



A GIS-based approach to compare economic damages of fluvial flooding in the Neckar River basin under current conditions and future scenarios

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Abstract

Fluvial floods can cause significant damages and are expected to increase in magnitude and frequency throughout the twenty-first century due to global warming. Alongside hazard characteristics, damage potentials depend on exposure and vulnerability, which are changing in the wake of socio-economic developments. In the context of continuously evolving damage-causing factors, assessments of future changes in flood damage potentials are increasingly asked for by decision-makers in flood risk management. This study addresses this need by (a) providing a systematic review of contemporary assessment approaches to quantitatively compare direct economic losses from fluvial flooding under current and future conditions and (b) combining the reviewed approaches to an applicable methodology which is used in a case study to quantify changing flood damage potentials in the Neckar River basin in southern Germany. Therefore, a scoping study of contemporary flood damage assessment approaches supported by geographic information systems (GIS) is performed. The subsequent case study of the Neckar River prognoses a significant increase in average annual flood damages in the study area throughout the twenty-first century. The case study produces valid results with regards to current precipitation data, whereas the absence of verification data makes the validation of projected scenarios more difficult. To account for uncertainties surrounding these future projections, a nascent qualitative confidence estimation is introduced to reflect on the strength of knowledge underlying the used flood damage assessment methodology.

Keywords Climate change · Flood damage · Fluvial flood · GIS · Neckar River · Strength of knowledge

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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 (Huber and Gullede 2011; Zlatanova et al. 2013; Munich RE 2017; IPCC 2019). While climate change is primarily affecting flood hazard characteristics, socio-economic developments can impact the level of flood exposure and vulnerability, which are also directly linked to the flood damage potential (Taubenböck et al. 2011; Simonovic 2012). In the wake of changing damage determinants, there is a growing demand for geospatial flood damage assessments, which may, for example, support flood risk maps in accordance with the European Floods Directive 2007/60/EC (European Parliament 2007). 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 (Hallegatte 2009; Neubert et al. 2016). Such damage assessments are especially important for economic hotspots with high population density, such as the Neckar River basin in southern Germany. The Neckar River flows through the biggest economic center of Germany and is of great relevance for the German and European industry (WMBWL 2012).

To date, few damage assessments combine current and future scenarios to clarify the need for further adaptation measures to maintain or reduce the current level of flood risk in view of changing flood conditions induced by climate change. Further, while weaknesses, uncertainties, and issues of incompleteness and data validation are partly mentioned in existing damage assessment studies, there are seldom explicit reflections on the incompleteness of flood damage assessments, underlying uncertainties, and lack of knowledge (Hammond et al. 2015).

This article addresses the existing need for adequate flood damage potential assessments in economic hotspot regions considering dynamic damage-causing factors by (a) providing a systematic review of contemporary assessment and validation approaches to quantitatively compare direct economic losses from fluvial flooding under current and future conditions, and (b) combining the reviewed assessment approaches and validation techniques to an applicable methodology which is used to quantify changing flood damage potentials in the Neckar River basin in southern Germany.

The following research questions underpin this study:

1. Which elements need to be considered in contemporary flood damage assessment approaches to (a) model and validate hazards as well as damages, and (b) support comparisons of direct economic damages under current annual flood levels and projected scenarios?
2. How will the average annual direct economic flood damages in the Neckar River basin change throughout the twenty-first century based on various future scenarios?

The article is structured according to three main components. Primarily it renders account of a scoping study performed to review and extract core elements of contemporary methodologies to assess fluvial flood damages with the support of geographic information systems (GIS). The outputs of the scoping study were used to develop an assessment methodology that would meet the criteria as set by research questions 1a and 1b. The resulting methodology is presented in Sect. 3 along with a suggested nascent approach for reflecting on the strength of knowledge underpinning the flood damage potential assessment performed in Sect. 4. Section 4 addresses the second research

question by applying the developed methodology in a case study of the Neckar River basin. The results of this case study are presented and discussed in Sect. 5 and Sect. 6.

2 Performance and outputs of the scoping study

A scoping study was performed to evaluate existing approaches for GIS-based flood damage assessments. The knowledge gained formed the basis for developing an assessment methodology applicable to quantitatively estimate direct economic damages along the Neckar River due to potential fluvial flooding under various future scenarios. Elsevier's abstract and citation database *Scopus* was consulted for the scoping study (Elsevier 2020). In January 2020, when the scoping study was performed, Scopus delivered 165 preliminary hits. These articles were delimited in accordance with a set of criteria that the foreseen assessment methodology for the Neckar River had to fulfill, leaving 48 relevant articles as basis for the study. The applied search string is provided in Appendix 1, while the criteria for the methodology development and article selection are presented in Table 1.

The scoping study revealed that almost all articles focused on GIS-based flood damage assessment comprised two main components: flood modeling (hazard assessment) and damage modeling (exposure and vulnerability assessment). In combination, these two assessment components allow the estimation of expected damages under given flood scenarios (Kobayashi et al. 2016; Komolafe et al. 2019).

Table 1 Article selection criteria for the review of contemporary assessment approaches

Criteria	Rationale
The assessment methodology should be based on GIS software	GIS is capable and efficient in processing substantial amounts of spatial and non-spatial data, which are relevant for flood damage assessments in large study areas such as the Neckar River basin (Komolafe et al. 2018a)
The assessment methodology should be applicable in the context of river basins	This criterion has to be fulfilled to be applicable in the basin of the Neckar River
The assessment methodology should be capable of assessing future flood damage potentials	This criterion has to be fulfilled to allow estimates of future flood damages in the Neckar River basin
The assessment methodology output should support the estimation of direct economic flood damages	Direct economic damages are especially interesting for the case study since the Neckar River basin is a highly economical and industrial area. While several other important damage categories exist, direct economic losses are most commonly used and suitable for this study due to the quantifiability and comparability under relatively low uncertainties (Chen et al. 2016; Albano et al. 2017)
The assessment methodology should be contemporary	Progressive methodological improvements in flood and damage assessment have taken place in recent years (Hammond et al. 2015). To focus on most contemporary approaches, only articles published after 2013 were considered in the scoping study

2.1 Hazard modeling

Hydrologic and hydraulic simulation software with GIS is often used to model characteristics of hypothetical or historical floods (Saini et al. 2016; Scorzini et al. 2018; Mahmood et al. 2019). Among the studied articles, the most often used simulation software was HEC-RAS with HEC-GeoRAS from the United States Army Corps of Engineers (USACE) (Tarigan et al. 2017; Mihiu-Pintilie et al. 2019; Zúñiga and Novelo-Casanova 2019). 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 studies (Cham and Mitani 2015; Komolafe et al. 2018b; Qiao et al. 2018, 2019).

Most of the reviewed simulations determined inundation area and flood depths. Some studies determined expected flow velocity and flood duration (Bormudoi et al. 2013; Gergel'ová et al. 2013). The reviewed studies distinguished between one-dimensional (1D), two-dimensional (2D), and 1D-2D hydraulic modeling. One-dimensional hydraulic modeling is based on the assumption that water solely flows from upstream to downstream. Two-dimensional hydraulic modeling is more reliable to accurately represent river flows and floods in topographically complex environments, where flow routes are not predefined, and water flow is believed to vary spatially along two dimensions; however, more detailed and comprehensive input data are required. Coupled 1D-2D hydraulic modeling aims to combine advantages of both 1D and 2D modeling. All three modeling types are generally adequate to model floods for damage assessments (Ahmadisharaf et al. 2015; Kobayashi et al. 2016; Nga et al. 2018). A small number of studies pursued a statistical survey- or index-based approach to determine flood characteristics (Ettinger et al. 2016; Brown et al. 2017; Waghwalwa and Agnihotri 2019).

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 (Ronco et al. 2014; Cham and Mitani 2015; Brown et al. 2017). More than half of the reviewed studies applied return periods to build flood scenarios (e.g., Muhadi and Abdullah 2015; Tarigan et al. 2018; Mahmood et al. 2019). It was common to include a minimum of three different return periods (e.g., Morita 2014; Karamouz et al. 2015), which is required when estimating average annual losses (Nga et al. 2018). Return periods between 2-years and 1000-years were considered, while 10-years, 50-years and 100-years were most frequently applied (e.g., Gusyev et al. 2015; Pathak et al. 2016).

To determine different flood return periods, occurrence frequencies and corresponding flood magnitudes need to be estimated (Scorzini et al. 2018; Waghwalwa and Agnihotri 2019). Where frequency analysis was performed, Gumbel distributions and Weibull distributions were the preferred statistical methods (Gusyev et al. 2015; Soliman et al. 2015). Several studies used Pearson type III, lognormal, or generalized extreme value (GEV) distributions in combination with Gumbel or Weibull to estimate flood frequencies (Eslamian 2014; Faghih et al. 2017). Existing flood frequencies based on expert judgment were often adopted instead of using any of the above-mentioned statistical methods (Ahmadisharaf et al. 2015; Aksoy et al. 2016; Arrighi et al. 2018; Schmid-Breton et al. 2018). In cases where frequency data are not available, it was recommended to use an ensemble of the above-described statistical extreme value distribution methods (Eslamian 2014; Faghih et al. 2017).

Most studies emphasized the need to validate modeled floods. A prominent validation approach was comparing modeled floods with historical flood events in terms of flood extent and flood depth (Yu et al. 2013; Mahmood et al. 2019). Based on the comparison between modeled floods and historical flood events, flood models can be calibrated and refined (Karamouz et al. 2015; Zúñiga and Novelo-Casanova 2019). In cases where flood extent and flood depths of historical floods were not fully available, some flood models were validated against historical watermarks and flood information in news reports. Validation through surveys and interviews in the study area was repeatedly applied. Lack of sufficient validation data was identified as common issue (e.g., Saini et al. 2016; Komolafe et al. 2019).

2.2 Quantification of flood damages

Fifteen studies were limited to flood modeling without quantifying damages (Acosta et al. 2017; Faghih et al. 2017). Two-thirds of the remaining studies 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 and Giuffrida 2018). A small number of studies applied ordinal damage classes to assess the "seriousness" of flooding instead of quantifying actual damages (Ronco et al. 2014; Ettinger et al. 2016). Economic losses can be either quantified per individual scenario (disaggregated) or aggregated as average annual losses (AAL). Both approaches were identified in the reviewed studies (Foudi et al. 2015; Lawrence et al. 2019).

The flood characteristics most commonly considered to influence damages are flood extent, flood depth, flow velocity, and flood duration. One study focusing on flood damages in agriculture emphasized the relevance of time and season of flood occurrence (Vozinaki et al. 2015). Flood extent and flood depth were 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 flow velocity and flood duration, most models were confined to flood extent and flood depth when assessing flood damages. This is rooted in the relative ease to accurately determine flood damages based on extent and inundation depths (Mohammadi et al. 2014; Komolafe et al. 2019).

Most reviewed flood damage assessment approaches, using extent and depth, were based on stage-damage functions. Stage-damage functions describe linkages between flood depths and corresponding monetary losses due to the inundation of exposed assets (Vozinaki et al. 2015; Arrighi et al. 2018). A distinction can be made 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 were commonly applied in the reviewed articles (Foudi et al. 2015; Vozinaki et al. 2015; Neubert et al. 2016; Komolafe et al. 2018a). Some studies adopted already existing stage-damage functions. 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 was preferred over a synthetic approach due to the presumed higher validity (Neubert et al. 2016; Komolafe et al. 2018a).

Most studies grouped flood-prone areas into land use categories with group-specific stage-damage functions. Land use categories were either determined through analyzing satellite imagery using remote sensing techniques or by simply adopting already existing land use data (Arrighi et al. 2018; Nga et al. 2018; Lawrence et al. 2019). A small number of studies

included impacts on people and the environment, which corresponded to difficulties to quantify expected damages (Saini et al. 2016; Trovato and Giuffrida 2018).

Raster formats were more prominent than vector-based approaches when modeling floods as well as their damages (Neubert et al. 2016; Jamali et al. 2018; Komolafe et al. 2018a). Parcel-level data on land use and properties were scarcely used (e.g., Lawrence et al. 2019).

Similar validation techniques, as used for flood models, were applied for validating damage assessments. While the need for validation was broadly acknowledged, many studies failed to validate their damage model due to limited access to historical data (Neubert et al. 2016; Komolafe et al. 2018b). When complete validation is not possible, it should be sought to at least partly validate outputs (Vozinaki et al. 2015).

2.3 Future projections

One-fifth of the articles considered climate change; half of these in relation to both flood modeling and damage modeling (Yu et al. 2013; Morita 2014; Neubert et al. 2016; Brown et al. 2017; Komolafe et al. 2018a). In terms of flood modeling, two generic approaches to integrate climate change were identified. The first approach is based on statistical downscaling of discharge and rainfall data from general circulation models (GCMs) to regional climate models (RCMs). While RCMs can improve resolution and performance of climate projections in regional settings, statistical downscaling comes along with significant uncertainties (Karamouz et al. 2015; Arunyanart et al. 2017). Based on RCMs, expected future rainfall and discharge levels can be estimated for different climate scenario to model future floods using the above-described simulation software (Yu et al. 2013; Neubert et al. 2016; Komolafe et al. 2018a). The second identified flood modeling approach is based on a return period shift method (RPS). Instead of estimating future rainfall and discharge levels, the RPS method estimates future shifts in average recurrence intervals of constant rainfall or discharge levels based on climate projections (Morita 2014; Brown et al. 2017).

Some studies integrated projections of future land use in their flood damage assessment (Yu et al. 2013; Morita 2014; Neubert et al. 2016), whereas others used static land use conditions as basis for assessments (Yu et al. 2013; Komolafe et al. 2018a). It is also possible to consider future changes in the economic values of land cover and consequently expected future maximum damages per asset. Some studies considered potential future flood adaptation measures in their damage assessments (Morita 2014; Neubert et al. 2016).

Validation of future flood and damage projections is challenging due to absent verification data, resulting in uncertainties regarding projected outcomes. Hence, most studies validated their models against historical records to account for model accuracy under today's conditions and were forced to solely trust in the quality of the projected input data (Yu et al. 2013; Morita 2014; Komolafe et al. 2018a). To address these common validation issues, this article proposes a nascent approach of explicitly reflecting on the strength of knowledge underlying such assessments.

3 Flood damage assessment approach

This approach combines the methods identified in the scoping study for the case study assessment of the Neckar River. The case study description (Sect. 4) renders account of the required input data and outlines the performed damage potential assessment in detail. The approach consists of two main components: fluvial flood modeling (hazard assessment)

and damage modeling (impact assessment), where the latter is split into exposure and vulnerability. In combination, the two assessment components allow the estimation and comparison of expected direct economic damages from different scenarios. A schematic representation of the assessment approach can be seen in Fig. 1.

3.1 Flood modeling

The flood component of the assessment approach is based on GIS and hydrologic and hydraulic simulation software. The damage component is based on stage-damage functions; thus, flood extents and flood depths are the flood characteristics of interest. A combination of HEC-RAS and HEC-GeoRAS is used for scenario-based flood modeling using estimated flood discharges (m^3/s).

3.2 Damage modeling

The damage modeling component of the assessment approach is based on land use raster data to assess flood exposure and on stage-damage functions to determine flood vulnerability. The approach is restricted to direct tangible damages due to the focus on economic damage potentials in the study area. Damages are quantified by overlaying simulated floods with exposed assets to determine monetary damages of 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.

3.3 Future projections

To estimate future flood conditions, precipitation scenario data from GCMs, which have been downscaled to RCMs are used. Based on downscaled precipitation data, future flood discharges are estimated for future 10-year, 50-year, and 100-year floods, based on a regionalized discharge estimation model. Data on estimated future change in precipitation are retrieved from a publicly available climate model. Representative concentration pathways (RCPs) are used for precipitation scenarios. Expected future changes in exposure and vulnerability, respectively, in land use and stage-damage as well as potential maximum damages, are also considered. Future land use, stage-damage functions, and potential maximum damages are estimated based on extrapolated trends and change rates. Future land use is simulated based on two land use raster datasets from different years in the past using the GIS-extension *Modules for Land Use Change Simulations* (MOLUSCE) (NextGIS 2013). Future stage-damage is based on growth rates of the relevant variables of the loss functions (Yu et al. 2013; Morita 2014; Neubert et al. 2016).

3.4 Strength of knowledge estimation

To account for uncertainties and to address identified challenges of validating damage estimations when lacking verification data, a nascent qualitative confidence estimation approach is introduced here to reflect on the strength of knowledge (SoK) underlying the

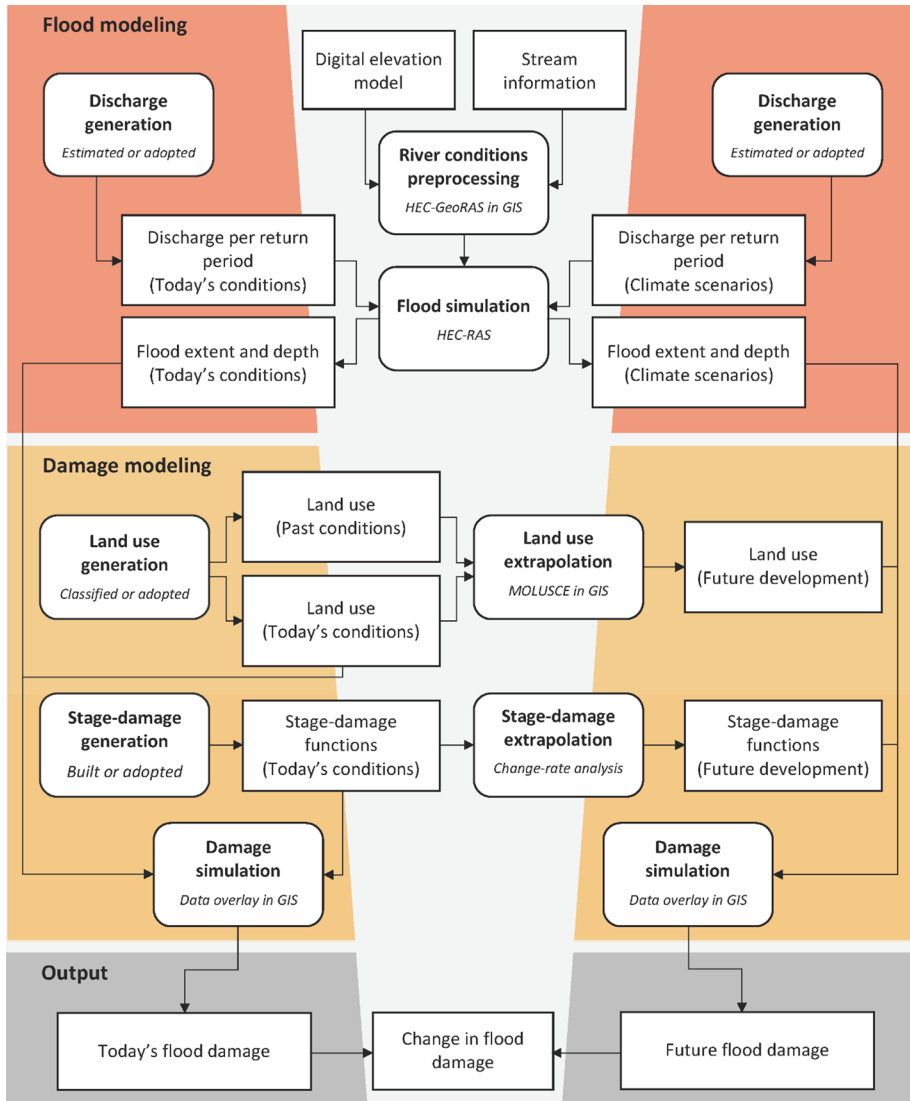


Fig. 1 Schematic assessment flow for the case study

case study in Sect. 4. The concept of SoK is used in risk science to qualitatively label the strength of knowledge, which motivates key assumptions and methodological choices regarding the assignment of probabilities (Askeland et al. 2017; Berner and Flage 2014; Flage and Aven 2009). Following the examples of Askeland, Flage and Aven (2017) and Bani-Mustafa Zeng, Zio & Vasseur (2019), key variables were defined to reflect on the SoK underlying the case study assessment. The SoK variables help to reflect on the confidence of the assessment results. The SoK is presented on an ordinal scale from weak to strong regarding the estimation of the flood hazard, exposure, and vulnerability (Table 8). The variables are aimed to depict assessment characteristics regarding expert agreement,

context specificity, timeliness, completeness, level of detail, and validation agreement of inputs and outputs of the case study assessment.

To achieve high trustworthiness of an assessment, strong knowledge about quality and reliability of the assessment components is vital. The evaluation of SoK is based on the confidence of the assessor, justified through reasoning and verification of modeling results. The variables are deliberately not aggregated to an overall confidence-score due to the ordinal nature of this qualitative confidence estimation. Such an aggregation of variables is left up to decision-makers in flood risk management. The implementation of the concept of SoK, including the variables, is presented in detail in Sect. 4.7.

4 Case study

This section describes how individual steps of assessing flood damage potentials along the Neckar River were performed and which data were used.

4.1 Study area

The Neckar River basin is located in southern Germany (Fig. 2) and comprises an area of almost 14,000 km² (LUBW 2020a). The Neckar River flows through the biggest economic center of Germany and is of great relevance for the German and European industry (WMBWL 2012).

4.2 Flood simulation

Neckar River characteristics, namely river centerline, riverbanks, streamflow, river cross-sections, reach lengths as well as 3D river geometry, were digitized 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 program Copernicus with a spatial resolution of 25 m was used to generate 3D river geometry (Copernicus 2016). The digitized river characteristics were further processed in HEC-RAS 5.0.7, where reach lengths were completed, and Manning's roughness values were assigned to 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 3 shows a small section of the simulated 100-year flood, including extent and inundation depth under today's conditions. The riverbanks (light blue lines) show the water extent under normal river flow conditions.

4.2.1 Flood scenarios and frequencies

Validated data on today's flood discharges for 10-year, 50-year, and 100-year floods (HQ10, HQ50, and HQ100) at 14 gauging stations along the Neckar River were retrieved from the regional state office (LUBW 2015, 2020a). An additional proxy gauging station

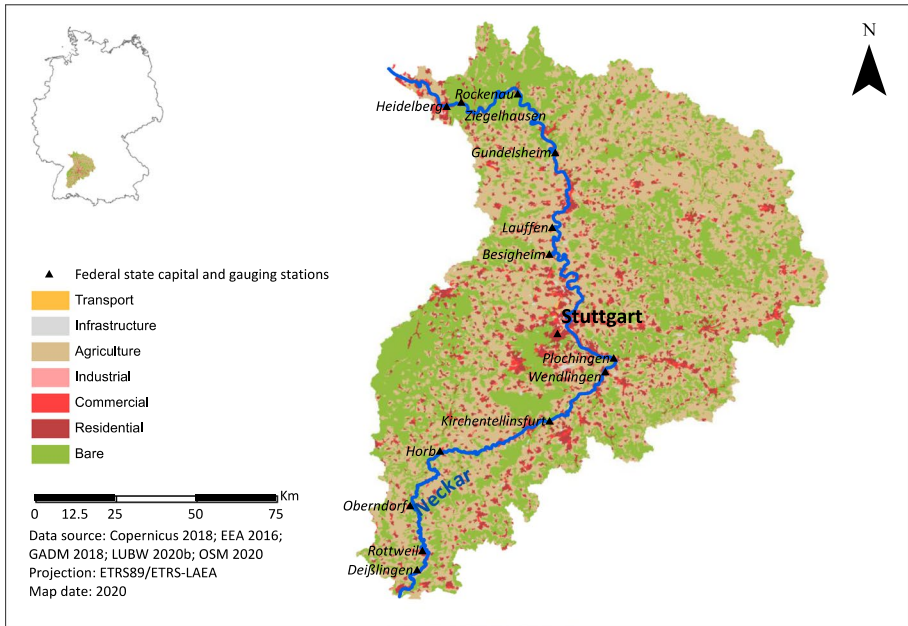


Fig. 2 Study area: Neckar River basin showing today’s land use

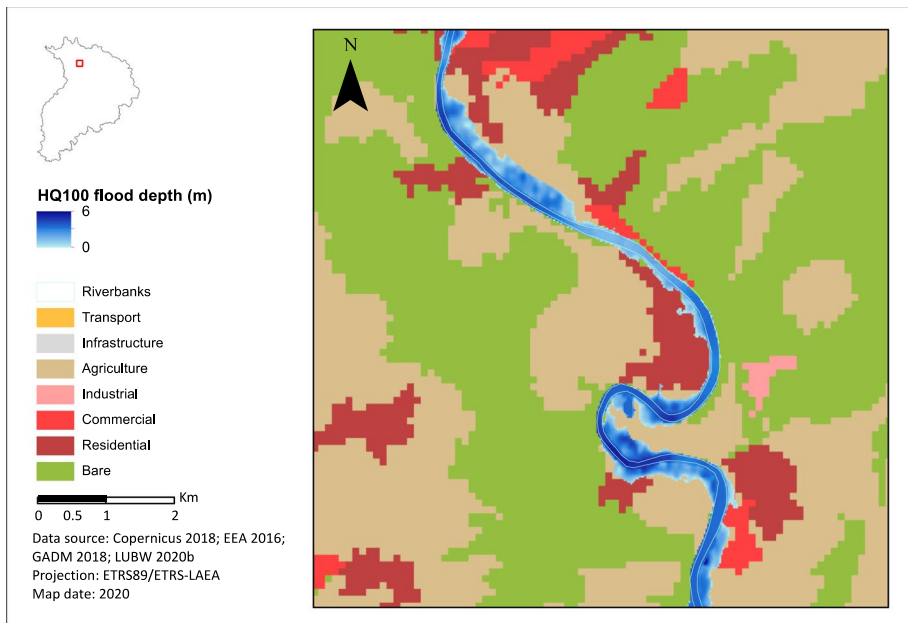


Fig. 3 Example section of the simulated 100-year flood under today’s conditions

at the river's source was introduced with discharge values 50% smaller than the discharges at the first official gauging station in downstream direction to simulate flood discharges between the river's source and the first official gauging station. In HEC-RAS, discharge values for three return periods were assigned to the gauging stations along the Neckar River (Table 2). The focus on these three most commonly used return periods allows the assessment of AAL while keeping the modeling expenses low (Karamouz et al. 2015; Pathak et al. 2016; Nga et al. 2018).

4.2.2 Flood validation

Calibration was done in HEC-RAS by varying Manning's roughness coefficient to align simulated floods 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 (Mahmood et al. 2019). Validated vector data on flood extents for 10-year, 50-year, and 100-year flood return periods 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 simulated flood extents and 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 (Reich et al. 2012). While the simulated flood extents are partly smaller than the reference extents, overall, the performed flood simulation tends to slightly overestimate areal flood extents compared to reference data by the LUBW.

4.3 Damage quantification

The simulated floods and the applied land use dataset were overlaid in GIS to identify the flood-affected assets and corresponding inundation depths. Using stage-damage functions,

Table 2 Gauging stations and flood discharges (m^3/s) under today's conditions (LUBW 2020a)

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

the damages for flood-affected areas were estimated in relation to flood depth, determining the fraction of the potential maximum damage of inundated assets.

4.3.1 Damage modeling: vulnerability

Since developing stage-damage functions require a lot of data, time, and expertise and is subject to significant uncertainties, existing and publicly available stage-damage functions, which have been tested and validated, were used in the case study instead of engaging in the development of such loss functions. This helps to minimize potential sources of error (Vozinaki et al. 2015; Scorzini et al. 2018). The applied stage-damage functions were adopted from the Joint Research Center (JRC) of the European Commission and based on following land use categories: agriculture, commerce, industry, infrastructure, residential areas, and transport (Huizinga et al. 2017). The loss functions consist of two components: stage-damage functions and estimated maximum flood damage per land use category. When combined, the two components can be used to estimate monetary flood damages per flooded m^2 . While the used functions were developed on a European level, maximum flood damage values were adjusted to economic damage potentials in Germany. The stage-damage functions were based on historical flood records, and their shapes can be seen in Fig. 4.

In the study by Huizinga et al. (2017), maximum flood damages are based on estimated construction costs, normalized to 2010 price levels. For agriculture, maximum flood damage refers to loss in output due to destroyed yields, based on the value per hectare of agriculture area.

In line with the methods presented by Huizinga et al. (2017), maximum flood damages were updated to 2018 since the land use dataset is also dated to this year (Copernicus 2018). The update is based on changes in agriculture area in hectare, value added in agriculture forestry and fishing, as well as Germany's GDP per capita (World Bank 2020a, 2020b, 2020c). Other data inputs and constants in the maximum damage calculation, developed by Huizinga et al. (2017), were left unchanged. For infrastructure and transport, an update of maximum damage was perceived to be invalid since maximum damage in

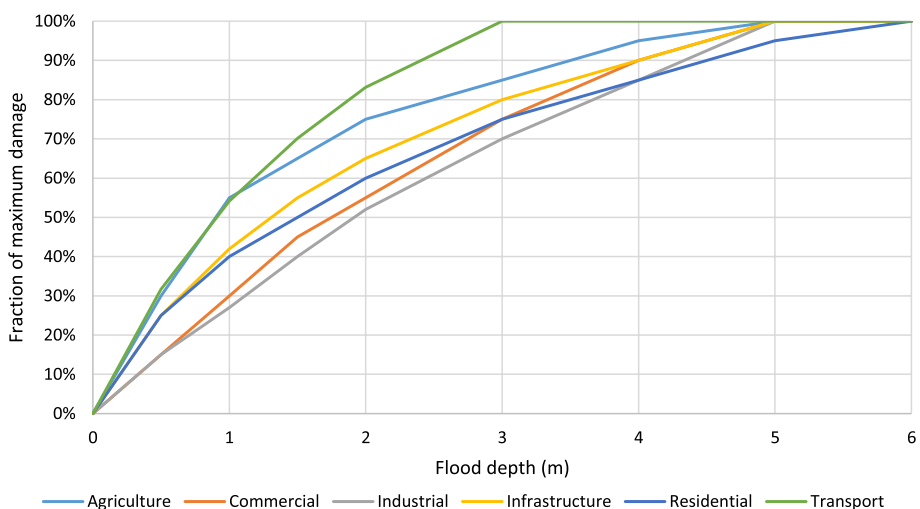


Fig. 4 Stage-damage functions under today's conditions (Huizinga et al. 2017)

these categories is based on a given European average damage value, which could not be reproduced and updated. Table 3 provides the updated maximum damage values scaled to the raster cell size of 25 m.

4.3.2 Damage modeling: exposure

The CORINE land cover 2018 (CLC 2018) from Copernicus was used to identify flood exposed assets. The raster dataset has a spatial resolution of 100 m and consists of 44 land use classes (Copernicus 2018). The land use classes of the CLC 2018 were reclassified to match the land use categories of the stage-damage functions, and the spatial resolution of the reclassified land use layer was resampled to a cell size of 25 m to align the cell size of the land use dataset with the other datasets. 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 Fig. 2.

4.3.3 Damage validation

The modeled flood damages were compared to reported damages of past events retrieved from damage studies and official documents of the federal state (Landtag-BW 1998; IKonNE 2002; Kron 2008). Comprehensive validation of modeled flood damages was not possible due to lacking availability and timeliness of reference damage data. However, the scale of the modeled flood damages seems reasonable in comparison to the available reference data.

4.4 Flood projections

Flood extents and depths were projected based on anticipated 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 RCPs. The RCP2.6 pathway characterizes 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 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).

Table 3 Maximum damage per land use raster cell under today's conditions (2018)

Agriculture	Commercial	Industrial	Residential	Infrastructure 2010	Transport 2010
95 €	213,306 €	172,146 €	102,979 €	15,000 €	454,375 €

Table 4 Change in mean annual precipitation in Baden-Wuerttemberg (GERICS 2018)

Period	RCP2.6		RCP8.5	
	(2036–2065)	(2071–2099)	(2036–2065)	(2071–2099)
Mean annual precipitation	0%	+1%	+5%	+3%

Table 5 Gauging stations and flood discharges (m³/s) under mid-century conditions

Period: 2036–2065	RCP2.6			RCP8.5		
	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

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 precipitation data in Table 4 were used to estimate changes in flood discharges for the three return periods, based on a regionalized flood discharge computation method by LUBW (2015), which is used by the state agency to generate flood discharges under today's conditions. For the future discharge estimation, mean annual precipitation data were updated according to RCP scenarios, while all other parameters in the computation model were kept constant. The estimated future flood discharges can be seen in Tables 5 and 6, whereas the computation method is provided in Appendix 2.

4.5 Damage projections

Flood vulnerability was projected by updating potential maximum damages while the loss functions were left unchanged. Potential maximum damages were updated for agriculture, commercial, industrial, and residential land use categories. Maximum damage for infrastructure and transport was left unchanged for the same reasons, as described in Sect. 4.3.1.

Table 6 Gauging stations and flood discharges (m³/s) under end-century conditions

Period: 2070–2099	RCP2.6			RCP8.5		
	HQ10	HQ50	HQ100	HQ10	HQ50	HQ100
Gauging station						
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

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 Sect. 4.3.1, using extrapolated inputs. 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 to 2018 as reference period (World Bank 2020a, 2020b, 2020c, 2020d). Estimated future maximum damage values per land use class can be seen in Table 7.

Future flood exposure was estimated using the GIS-extension MOLUSCE to simulate future land use in the study area (NextGIS 2013). Modeled 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

Table 7 Maximum damage per land use raster cell under future conditions

Land use	2036–2065	2070–2099
Agriculture	259 €	714 €
Commercial	265,739 €	332,836 €
Industrial	210,217 €	257,960 €
Residential	130,505 €	166,344 €
Infrastructure 2010	15,000 €	15,000 €
Transport 2010	454,375 €	454,375 €

future land use transition potential in the study area (NextGIS 2013). After the artificial neural network was trained, future land use was modeled 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 Sect. 4.3.2 to be compatible with the applied loss functions.

The MOLUSCE-based simulation of future land use suggests an 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.

4.6 Validation of projections

Validation of future flood and damage projections is challenging due to absent empirical verification data. It was not possible to validate estimations regarding 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 PricewaterhouseCoopers with good agreement between the estimates (PWC 2017).

4.7 Strength of knowledge underlying the case study

The SoK underlying the flood damage assessment along the Neckar River was evaluated and made explicit to facilitate the understanding of the authors' confidence in the assessment inputs and outputs. This nascent confidence estimation is based on key variables that were perceived to have the highest impact on the performed simulation of floods, exposure, and vulnerability, as well as their credibility. The authors' confidence was made explicit for the assessment of flood damage potentials along the Neckar River under today's conditions as well as under expected mid-century and end-century conditions (Table 8).

Since flood discharges for today's conditions were readily available and validated by the official agency in the study area, expert agreement on precipitation data validity as well as context specificity of this data is perceived to be strong. The same applies to the regionalized 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 deemed as moderate since 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. Even though the discharge data are dated to 2013, the timeliness of the data is believed to be strong since no substantial changes in discharge were perceived throughout the last years, and the data are still used by the official agency in the study area. Considering the size of the study area, the level of detail of the modeled floods is judged to be strong, even though a higher spatial resolution than 25 m would be favorable. The validation agreement between modeled floods and reference data is moderate, as described above.

Table 8 Strength of knowledge estimation for the case study of the Neckar River

	Today	2036–2065	2070–2099
SoK Flood simulation			
<i>Input confidence</i>			
Expert agreement: validity of precipitation data	Strong	Moderate	Weak
Context specificity: precipitation data	Strong	Moderate	Moderate
Suitability: flood discharge computation method	Strong	Moderate	Weak
Consideration: defining aspects for flood discharge estimation	Moderate	Moderate	Weak
Timeliness: computed flood discharge data	Strong	Strong	Strong
<i>Output confidence</i>			
Level of detail: modeled floods in terms of spatial resolution	Strong	Strong	Strong
Validation agreement: modeled floods and reference data	Moderate	Weak	Weak
SoK Exposure			
<i>Input confidence</i>			
Suitability: applied land use classification method	Strong	Strong	Strong
Consideration: defining aspects for land use classification	Strong	Moderate	Moderate
Timeliness: land use data	Moderate	Strong	Strong
<i>Output confidence</i>			
Level of detail: land use in terms of spatial resolution	Moderate	Moderate	Moderate
Validation agreement: land use classification and reference data	Strong	Weak	Weak
SoK Vulnerability			
<i>Input confidence</i>			
Timeliness: considered stage-damage data	Moderate	Strong	Strong
Context specificity: loss functions	Moderate	Moderate	Moderate
Context specificity: data to estimate potential maximum damages	Strong	Strong	Strong
Consideration: defining factors for maximum damage estimation	Moderate	Moderate	Weak
<i>Output confidence</i>			
Level of detail: loss functions in terms of depth-damage sensitivity	Strong	Strong	Strong
Validation agreement: applied loss functions and reference data	Strong	Weak	Weak
Validation agreement: maximum damage and reference data	Moderate	Moderate	Weak

The timeliness of the data underlying the computation of the used loss functions is seen to be moderate since it is dated to 2010 (Huizinga et al. 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 perceived as strong since country-specific data inputs were available (World Bank 2020a, 2020b, 2020c). The confidence in the completeness of the estimation of maximum damages is viewed as moderate since not all relevant factors could be updated. The reliability of the loss functions is characterized by a strong level of detail and strong validation agreement with reference data (Huizinga et al. 2017). The updated potential maximum damage data were not validated against reference data; however, the used maximum damage computation method was validated by Huizinga et al. (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 regarded as moderately reliable and their timeliness

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

The expert agreement on the validity of the used mean annual precipitation data and their context specificity is judged to be moderate for the mid-century and weak for the end-century due to 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 deemed as moderate for the mid-century and weak for the end-century 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 periods (GERICS 2018; KLIWA 2017). Even though the regionalized 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 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 perceived to be weak for the end-century. The timeliness of the computed flood discharges is regarded as high, as discharges were deliberately assessed for the mid-century and end-century. The level of detail of the modeled floods is similar to the simulation under today's condition and thus considered as strong. 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 viewed as high, since the used GIS-extension MOLUSCE was deliberately developed for such analysis purposes. 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 modeled future land use is regarded as moderate. Validation of the modeled 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, as the data were explicitly projected to the three assessment periods of interest. 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, however, is based on country-specific input data, which is why the context specificity of the future maximum damage is seen as high. Since it was not possible to update all relevant factors for estimating maximum damages, the completeness of these relevant factors is based on moderate SoK for the mid-century and weak for the end-century. The reliability of the vulnerability estimation outputs is supported by a strong level of detail of the loss functions in terms of depth-damage sensitivity. It was not possible to validate 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 potential maximum damages is deemed as moderate 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 show that the confidence in the assessment inputs and outputs decreases as the 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

Table 9 Estimated flood damages along the Neckar River under today’s conditions

Scenario	HQ10	HQ50	HQ100	AAL
Estimated flood damages	682,673,075 €	905,063,218 €	955,921,365 €	95,927,786 €

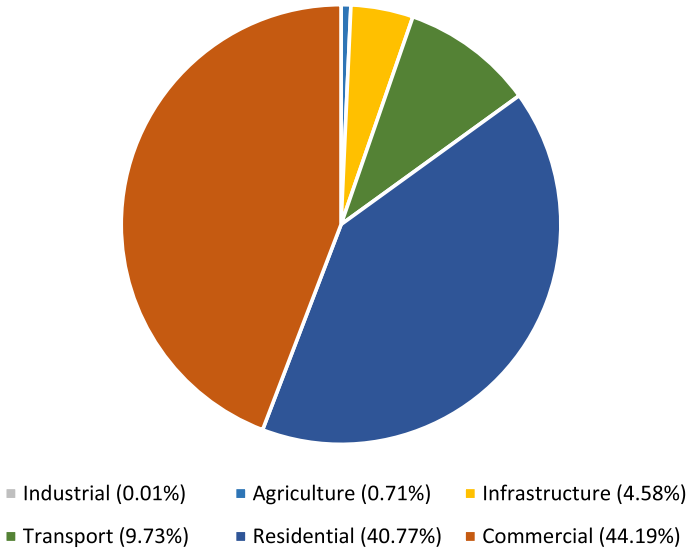


Fig. 5 AAL per land use category under today’s conditions in percentage of total AAL

is rather moderate to weak. The decrease in confidence in future projections is substantial for the flood simulation and vulnerability estimation.

5 Case study results

The outputs from the flood simulation as well as the exposure and vulnerability modeling were combined and processed in ArcGIS ModelBuilder to estimate flood damage potentials along the Neckar River under today’s conditions as well as for different scenarios for the mid-century (2036–2065) and the end-century (2070–2099). Table 9 shows estimated damages under today’s flood, land use, and stage-damage conditions.

Most significant damages occur in commercial and residential areas along the Neckar river, as shown in Fig. 5. Agriculture and industrial areas barely account for substantial flood damages compared to the other four land use categories.

All simulated future scenario conditions suggest an increase in flood damages along the Neckar River throughout the twenty-first century compared to today’s damage levels. It was distinguished between fully dynamic and partly constant scenarios. The dynamic scenarios are based on expected changes in flood characteristics, exposure, and vulnerability

to portray a complete picture of potential future flood damages. In the constant scenarios, flood exposure and vulnerability were kept unchanged to solely focus on the impact of changing flood characteristics on potential future flood damages. The 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 twenty-first century (Fig. 6).

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 (Fig. 7).

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 average annual flood damages in the study area is low.

6 Discussion

To address the first research question, core elements of contemporary flood damage assessment approaches to model and validate hazards and damages as well as enabling comparisons of direct economic damages under current annual flood levels and projected scenarios were identified. Almost all GIS-based assessment approaches are split into flood modeling (hazard assessment) and damage modeling (exposure and vulnerability assessment). In combination, these approaches allow the estimation of expected damages under various scenarios. Flood modeling is commonly based on a combination of GIS, hydrologic, and hydraulic simulation software. The damage modeling is mostly based on stage-damage functions, which describe the linkage between flood depths and corresponding monetary damages of exposed assets. Challenges of validating assessments, e.g., due to lacking reference data, were identified as a prevalent issue in the reviewed articles. These findings of the scoping study were used to develop a methodology addressing the second research question.

The second research question addresses how average annual direct economic flood damages in the Neckar River basin might change throughout the twenty-first century, based on

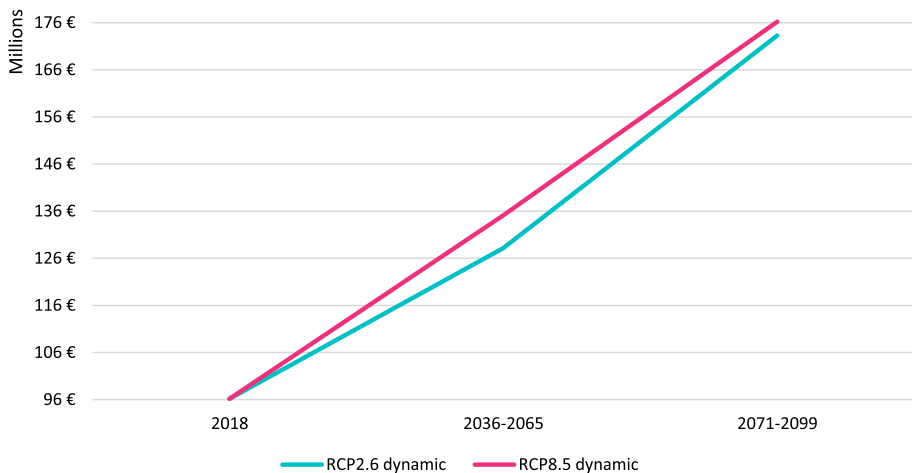


Fig. 6 Future AAL for RCP2.6 and RCP8.5 based on fully dynamic scenarios

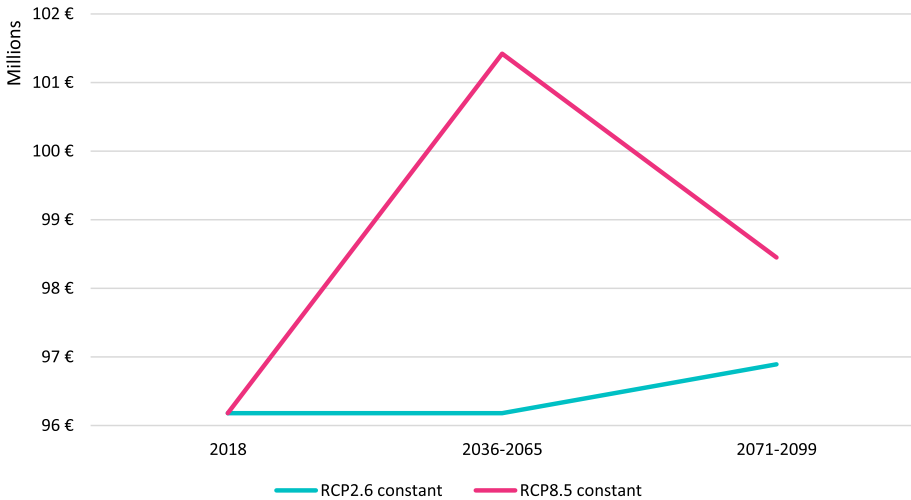


Fig. 7 Future AAL for RCP2.6 and RCP8.5 based on partly constant scenarios

various future scenarios. The results of the case study indicate a significant increase in average annual flood damages along the Neckar river throughout the twenty-first century. The projected increase in damages primarily arises from changes in flood exposure and flood vulnerability. The expansion of residential and commercial sites in the study area throughout 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 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 substantial than the impact of changing flood exposure and flood vulnerability. The assessed damages under today's conditions are in line with available reference data (Landtag-BW 1998; IKonNE 2002; Kron 2008). The validity of estimated future flood damages is more difficult to assess given a significant ambiguity in the scarcely available reference data. 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 2005, 2018; LUBW 2015). Yet, some studies project a decrease in flood levels for the Neckar River due to climate change (Huang et al. 2013, 2015). This ambiguity derives from substantial differences in available datasets on estimated future rainfall patterns in the study area and uncertainty regarding the suitability of the applied precipitation-based discharge estimation methods for the assessment of future floods (Eslamian 2014; GERICS 2018; PIK 2020).

The estimated future damages are primarily limited by unclear validity of the used precipitation data and their meaningful transformation into future flood discharges. 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 precipitation extremes (LUBW 2013; KLIWA 2016). Such changes in extremes are not fully accounted for when focusing on average annual precipitation, which might be relatively stable, while precipitation distribution between seasons shifts considerably. For the case study, statistical trends based on historical data were used to estimate future land use changes and developments in the potential maximum flood damage. In this sense, the projected information on flood exposure

and vulnerability is a description of what these damage components will look like *if* current development trends continue throughout the twenty-first century. Similar simplifications were made for several sub-parameters, e.g., 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 (Appendix 2). Parameter interdependencies were disregarded since no adequate scaling and transformation method was found to meaningfully link parameters with each other beyond one of the two method components. The validity of these projected future damages is difficult to assess due to lacking or ambiguous validation data. The described limitations of the case study are reflected in the previously described nascent SoK-estimation approach, which show decreasing confidence in simulated flood damages as the projections go further into the future.

Beyond the simulated damages along the Neckar River, the case study has shown how contemporary concepts of flood damage potential assessment might be implemented in practice. Statistical extreme value distribution in combination with rainfall runoff-modeling based on daily rainfall projections might be used in future studies of the Neckar River to estimate future flood discharges more accurately instead of using a regionalized 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. A direct comparison of rainfall runoff-modeling using daily rainfall projections, and a regionalized flood discharge estimation method using average annual precipitation data, might be implemented in future studies to evaluate the performance of the two approaches.

While the provided findings on direct tangible damage potentials along the Neckar River are valuable for flood risk management in the study area, an integration of indirect and intangible damages would be desirable in future studies to provide a more complete picture of flood risk. The Collaborative Research on Flood Risk in Urban Areas (CORFU) project can be an entry point to this end (Chen et al. 2016).

As a final remark, we would like to highlight the need to reflect upon and make explicit assumptions and simplifications, which may limit the validity of any study. The performed scoping study shows that this is not always done. Future studies should focus more on establishing parameters to facilitate the judgment of validity beyond pure numbers, e.g., regarding the suitability of land use classifications and spatial resolutions, expert agreement on precipitation data; suitability of flood discharge computation method; context specificity and level of details regarding stage-damage data. The here presented nascent SoK-estimation approach, based on the work by Flage and Aven (2009), Berner and Flage (2014), and Askeland et al. (2017), can be an entry point for future studies to further enhance the treatment of validity issues and uncertainties.

7 Conclusions

The findings of the performed scoping study show which elements need to be considered in contemporary GIS-based assessments of current and future flood damages, and therefore give an answer to the first research question. The findings of the scoping study can be used by practitioners in flood risk management to develop suitable assessment approaches to estimate flood damages for different future scenarios and to compare the results with today's flood damage levels. The article describes which contemporary methods exist, how these might be implemented in practice, and how prevalent issues of assessment validity might be addressed through a qualitative strength of knowledge estimation. The second research question is answered by

the results of the case study, suggesting a significant increase in average annual flood damages along the Neckar river throughout the twenty-first 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 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. The here presented basic confidence estimation might be enhanced in future studies to achieve a more advanced reflection of strength of knowledge, which will allow for better handling of validation issues and uncertainties.

Appendix 1. The applied search string for the Scopus based scoping study

(TITLE-ABS-KEY("flood*" W/2 ("damage" OR "loss" OR "impact")) AND TITLE-ABSKEY("assess*" OR "analy*" OR "model*" OR "estim*" 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)).

Appendix 2. Regionalized flood discharge computation method by the LUBW

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

$$Y = MHq$$

$$Y_T = Hq_T / MHq$$

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

A_{Eo} : Area of the river basin [km²], 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 (m³ / s / km²), 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 (m³ / s / km²), S: Development share [%] (kept constant in the case study), W: Share of woods [%] (kept constant in the case study), Y, Y_T : Dependent variable.

See Table 10.

Table 10 Coefficients for the flood discharge estimation (LUBW 2015)

	C0	C1 (AEo)	C2 (S+1)	C3 (W+1)	C4 (I _g)	C5 (L)	C6 (LC)	C7 (hNG)	C8 (LF)	R2
MHq	-16.7017	-0.2496	0.0582	-0.0748	-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

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Availability of data and material Only publicly available datasets were used for the analysis.

Declarations

Conflict of interest The authors have no conflicts of interest to declare.

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