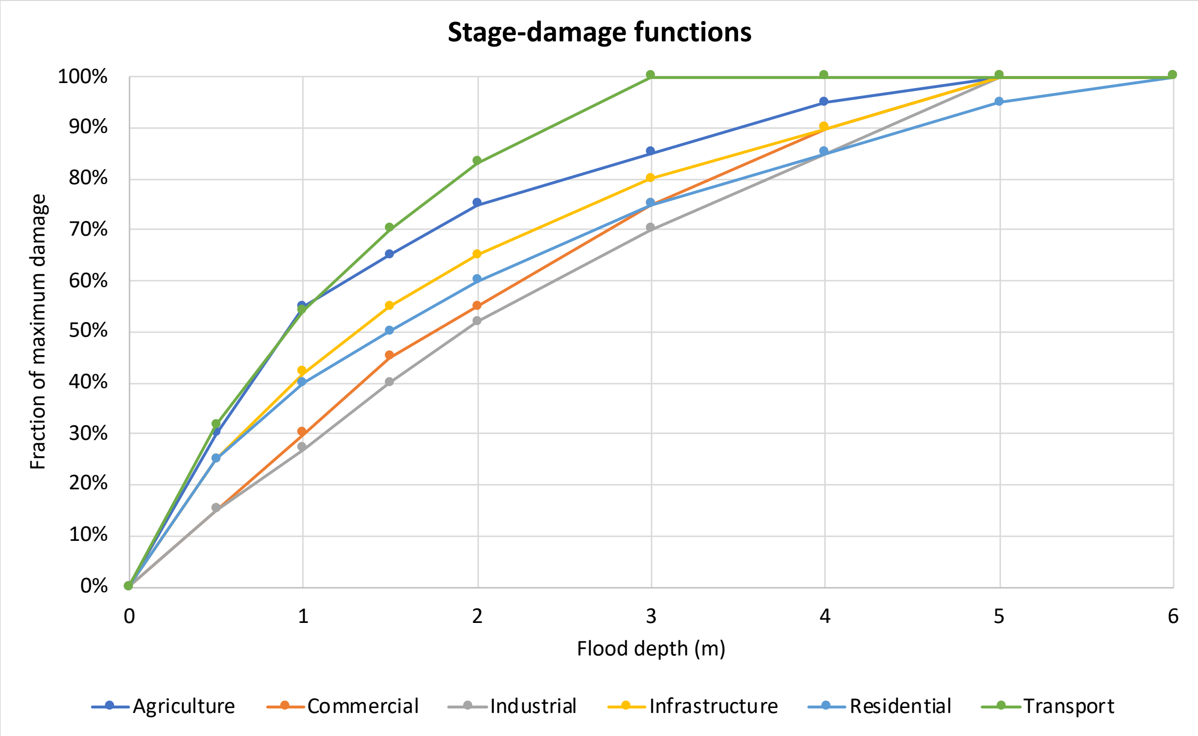


*Figure 6: Stage-damage functions under today's conditions (own representation). Data: Huizinga, de Moel & Szewczyk 2017*

For the case study of this research project, the maximum flood damages were updated to 2018, since the used land use data is also dated to this year (Copernicus 2018). The update is based on changes in the agriculture area in hectare, value added in agriculture forestry and fishing as well as Germany's GDP per capita (World Bank 2020a; World Bank 2020b; World Bank 2020c). Other data inputs and constants in the maximum damage calculation, developed by Huizinga, de Moel & Szewczyk (2017), were left unchanged. For infrastructure and transport, an update of the maximum damage was perceived to be invalid since the maximum damage in these categories is based on a given European average damage value, which could not be reproduced and updated.

| Time | Agriculture | Commercial | Industrial | Residential | Infrastructure 2010 | Transport 2010 |
|---|---|---|---|---|---|---|
| **2018** | 95 € | 213.306 € | 172.146 € | 102.979 € | 15.000 € | 454.375 € |

*Figure 7: Maximum damage per land use raster cell under today's conditions (own representation)*

The updated maximum damage values were scaled to the case study raster cell size of 25 m. An overview of the used maximum damage values per land use under today's conditions can be seen in figure 7.

#### 4.2.2.3 Damage modelling: Exposure

The CORINE land cover 2018 (CLC 2018) from Copernicus was used to identify the flood exposed assets. The raster dataset has a spatial resolution of 100 m and consists of 44 land use classes (Copernicus 2018). The CLC 2018 represents the most recent land use dataset with the highest spatial resolution that covers the entire study area and that is publicly available.

The CLC 2018 land use layer is based on the Lambert Azimuthal Equal Area projection (LAEA) with the ETRS89 geodetic datum. This applies to all raster and vector layers, which were used in the case study. LAEA is the recommend projection for geospatial studies within Europe with the requirement for true area representation (Butler, Schmidt, Spingmeyer & Livni 2007).

The land use classes of the CLC 2018 land use layer were reclassified to match with the land use categories of the stage-damage functions. In addition to the six land use categories referring to the loss functions, a seventh category named "bare" was introduced to account for areas such as forests, meadows or other bare surfaces where no flood damage is expected. The reclassified land use layer can be seen in figure 3.

The spatial resolution of the reclassified land use layer was resampled to a cell size of 25 m. This does not increase the spatial precision of the land use dataset but aligns the cell size of the land use dataset with the other datasets.

#### 4.2.2.4 Damage validation

In the study of Huizinga, de Moel & Szewczyk (2017), the developed loss functions were empirically validated with fairly good results. The loss functions tend to overestimate flood damages slightly. The maximum damage estimation method was also empirically validated (Huizinga, de Moel & Szewczyk 2017).

The applied stage-damage functions are compatible with the CLC land use dataset, which was shown in previous studies (Huizinga, de Moel & Szewczyk 2017). The CLC 2018 land cover was validated by Copernicus (2018) with thematic accuracy higher than 85%.

The modelled flood damages were compared to reported damages of past events in various locations along the Neckar river. Historical damage information was retrieved from damage studies and official documents of the federal state (Korn 2008; IKoNE 2002; Landtag BW 1998). A comprehensive validation of the modelled flood damages was not possible due to lacking availability and timeliness of reference damage data. However, the scale of the modelled flood damages seems reasonable in comparison to the available reference data.

#### 4.2.2.5 Strength of knowledge

The timeliness of the data underlying the computation of the used loss functions is seen to be moderately high since it is dated to 2010 (Huizinga, de Moel & Szewczyk 2017). Since the loss functions are based on the European average, the context specificity of the loss function applied in Germany is based on moderate confidence. The context specificity of the used data to estimate potential maximum depths in the study area is moderately high since country-specific data inputs were available (World Bank 2020a; World Bank 2020b; World Bank 2020c). The confidence in the completeness of the estimation of maximum damages is moderate since not all relevant factors could be updated.

The reliability of the loss functions is characterised by a moderately high level of detail and moderately high validation agreement with the reference data (Huizinga, de Moel & Szewczyk 2017). The updated potential maximum damage data was not validated against reference data; however, the used maximum damage computation method was validated by Huizinga, de Moel & Szewczyk 2017, showing good results. The validity of the updated potential maximum damage is thus believed to be moderate.

The land use classification method used by Copernicus (2018) is perceived to be based on strong knowledge. The completeness of considered aspects of the land use classification is moderately reliable while their timeliness is high.

The reliability of the exposure output data is characterised by a moderately low level of detail due to the limited spatial resolution of the CLC 2018 land use dataset, which is however offset by a moderately high validation agreement of the land use classification with the reference data (Copernicus 2018).

### 4.2.3 Future projections

In this section, it is described how flood damages along the Neckar river were estimated for future states by applying projected input data.

#### 4.2.3.1 Flood projections

Flood extents and depths were projected based on changes in average annual rainfalls in Baden-Wuerttemberg for the period 2036-2065 representing the mid-century and for the period 2070-

2099 representing the end-century. The rainfall projections are based on two representative concentration pathways. The RCP scenario family represents different greenhouse gas concentration pathways for the 21st century. The RCP2.6 pathway characterises a scenario of strong climate action where carbon emissions are cut fast and resolute. In this scenario, it is likely that global warming can be limited to no more than 2 °C global mean surface temperature (GMST) above the pre-industrial average, which is in line with the Paris agreement (IPCC 2014). In the high concentration pathway RCP8.5, emission rates are expected to rise continuously even after 2100. This pathway is often called the Business-as-Usual scenario and refers to the current emission trajectory with only minor climate action, which is likely to result in global warming of more than 4 °C (GMST) (IPCC 2014).

The used precipitation data for RCP2.6 and RCP8.5 are based on estimates by the Climate Service Center Germany (GERICS) using an ensemble of regional climate projections from EURO-CORDEX and ReKliEs-De (GERICS 2018). The projected changes in precipitation, which were used in the case study, can be seen in figure 8.

| Variable | RCP2.6 (2036-2065) | RCP2.6 (2071-2099) | RCP8.5 (2036-2065) | RCP8.5 (2071-2099) |
|---|---|---|---|---|
| **Mean annual precipitation** | 0% | +1% | +5% | +3% |

*Figure 8: Change in mean annual precipitation in Baden-Wuerttemberg (own representation). Data: GERICS 2018*

The precipitation data in figure 8 was used to estimate changes in flood discharges for the three return periods, based on a regionalised flood discharge computation method by the LUBW (2015), which was used by the state agency to generate flood discharges under today's conditions. For the future discharge estimation, mean annual precipitation data was updated according to the RCP scenarios, while all other parameters in the computation model were kept constant.

The estimated future flood discharges can be seen in figure 9. The computation method can be seen in appendix II.

In addition to the used discharge estimation method, the simulated future discharges were compared to the outputs of another discharge estimation method, which is often applied in southern Germany to estimate future discharges. In Baden-Wuerttemberg, today's flood discharge values are commonly multiplied by standard climate-change-factors to account for expected changes in flood discharge until the mid-century. These climate-change-factors are used for flood control and risk-based land use planning in southern Germany (LUBW 2020a; Hennegriff 2010).

| Period: 2036-2065 | RCP2.6 | | | RCP8.5 | | |
|---|---|---|---|---|---|---|
| Gauging station | HQ10 | HQ50 | HQ100 | HQ10 | HQ50 | HQ100 |
| Dummy station (Neckar's source) | 7 | 11 | 12 | 8 | 11 | 13 |
| Deißlingen | *22* | *32* | *37* | *23* | *34* | *39* |
| Rottweil | *158* | *228* | *259* | *167* | *237* | *267* |
| Oberndorf | *207* | *304* | *348* | *219* | *315* | *358* |
| Horb | *345* | *488* | *550* | *365* | *506* | *567* |
| Kirchentellinsfurt | *500* | *715* | *808* | *528* | *742* | *833* |
| Wendlingen (Weir) | *605* | *861* | *974* | *639* | *894* | *1004* |
| Wendlingen (Waste water treatment plant) | *638* | *903* | *1018* | *674* | *937* | *1050* |
| Plochingen | *720* | *1016* | *1145* | *761* | *1054* | *1181* |
| Besigheim | *1196* | *1672* | *1874* | *1263* | *1735* | *1932* |
| Lauffen | *1209* | *1679* | *1877* | *1276* | *1742* | *1935* |
| Gundelsheim | *1695* | *2339* | *2612* | *1790* | *2427* | *2693* |
| Rockenau | *1768* | *2402* | *2665* | *1867* | *2492* | *2747* |
| Ziegelhausen | *1875* | *2529* | *2796* | *1980* | *2624* | *2882* |
| Heidelberg | *1885* | *2542* | *2811* | *1990* | *2638* | *2898* |
| **Period: 2070-2099** | **RCP2.6** | | | **RCP8.5** | | |
| **Gauging station** | **HQ10** | **HQ50** | **HQ100** | **HQ10** | **HQ50** | **HQ100** |
| Dummy station (Neckar's source) | 7 | 11 | 13 | 7 | 11 | 13 |
| Deißlingen | *22* | *33* | *38* | *22* | *33* | *38* |
| Rottweil | *160* | *230* | *261* | *164* | *233* | *264* |
| Oberndorf | *210* | *306* | *350* | *214* | *311* | *354* |
| Horb | *349* | *492* | *553* | *357* | *499* | *560* |
| Kirchentellinsfurt | *505* | *720* | *813* | *516* | *731* | *823* |
| Wendlingen (Weir) | *611* | *868* | *980* | *625* | *881* | *992* |
| Wendlingen (Waste water treatment plant) | *646* | *910* | *1025* | *660* | *924* | *1037* |
| Plochingen | *728* | *1024* | *1153* | *745* | *1039* | *1167* |
| Besigheim | *1210* | *1685* | *1886* | *1236* | *1710* | *1909* |
| Lauffen | *1222* | *1692* | *1888* | *1249* | *1717* | *1912* |
| Gundelsheim | *1714* | *2357* | *2628* | *1752* | *2392* | *2661* |
| Rockenau | *1788* | *2420* | *2681* | *1828* | *2456* | *2714* |
| Ziegelhausen | *1896* | *2548* | *2813* | *1938* | *2586* | *2848* |
| Heidelberg | *1906* | *2561* | *2828* | *1948* | *2600* | *2863* |

*Figure 9: Gauging stations and flood discharges ($m^3/s$) under future conditions (own representation)*

In addition to the estimated discharges based on the RCP pathways, discharges based on the region-specific climate-change-factors for Baden-Wuerttemberg are considered in this case study to broaden the scope of scenarios and to account for immanent uncertainties in the estimated discharges. Estimated discharges based on the climate-change-factors can be seen in figure 10. Future flood extents and depths were simulated in HEC-RAS using the same digitised river characteristics as in the flood simulation under today's conditions.

| Period: until mid-century | Climate-change-factor based | | |
|---|---|---|---|
| **Gauging station** | **HQ10** | **HQ50** | **HQ100** |
| Dummy station (Neckar's source) | 12 | 15 | 16 |
| Deißlingen | 35 | 44 | 47 |
| Rottweil | 254 | 308 | 324 |
| Oberndorf | 332 | 410 | 435 |
| Horb | 553 | 658 | 687 |
| Kirchentellinsfurt | 700 | 880 | 930 |
| Wendlingen (Weir) | 848 | 1059 | 1118 |
| Wendlingen (Waste water treatment plant) | 895 | 1113 | 1174 |
| Plochingen | 1009 | 1249 | 1317 |
| Besigheim | 1677 | 2054 | 2151 |
| Lauffen | 1694 | 2065 | 2158 |
| Gundelsheim | 2371 | 2878 | 3008 |
| Rockenau | 2477 | 2954 | 3065 |
| Ziegelhausen | 2630 | 3118 | 3226 |
| Heidelberg | 2639 | 3131 | 3241 |

*Figure 10: Gauging stations and flood discharges ($m^3/s$) based on the regional climate-change-factors (own representation). Data: LUBW 2015*

### 4.2.3.2 Damage projections

Flood vulnerability was projected by updating the potential maximum damages while the loss functions were left unchanged. Potential maximum damages were updated for agriculture, commercial, industrial and residential. Maximum damage for infrastructure and transport was left unchanged for the same reasons as described in section 4.2.2.2.

Maximum damage values for agriculture, commercial, industrial and residential were estimated for the mid-century (2036-2065) and for the end-century (2070-2099). The projected maximum damage values for these classes are based on the same computation method as described in section 4.2.2.2, using extrapolated inputs for agriculture area in hectare, value added in agriculture, forestry and fishing and the GDP per capita (World Bank 2020a; World Bank 2020b; World Bank 2020c). The data inputs for agriculture area in hectare, value added in agriculture, forestry and fishing and the GDP per capita were estimated for the mid-century and the end-century based on average annual change rates throughout the reference period. For agriculture area in hectare and value added in agriculture, forestry and fishing, the period 1991-2016 was used as reference to estimate the average annual change rate in surface area (0.9900) and the change rate for value added (1.0290). The average annual change rate for GDP per capita (1.0187) is based on values from 1971-2018 as reference period (World Bank 2020a; World Bank 2020b; World Bank 2020c; World Bank 2020d). Estimated future maximum damage values per land use class can be seen in figure 11.

| Time | Agriculture | Commercial | Industrial | Residential | Infrastructure 2010 | Transport 2010 |
|---|---|---|---|---|---|---|
| **2036-2065** | 259 € | 265.739 € | 210.217 € | 130.505 € | 15.000 € | 454.375 € |
| **2070-2099** | 714 € | 332.836 € | 257.960 € | 166.344 € | 15.000 € | 454.375 € |

*Figure 11: Maximum damage per land use raster cell under future conditions (own representation)*

Future flood exposure was estimated using the GIS-extension MOLUSCE to simulate future land use in the study area (NextGIS 2013). Modelled land use changes were based on CORINE land covers from 1990 and 2018 (Copernicus 2018). These two land covers and a slope raster were used to train an artificial neural network in MOLUSCE to identify future land use transition potential in the study area (NextGIS 2013). After the artificial neural network was trained, future land use was modelled in MOLUSCE based on a cellular automata simulation (NextGIS 2013). MOLUSCE was run with both, one and two simulation iterations to generate two land use raster datasets for 2046 and for 2074, representing land use in the study area for the mid-century and the end-century. QGIS 2.18.0 was used for the land use simulation, since the MOLUSCE GIS-extension is not compatible with ArcGIS.

The estimated future land use raster datasets were reclassified and resampled as described in section 4.2.2.3 to be compatible with the applied loss functions.

The simulated surface area changes of the different land use categories can be seen in figure 12. The MOLUSCE-based simulation of future land use suggests and extension of commercial and residential areas at the expense of all other land use categories, which are expected to decline. The simulated decline in transport and infrastructure seems to be unrealistically strong. Transport and infrastructure appear to be generally underrepresented in the CLC-based land use datasets due to the spatial resolution of 100 m, which might be too coarse to adequately capture transport and infrastructure related features of smaller width than 100 m such as roads. The resulting distorted representation of land use features and their future growth is expected to be acceptably low for the estimation of flood damages.

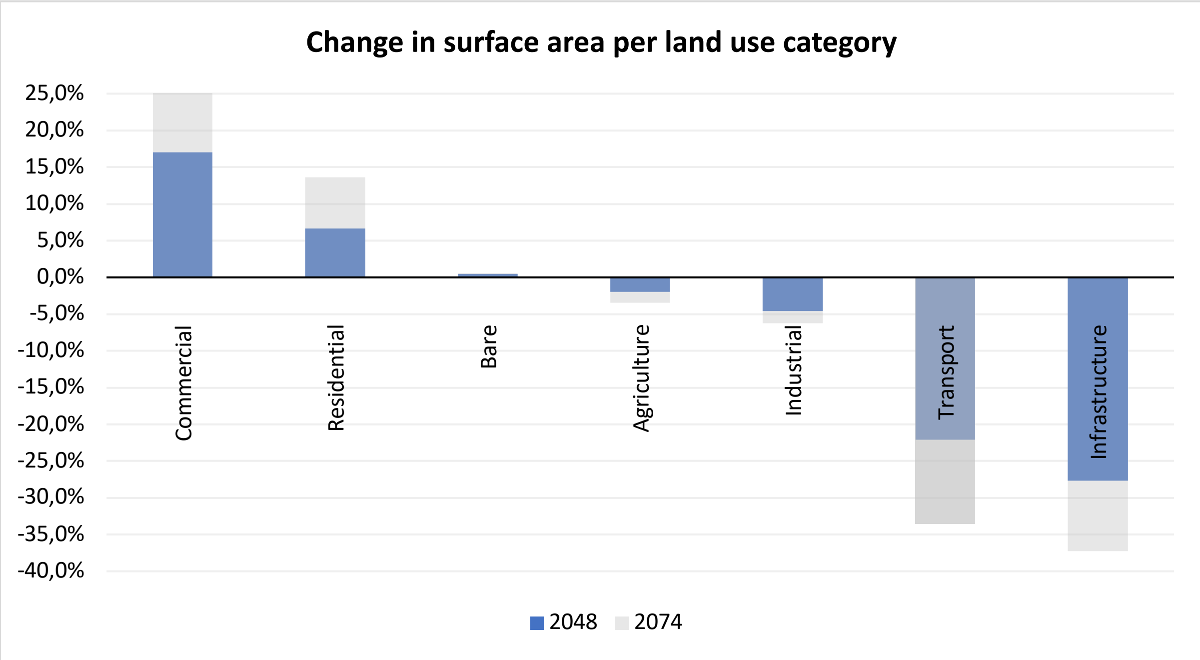


*Figure 12: Change in surface area per land use category for the mid-century and the end-century (own representation)*

### 4.2.3.3 Validation of projections

It was not possible to validate the estimations regarding the future flood hazard characteristics, flood vulnerability or flood exposure due to the nonexistence of reference data. For the mid-century maximum damage, estimated values for GDP per capita were compared to estimates by PWC with good agreement between the estimates (PWC 2017).

The nonexistence of reference data for the simulation validation is a major limiting factor of the case study and gives rise to significant uncertainties. It is estimated that the uncertainties are larger for the end-century than for the mid-century.

### 4.2.3.4 Strength of knowledge

The expert agreement on the validity of the used mean annual precipitation data and their context specificity is moderately-weak for the mid-century and weak for the end-century due to the significant uncertainties in estimating future average annual precipitation. The confidence in the used flood discharge computation methods, as well as the consideration of all relevant aspects, is estimated to be moderately-weak since the method only considers mean annual area precipitation in the study area. Mean annual precipitation is expected to stay relatively stable in the future while there will be significant shifts in rainfall patterns for the winter and summer period (GERICS 2018; KLIWA 2017). Even though the regionalised discharge estimation method is deliberately focused on mean annual precipitation, which is the relevant variable for flood discharge estimations in large river basins such as the Neckar river basin, relevant future rainfall shifts between the seasons cannot be adequately captured by this method. Other input parameters than the mean annual area precipitation were kept constant in the discharge estimation model, which can only deliver a simplified picture of reality. The resulting uncertainty increases over time, which is why the reliability in the consideration of all relevant aspects is weak for the end-century.

The timeliness of the computed flood discharges is high. The level of detail of the modelled floods is similar to the simulation under today's condition and thus moderately-high. Since no validation of future floods was possible, the reliability of the outputs is low.

Regarding the estimation of future flood exposure, the suitability of the applied land use classification method as well as the timeliness of the used data is high. However, the estimation is only based on past development patterns and does not consider land use plans or land use policy documents, which is why the consideration of all relevant aspects for the land use classification is moderately reliable.

Similar to the spatial resolution of the land use under today's conditions, the resolution of the modelled future land use is moderately-low. Validation of the modelled future land use was not possible due to the nonexistence of reference data.

Regarding the estimation of future flood vulnerability, the confidence is high regarding the timeliness of the used data. The used loss functions, based on European conditions, suggest moderate context specificity of these functions for estimating future flood damages in Germany. The estimated maximum damage instead is based on country-specific input data, which is why the context specificity of the future maximum damage is moderately-high. Since it was not possible to update all relevant factors for estimating maximum damages, the completeness of these relevant factors is based on moderately-weak knowledge.

The reliability of the vulnerability estimation outputs is supported by a moderately-high level of detail of the loss functions in terms of depth-damage sensitivity. It was not possible to validate the loss functions and the potential maximum damage for future states due to lacking validation data. Thus, the underlying knowledge for the loss functions is weak. The knowledge regarding the potential maximum damages is moderately-weak for the mid-century, since at least some inputs could be validated. For the end-century, the potential maximum damages are based on weak knowledge.

The SoK-estimations for the three considered periods show that the confidence in the assessment inputs and outputs decreases as the damage projections go further into the future. While the flood damage estimations under today's conditions are mostly based on moderate to strong knowledge, the confidence underlying the damage projections for the mid-century and the end-century is rather moderate to weak. The decrease in confidence in the future damage projections is especially significant for the flood simulation and the flood vulnerability estimation. An overview of all SoK-estimation values under today's and future conditions can be seen in appendix III-V.

## 4.3 Study results

The outputs from the flood simulation as well as the exposure and vulnerability modelling were combined and processed in ArcGIS ModelBuilder to estimate flood damages along the Neckar river under today's conditions as well as for different future scenarios for the periods 2036-2065 representing the mid-century, and for 2071-2099 representing the end-century. The estimated damages under today's flood, land use and stage-damage conditions can be seen in figure 13.

| Scenario | HQ10 | HQ50 | HQ100 | AAL |
|---|---|---|---|---|
| **Estimated flood damages** | 682.673.075 € | 905.063.218 € | 955.921.365 € | 95.927.786 € |

*Figure 13: Estimated flood damages along the Neckar river under today's conditions (own representation)*

Most significant damages occur in commercial and residential areas along the Neckar river, as shown in figure 14. Agriculture and industrial areas barely account for substantial flood damages compared to the other four land use categories.

All simulated scenarios suggest an increase in flood damages along the Neckar river throughout the 21$^{st}$ century compared to today's damage levels.

To analyse the impact of climate change on changes in average annual flood damages in the study area, it was distinguished between fully dynamic and partly constant scenarios. The dynamic scenarios are based on expected changes in flood characteristics, flood exposure and in flood vulnerability to portray a complete and realistic picture of potential future flood damages. In the constant scenarios, flood exposure and flood vulnerability were kept unchanged to solely focus on the impact of changing flood characteristics on potential future flood damages.

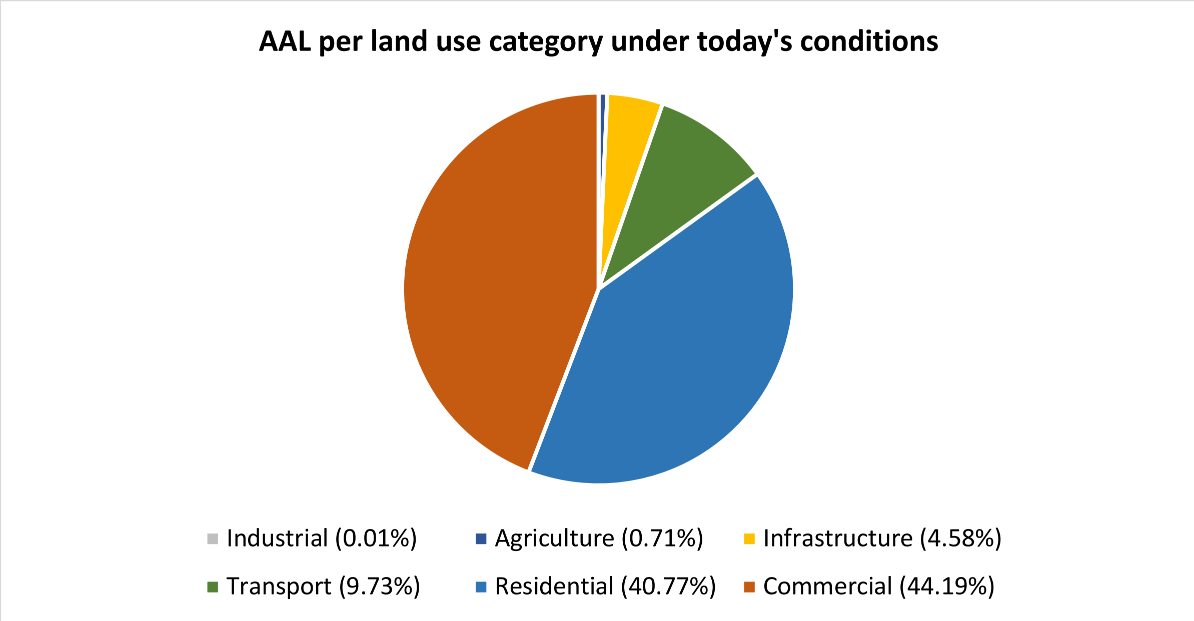


*Figure 14: AAL per land use category under today's conditions in percentage of total AAL (own representation)*

The RCP-based fully dynamic scenarios suggest an increase in AAL by 33% to 41% until the mid-century and 80% to 83% damage increase until the end of the 21st century. The expected change in average annual flood damages throughout the 21st century can be seen in figure 15.

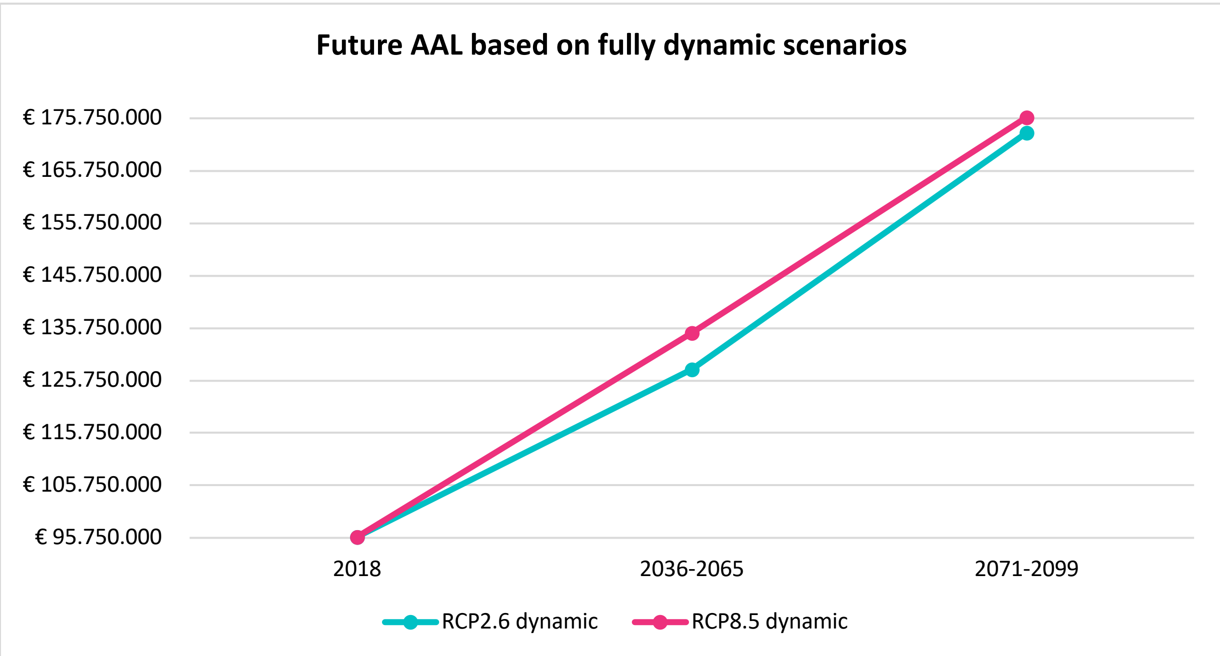


*Figure 15: Future AAL for RCP2.6 and RCP8.5 based on fully dynamic scenarios (own representation)*

While climate-related changes in the flood hazard matter for the level of potential future damages in the study area, their impact is significantly lower than the impact of changes in flood exposure and flood vulnerability. This can be seen in figure 16, where only flood characteristics were projected to the future while flood exposure and flood vulnerability were kept constant.

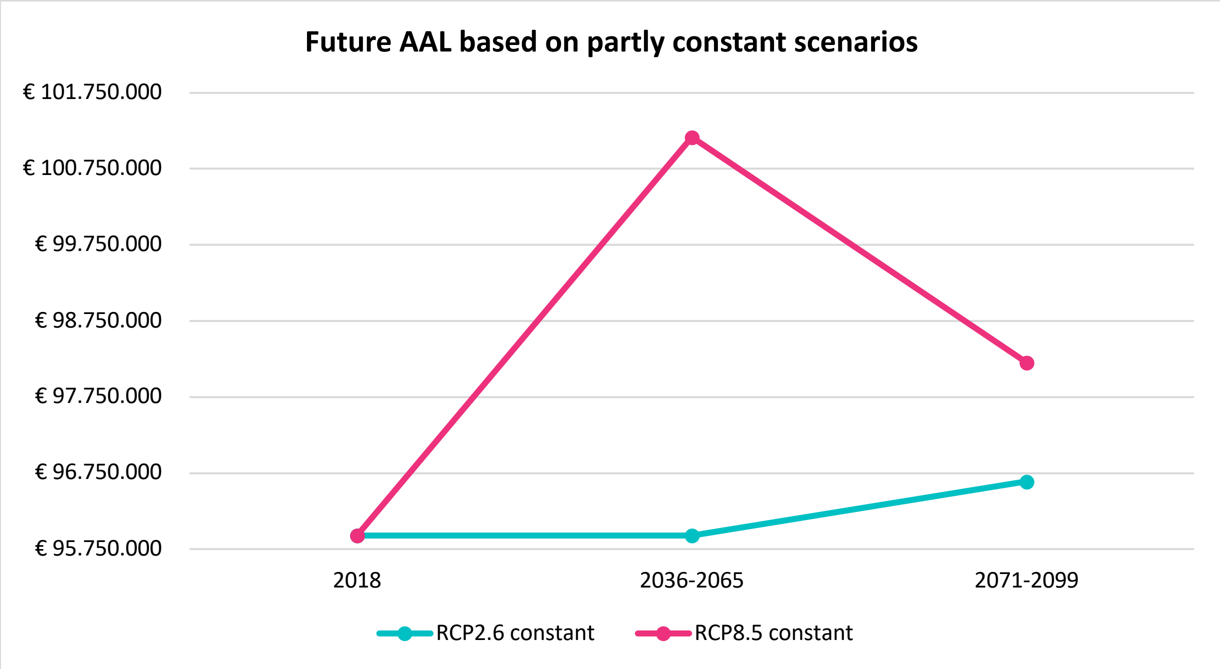


*Figure 16: Future AAL for RCP2.6 and RCP8.5 based on partly constant scenarios (own representation)*

The RCP-based partly constant scenarios suggest an increase in AAL by 0% to 5% until the mid-century and 1% to 2% damage increase until the end of the 21st century. While the increase in flood damages is expected to be larger for the Business-as-Usual scenario (RCP8.5) than for the low emission scenario (RCP2.6), the differences between the scenarios are small, and the overall contribution of climate change to the average annual flood damages in the study area is merely significant.

In contrast to the RCP-based scenarios, the scenarios based on the climate-change-factor suggest a significant impact of climate change on future flood damages in the study area, as shown in figure 17.

For both, the partly constant and the fully dynamic scenarios, the projected average annual flood damage increase based on the climate-change-factor is significantly larger than the estimated increases based on the RCP pathways. The constant scenario under RCP2.6 is not shown in the figure, since no changes in flood damages are expected under this scenario.

The discrepancy in the projections between the RCPs and the climate-change-factor reveals the uncertainties underlying the projections of future flood frequency and magnitude. Limitations and uncertainties of the presented results are discussed in the subsequent section.

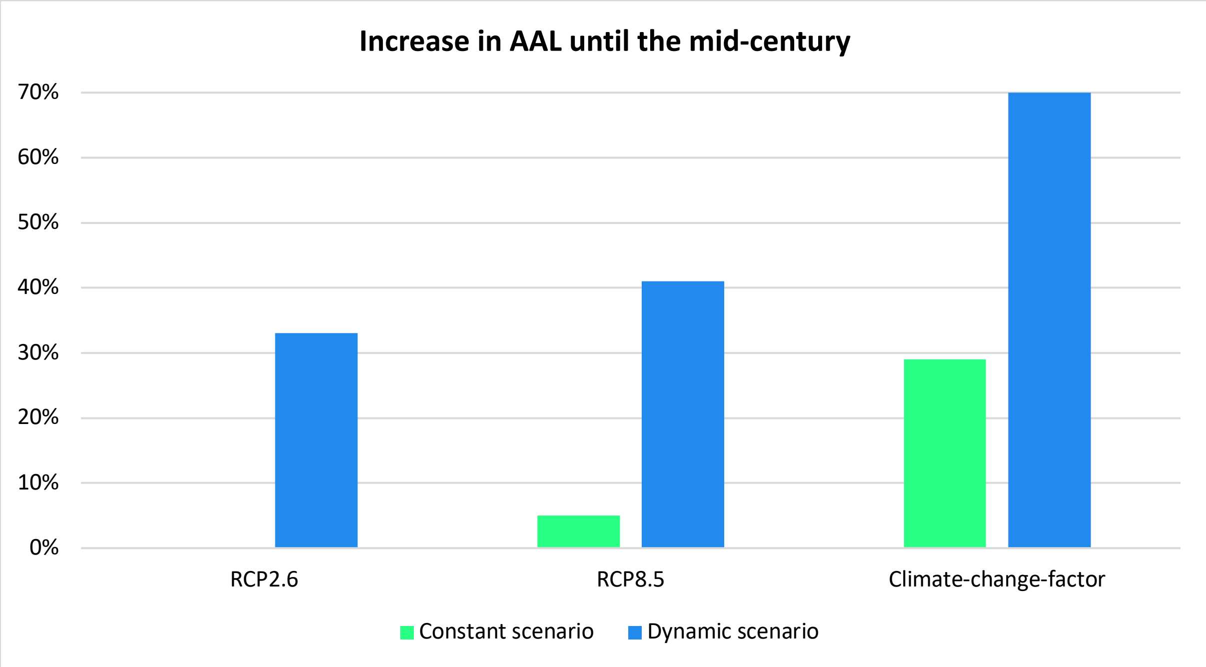


*Figure 17: Increase in AAL until the mid-century based on different scenarios (own representation)*

## 5. Discussion

The results of the case study, based on the developed flood damage assessment framework, indicate a significant increase in average annual flood damages along the Neckar river throughout the 21st century. The projected increase in damages primarily arise from changes in flood exposure and flood vulnerability. The expansion of residential and commercial sites in the study area throughout the coming decades will put more assets of high damage potential at risk, while the potential maximum damages of the exposed asset categories continue to rise due to the simulated increases in construction costs and property values.

The increase in flood damages is also linked to climate change-related shifts in precipitation patterns, leading to higher flood discharge volumes. However, the impact of climate change on rising flood damages in the study area seems to be less significant than the impact of changing flood exposure and flood vulnerability.

The results of the case study delineate future flood damages along the Neckar river for potential climate scenarios, using and extrapolated development trajectory for flood exposure and flood vulnerability based on perceived past changes in these damage components. The results of the case study elucidate the dynamic interplay of the flood hazard, flood exposure and flood vulnerability in the study area, which can inform and facilitate risk-based land use planning and climate change adaptation in the wake of global warming.

The perceived changes in flood damage in the study area throughout the coming decades is not generalisable to other study areas since the changes in the flood component as well as changes in flood exposure and flood vulnerability are highly context-specific. However, the developed flood damage assessment framework is adoptable to other study areas to analyse long-term changes in flood damage potential. The comprehensive use of Europe-wide datasets regarding vulnerability, exposure and elevation makes the case study results easily comparable to potential studies in other European river basins using the same assessment framework and data.

For the performed case study, the impact of climate change on flood conditions and flood damages in the study area remains uncertain, which is shown by the ambiguous prospects of the used RCP pathways compared to the applied climate-change-factor. This ambiguity is reflected in similar studies on future flood conditions and flood damages in this study area. Most reviewed studies indicate a climate-related increase in flood frequency and magnitude in the future and thus rising flood damages along the Neckar river (KLIWA 2018; LUBW 2015; KLIWA 2005). Conversely, some studies prognose a decrease in flood levels for the Neckar river due to climate change (Huang, Krysanova & Hattermann 2015; Huang, Hattermann, Krysanova & Bronstert 2013).

The ambiguity derives from substantial differences in the available datasets on estimated future rainfall patterns in the study area and uncertainty regarding the suitability of today's precipitation-based discharge estimation methods for the assessment of future floods (GERICS 2018; PIK 2020; Eslamian 2014).

The results of the case study are primarily limited by the unclear validity of the used precipitation data and their meaningful transformation into future flood discharges. The adequacy of the used regionalised flood discharge estimation method is potentially limited for the estimation of future flood discharges since the method is based on average annual area precipitation. The focus on average annual precipitation could result in a distorted picture of future flood discharges, since climate change is expected to cause significant changes in the precipitation extremes. This means that precipitation amounts will substantially shift between the seasons, with less precipitation during summertime and significantly more precipitation during the winter (KLIWA 2016; LUBW 2013). Such changes in the extremes are not fully accounted for when focusing on the average annual precipitation, which might be relatively stable, while the precipitation distribution between the seasons shifts considerably.

Another limiting factor is the simple use of historical data to estimate future land use changes and developments in the potential maximum flood damage. The applied extrapolation techniques for flood exposure and flood vulnerability are solely informed by statistical trends from the past without considering alternative development scenarios based on policy plans and other real-world alternating factors or limits. In this sense, the projected information on flood exposure and flood vulnerability is only a description of what these damage components will look like if the current development trend is continued throughout the 21st century.

The projected developments are further simplified since some parameters were kept constant, while others were updated. This applies to the stage-damage functions, which were not projected, as well as for several constants, and parameters in the discharge estimation method and the potential maximum damage estimation, which could not be projected or reproduced.

Parameter interdependencies between future flood conditions, flood exposure and flood vulnerability were not taken into account. Changes in agriculture area were modelled separately for the land use datasets (flood exposure) and for the potential maximum damage in agriculture (flood vulnerability). Changes in urban and bare areas were considered for the extrapolation of future land use (flood exposure) but kept constant in the regionalised flood discharge estimation model (flood hazard). These parameter interdependencies were disregarded in the parameter extrapolation since no adequate scaling and transformation method was found to meaningful link parameters with each other beyond one damage components.

The described limitations of the case study are reflected in the confidence values of the previously described SoK-estimation, which show decreasing confidence in the simulated flood damages as the projections go further into the future.

The case study has shown how it is possible to estimate future changes in flood damage levels based on the developed flood damage assessment framework. The application of the framework and the methods for modelling the individual framework components can be refined in future studies to increase the level of detail and consistency between the assessment components.

## 6. Conclusion

The developed flood damage assessment framework, informed by the results of the performed scoping study on GIS-based flood damage estimation methods, can be used by practitioners in flood risk management to estimate flood damages for different future scenarios and to compare the results with today’s flood damage levels. In this sense, the developed framework gives an answer to the first research question of this thesis on how to assess future changes in average annual fluvial flood damages and how to compare them to today's average annual flood damages.

The developed framework provides the overarching guidance and structure, which is required when performing future-oriented flood damage assessments. Depending on the purpose and the context of an assessment project, different projection and simulation methods might be used in combination with the developed framework. In the sections on the scoping study and the framework description, it is described which methods exist, and which might be most suitable in different contexts. The performed case study has exemplified how the use of the flood damage assessment framework might look like in practice.

The second research question regarding the expected changes in future flood damages in the Neckar river basin is answered through the case study. The results of the case study suggest a significant increase in average annual flood damages along the Neckar river throughout the 21$^{st}$ century. Depending on the underlying scenario, the simulated increase ranges between 33% and 70% for the mid-century and between 80% and 83% for the end-century. The increase in AAL is primarily caused by changes in flood exposure and flood vulnerability and to a smaller extent due to climate-change-related increases in flood frequency and magnitude.

The estimated flood damages under today's conditions are mostly based on moderate to strong knowledge and in good agreement with the scarcely available reference data. The estimated future flood damages are based on less strong knowledge due to lacking validation data and uncertainties regarding the choice of input data and most suitable data processing methods.

Some recommendations are pointed out in the following on how to increase the SoK underlying damage projections in potential future studies using the developed assessment framework.

Statistical extreme value distribution in combination with rainfall runoff-modelling based on daily rainfall projections might be used to estimate future flood discharges instead of using a regionalised flood discharge estimation method based on average annual precipitation data. This could lead to a better integration of future rainfall shifts between the seasons, which is interesting in the context of climate change.

Regarding the flood exposure and flood vulnerability, existing information on land use and policy planning, as well as foreseeable economic developments, could be integrated into the estimation of future land use and stage-damage. This would enable different scenario projections for flood exposure and vulnerability, which go beyond statistical trend extrapolations.

A higher spatial resolution of the elevation and land use data could improve the level of detail of all assessment components and thus, the accuracy of the assessment results. The level of detail could also be increased by considering more influencing factors such as existing flood protection measures as well as future flood adaptation plans.

More comprehensive reference data for the validation of the assessment results are favourable, even though validations of projections that go far into the future will remain challenging.

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## 8. Appendix

### I: Scopus search string

*(TITLE-ABS-KEY("flood*" W/2 ("damage" OR "loss" OR "impact")) AND TITLE-ABS-KEY("assess*" OR "analy*" OR "model*" OR "estimat*" OR "project*" OR “simulat*”) AND TITLE-ABS-KEY("gis") AND TITLE-ABS-KEY("basin" OR "catchment" OR "watershed" OR "drainage")) AND (LIMIT-TO(PUBYEAR, 2020) OR LIMIT-TO(PUBYEAR, 2019) OR LIMIT-TO(PUBYEAR, 2018) OR LIMIT-TO(PUBYEAR, 2017) OR LIMIT-TO(PUBYEAR, 2016) OR LIMIT-TO(PUBYEAR, 2015) OR LIMIT-TO(PUBYEAR, 2014) OR LIMIT-TO(PUBYEAR, 2013))*

## II: Regionalised flood discharge computation method by the LUBW

Regionalised flood discharge computation method:

$$\ln(Y) = C0 + C1 \cdot \ln(A_{Eo}) + C2 \cdot \ln(S + 1) + C3 \cdot \ln(W + 1) + C4 \cdot \ln(I_g) + C5 \cdot \ln(L) + C6 \cdot \ln(L_C) + C7 \cdot \ln(hN_G) + C8 \cdot \ln(LF)$$

$Y =$ MHq

$Y_T =$ $Hq_T$ / MHq

$HQ_T =$ $Y_T \cdot MHq \cdot A_{Eo} = Y_T \cdot MHQ$

Parameters, coefficients and constants:

$A_{Eo}$: Area of the river basin [$km^2$]

C0-C8: Coefficients

$hN_G$: Average annual area precipitation [mm] (projected in the case study)

$Hq_T$: Dispense of T-annual maximum discharge $HQ_T$ ($m^3$ / s / $km^2$)

$I_g$: Slope [%]

L: Flow length along the main stream from the water shed to the mouth [km]

$L_C$: Flow length along the main stream from the area focus to the mouth [km]

LF: Region specific landscape factor

MHq: Dispense of the mean annual maximum discharge MHQ ($m^3$ / s / $km^2$)

S: Development share [%] (kept constant in the case study)

W: Share of woods [%] (kept constant in the case study)

Y, $Y_T$: Dependent variable

Formulas and data for the different parameters by the LUBW (2020a; 2015)

| | C0 | C1 (AEo) | C2 (S+1) | C3 (W+1) | C4 (Ig) | C5 (L) | C6 (LC) | C7 (hNG) | C8 (LF) | R2 |
|---|---|---|---|---|---|---|---|---|---|---|
| MHq | -16,7017 | -0,2496 | 0,0582 | -0,271 | -0,0702 | 0,1573 | -0,0857 | 1,46 | 1,6066 | 0,996 |
| Y10 | 2,4613 | 0,027 | -0,0078 | 0,0929 | 0,0668 | -0,0748 | 0,0418 | -0,3395 | 0,0279 | 0,998 |
| Y50 | 4,9449 | 0,0513 | -0,0175 | 0,1792 | 0,1646 | -0,1036 | 0,0518 | -0,7038 | 0,0527 | 0,998 |
| Y100 | 5,8368 | 0,0596 | -0,0205 | 0,2078 | 0,2029 | -0,1077 | 0,0509 | -0,8344 | 0,0607 | 0,998 |

*Coefficients for the flood discharge estimation. Data: LUBW (2015)*

**III: SoK-estimation under today's conditions**

| Strength of knowledge estimation | |
|---|---|
| **Flood component** | |
| ***SoK Flood simulation*** | |
| **Confidence in the inputs** | |
| Expert agreement on validity of used precipitation data | S |
| Context specificity of used precipitation data | S |
| Suitability of used flood discharge computation method | S |
| Consideration of all relevant aspects for flood discharge estimation | MS |
| Timeliness of computed flood discharge data | MS |
| **Confidence in the outputs** | |
| Level of detail of modelled floods in terms of spatial resolution | MS |
| Validation agreement of modelled floods with reference data | M |
| **Damage component** | |
| ***SoK Exposure*** | |
| **Confidence in the inputs** | |
| Suitability of applied land use classification method | S |
| Consideration of all relevant aspects for land use classification | MS |
| Timeliness of used land use data | M |
| **Confidence in the outputs** | |
| Level of detail of land use in terms of spatial resolution | MW |
| Land use classification validation agreement with reference data | MS |
| ***SoK Vulnerability*** | |
| **Confidence in the inputs** | |
| Timeliness of considered stage-damage data | MS |
| Context specificity of used loss functions | M |
| Context specificity of used data to estimate potential maximum damages | MS |
| Consideration of all relevant factors for maximum damage estimation | M |
| **Confidence in the outputs** | |
| Level of detail of loss functions in terms of depth-damage sensitivity | MS |
| Validation agreement of applied loss functions with reference data | MS |
| Validation agreement of potential maximum damage with reference data | M |
| **Strength of knowledge legend:** | |
| Strong knowledge | S |
| Moderately-strong knowledge | MS |
| Moderate knowledge | M |
| Moderately-weak knowledge | MW |
| Weak knowledge | W |

**IV: SoK-estimation for the mid-century conditions**

| Strength of knowledge estimation | |
|---|---|
| **Flood component** | |
| ***SoK Flood simulation*** | |
| **Confidence in the inputs** | |
| Expert agreement on validity of used precipitation data | MW |
| Context specificity of used precipitation data | MW |
| Suitability of used flood discharge computation method | MW |
| Consideration of all relevant aspects for flood discharge estimation | MW |
| Timeliness of computed flood discharge data | S |
| **Confidence in the outputs** | |
| Level of detail of modelled floods in terms of spatial resolution | MS |
| Validation agreement of modelled floods with reference data | W |
| **Damage component** | |
| ***SoK Exposure*** | |
| **Confidence in the inputs** | |
| Suitability of applied land use classification method | S |
| Consideration of all relevant aspects for land use classification | M |
| Timeliness of used land use data | S |
| **Confidence in the outputs** | |
| Level of detail of land use in terms of spatial resolution | MW |
| Land use classification validation agreement with reference data | W |
| ***SoK Vulnerability*** | |
| **Confidence in the inputs** | |
| Timeliness of considered stage-damage data | S |
| Context specificity of used loss functions | M |
| Context specificity of used data to estimate potential maximum damages | MS |
| Consideration of all relevant factors for maximum damage estimation | MW |
| **Confidence in the outputs** | |
| Level of detail of loss functions in terms of depth-damage sensitivity | MS |
| Validation agreement of applied loss functions with reference data | MW |
| Validation agreement of potential maximum damage with reference data | W |
| **Strength of knowledge legend:** | |
| Strong knowledge | S |
| Moderately-strong knowledge | MS |
| Moderate knowledge | M |
| Moderately-weak knowledge | MW |
| Weak knowledge | W |

**V: SoK-estimation for the end-century conditions**

| Strength of knowledge estimation | |
|---|---|
| **Flood component** | |
| ***SoK Flood simulation*** | |
| **Confidence in the inputs** | |
| Expert agreement on validity of used precipitation data | W |
| Context specificity of used precipitation data | W |
| Suitability of used flood discharge computation method | MW |
| Consideration of all relevant aspects for flood discharge estimation | W |
| Timeliness of computed flood discharge data | S |
| **Confidence in the outputs** | |
| Level of detail of modelled floods in terms of spatial resolution | MS |
| Validation agreement of modelled floods with reference data | W |
| **Damage component** | |
| ***SoK Exposure*** | |
| **Confidence in the inputs** | |
| Suitability of applied land use classification method | S |
| Consideration of all relevant aspects for land use classification | M |
| Timeliness of used land use data | S |
| **Confidence in the outputs** | |
| Level of detail of land use in terms of spatial resolution | MW |
| Land use classification validation agreement with reference data | W |
| ***SoK Vulnerability*** | |
| **Confidence in the inputs** | |
| Timeliness of considered stage-damage data | S |
| Context specificity of used loss functions | M |
| Context specificity of used data to estimate potential maximum damages | MS |
| Consideration of all relevant factors for maximum damage estimation | MW |
| **Confidence in the outputs** | |
| Level of detail of loss functions in terms of depth-damage sensitivity | MS |
| Validation agreement of applied loss functions with reference data | W |
| Validation agreement of potential maximum damage with reference data | W |
| **Strength of knowledge legend:** | |
| Strong knowledge | S |
| Moderately-strong knowledge | MS |
| Moderate knowledge | M |
| Moderately-weak knowledge | MW |
| Weak knowledge | W |