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# Using hydro-morphological assessment parameters to estimate the flood-induced vulnerability of watercourses - a methodological approach across three spatial scales in Germany and the Czech Republic

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## Abstract

In addition to their ecological importance, rivers and streams have always been used in diverse ways by humans, resulting in the development of settlements and their connected built environments along many of the world's watercourses. During heavy rainfall, buildings, traffic infrastructure and water-related infrastructure are exposed to potential hazards in the form of (flash) floods. In contrast to near-natural watercourses, anthropogenically modified channels in urban areas are particularly susceptible to damage by flooding. Previous damage assessments have highlighted the need to forecast such damage to watercourses in order to identify critical areas and justify the selection and expansion of adaptation measures. Within the scope of the current study, we have developed a method based on the hydro-morphological properties of watercourses to make transferable estimates of the economic damage potential based on ecologically-relevant parameters. Using a scale-specific cause-effect analysis, we have identified characteristics of the watercourse type and adjacent structures as well as construction-related properties of reinforcements that can increase the damage potential during flooding. In this way, we are able to show that several influencing factors determine the vulnerability of watercourses: in addition to the specific longitudinal gradient and size (macroscale) of various watercourse types, damage-relevant boundary conditions in watercourse sections (mesoscale) and the resistance of typical bed and bank constructions are also important, reflecting the specific structural conditions. Taking rivers in Germany and the Czech Republic as case studies, in the following, we review the local identification of critical areas and describe the necessary data management. The presented "Hydro-morphological based Vulnerability Assessment-Concept (HyVAC)" can contribute to the flood damage prevention at watercourses by utilizing existing basic data to the greatest possible extent and thus is suitable for preliminary investigations according to the EC Flood Risk Management Directive.

**KEYWORDS**
assessment parameters, flood risk management, hydro-morphology, vulnerability, watercourses

## 1 | INTRODUCTION

Past flood events have shown that countries face immense reconstruction costs for damaged buildings, transportation routes, and utility infrastructure, as well as facilities and structures along watercourses (Barredo, 2007, Wingfield, Macdonald, Peters, Spees, & Potter, 2019). In view of the projected increase in extreme precipitation events due to climate change, the level of hazard can be expected to rise (Alfieri, Feyen, Dottori, & Bianchi, 2015; Diakakis et al., 2019; Dourte, Fraisse, & Bartels, 2015). Accordingly, without suitable adaptation and preparedness measures, the financial impact of extreme flood events is likely to increase (Price, Wright, Fant, & Strzepek, 2016; Wagenaar et al., 2019). There is no doubt that the intensive redesign and straightening of watercourses in urban spaces leads to increased runoff and greater hydraulic stress on channels. Due to their high restoration costs after flooding, the various forms of bed and bank construction are linked to different levels of economic damage. Clearly, it is important to be able to assess this type of damage. In natural hazard research, the determination of flood risk is described in terms of vulnerability under diverse situations (Birkmann et al., 2011; Cutter, 1996; Greiving et al., 2015; Paul, 2013; Rehan, 2018). Although the concept of vulnerability has been the subject of some discussion (e.g., Gallopin, 2006), the determining factor in assessing physical-infrastructural vulnerability in a flood event is the resistance to impact (Marchi, Cavalli, Amponsah, Borga, & Crema, 2016; Neubert, Naumann, Hennersdorf, & Nikolowski, 2016; Rana & Routray, 2018).

Hydrological processes occur over a wide range of spatial and temporal scales. A "scale" can be defined as a characteristic area in space or a period of time in which processes occur (Salvadore, Bronders, & Batelaan, 2015). It is usual to consider the respective vulnerable receptors under defined spatial scales (e.g., López-Tarazón, Bronstert, Thieken, & Petrow, 2019; Neubert et al., 2016; Rehan, 2018). In addition to macroscale regional analyses (e.g., Apel, Aronica, Kreibich, & Thieken, 2009; De Kok & Grossmann, 2010; Neubert et al., 2016), mesoscale approaches have been applied to assess the flood vulnerability of specific forms of land use (e.g., Neubert et al., 2016; Scorzini & Leopardi, 2017). To increase the accuracy of spatial assessments, microscale studies are also conducted in analyses of flood risk and vulnerability. At this scale, individual objects such as buildings (Arrighi, Brugioni, Castelli, Franceschini, & Mazzanti, 2013; Rehan, 2018) or road infrastructure (EEA, 2014; Golz, Bohnenkamp, & Heyer, 2017) can be investigated.

Across scales, streams have not been adequately investigated with respect to potential infrastructural damage (Bjerklie, 2007; MacBroom, Schiff, & Louisos, 2017). Within the framework of macroscale observations, geomorphological studies are used to identify particularly vulnerable watercourses. Using the (specific) stream power, areas in watercourses can be identified where the impact intensity is high during flood events, thereby causing intensive erosion (e.g., Buraas, Renshaw, Magilligan, & Dade, 2014; Knighton, 1999; Vocal Ferencevic & Ashmore, 2011). At the level of sections (mesoscale), the intensity of damage depends on the flow conditions in the watercourse and in the floodplain. The more heterogeneous the design of watercourses and their surroundings, the greater the occurrence of damage-inducing flow patterns, which can lead to damage in the presence of vulnerable elements, for example, bank constructions and bridges (De Cicco, Paris, Ruiz-Villanueva, Solari, & Stoffel, 2018; Hajdukiewicz, Wyżga, Mikuś, Zawiejska, & Radecki-Pawlik, 2016; Khatua & Patra, 2007; MacBroom et al., 2017; McBride, Hession, Rizzo, & Thompson, 2007; Ruiz-Villanueva, Bodoque, Díez-Herrero, Eguibar, & Pardo-Igúzquiza, 2013; Song, Ku, Kim, & Park, 2018). At the microscale, previous analyses have assessed the resistance of technical or technical-biological structures in watercourses to draw conclusions on potential damage processes (Davis & Harden, 2014; Gerstgraser, 2000a & 2000b; Hopkinson & Wynn-Thompson, 2016; Klösch et al., 2018; Kolb, 1979; Magilligan, 1992). Here the correlation between damage mechanisms and existing impact variables has been analyzed in order to characterize the critical impact intensity (Jirka & Lang, 2009; Sabrowski, 2008; Stotts, O'Neal, & Pizzuto, 2015; Suaznabar et al., 2017).

To complement the highly detailed case study observations already available, we now require an overarching methodological approach to characterize watercourses and, in particular, the variation of existing structural assets in the channel as receptors in flood risk assessments and to take account of typical interaction processes between the watercourse and the floodplain.

In this study, we build on previous theoretical-methodological work to present a multi-scale approach for the assessment of watercourse vulnerability. Reflecting the three named spatial scales, this multi-scale approach integrates important aspects over four main steps:

Step 1: Macroscale: the large-scale classification of watercourses with respect to their flood-induced vulnerability: differentiation based on a) slope and b) discharge classes.

Step 2: Mesoscale: assessing potential interaction between the built environment and the watercourse channel in damage mechanism analysis by highlighting damage-inducing boundary conditions based on potentially occurring damage mechanisms: a) punctual, b) linear and c) planar.

Step 3: Microscale: the characterization of the resistance of typical bank and bed infrastructures in watercourses, taking into account the structural condition of the various construction types: a) resistance and b) structural condition of the construction types.

Step 4: Combination across scales: a) integrating the microscale assessment to the mesoscale and b) integrating the mesoscale assessment to the macroscale.

Accordingly, this study suggests a wide-scale methodology to identify particularly vulnerable areas of watercourses in a step-by-step manner, from which it is possible to derive measures for damage prevention. Since we adopt an application-oriented approach, the necessary data requirements to represent the spatial occurrence will also be detailed alongside the theoretical-methodological framework. Here the interpretation of existing remote-sensing data, as well as hydro-morphological assessment parameters of watercourses, are key factors (readily available information according to EC FD) in assessing the flood-induced vulnerability of watercourses. This also ensures the transferability of the method. The described steps thus characterize our so-called *Hydro-morphological based Vulnerability Assessment-Concept (HyVAC)*.

## 2 | HYDRO-MORPHOLOGICAL BASED VULNERABILITY ASSESSMENT CONCEPT

### 2.1 | Concept of the assessment method

In the context of vulnerability research, this paper views watercourses as parts of the built environment and draws on methodological principles of vulnerability. For this purpose, the conceptual understanding of hazard, spatial occurrence, and vulnerability are applied according to their common usage in research on natural hazards and risk. Here flood risk represents the degree of potential damage to exposed receptors under specific impact scenarios (hazards) and the associated ranges of impact magnitudes (for a more detailed discussion of terms, see Cutter, 1996, Adger, 2006, Birkmann et al., 2011, Paul, 2013, Schanze, 2016.)

The potential economic impact of flood events on watercourses can be described by means of three spatial scales in the case-study regions (Figure 1). At the macroscale, climatic influences (heavy and continuous rainfall) cause specific precipitation-runoff processes depending on the ecoregion and catchment size. In turn, the flow force of the water increases as a function of the flow rate. At the mesoscale, the extent of damage to the watercourse during flooding will depend on settlement patterns, adjacent infrastructure (e.g., roads) or certain forms of land use (e.g., agriculture) along the watercourse. In this respect, the presence and resistance of these damage-relevant structures must be taken into account. At the microscale, namely, the level of individual objects, the type of bank and bed constructions must be characterized by their location, whereby previous damage influences the level of vulnerability.

HyVAC combines existing sources of data on watercourses from the fields of hydrology, ecology, geomorphology (macroscale) and land use (mesoscale), as well as hydro-morphology, hydraulic engineering and channel hydraulics (microscale). Once the parameters have been specified, they can be used to assess the vulnerability of watercourses when flooded.

### 2.2 | Analysis of empirical base data in Germany and the Czech Republic

Within the framework of data screening, we analyzed existing German and Czech forms of assessment and classification of watercourses to derive relevant information and to examine their ease of transferability. The transnational approach is justified by the joint river basin management of the Elbe and the related cooperation of the two countries in flood risk management. The analysis showed that Germany follows the system B) according to EC-WFD (EC, 2000) to classify 25 watercourse types based on eco-regional, hydro-morphological, biological and chemical–physical parameters (Briem, 2003; Pottgiesser, 2018). In Czechia, system A) of the WFD (EC, 2000) is used to classify 11 watercourse types into seven groups according to the ecoregion, elevation, catchment size, and geology (Kujanová, Matoušková, & Kliment, 2016). Hence, the Czech approach is based on a somewhat coarser eco-morphological classification of watercourses. Following previously conducted regionalization methods (Amiri, Baheri, Fohrer, & Adamowski, 2019; Belletti, Rinaldi, Buijse, Gurnell, & Mosselman, 2015; Turak & Koop, 2008), in the present study, we

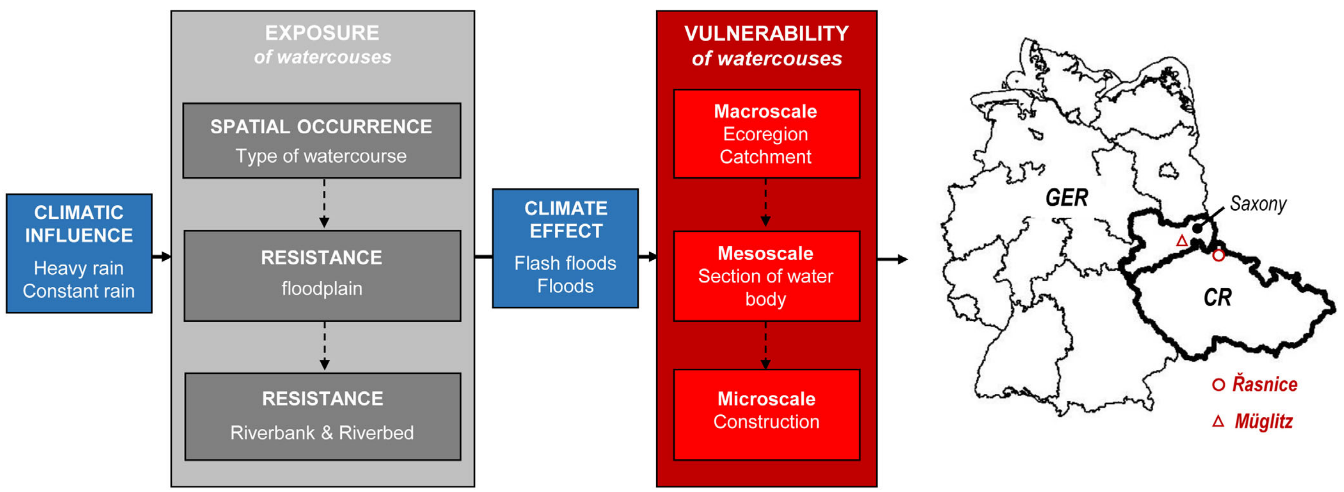


**FIGURE 1** Impact chain of climatic influences on watercourse systems; based on Birkmann et al., 2011, Greiving et al., 2015, Schanze, 2016, UBA, 2017 [Color figure can be viewed at wileyonlinelibrary.com]

adopt the characteristics of existing watercourse types as defined in Germany (Pottgiesser, 2018; UBA, 2014) and compare these with Czech data (Kujanová et al., 2016; Matoušková, 2008; Tomšová, 2013). In particular, we investigate whether such parameters can be used to compare the vulnerability of watercourse types.

In Germany, the hydro-morphology of watercourses is recorded using the so-called "hydro-morphological survey protocol" (Gellert, Pottgiesser, & Euler, 2014; LANUV NRW, 2012; LAWA, 2019). On the basis of typological references (Pottgiesser, 2018, UBA, 2014), 34 individual parameters are recorded for the watercourse, the channel and the adjacent land use of the floodplain (some parameters may be slightly adjusted depending on the federal state). In Czechia, two methods are employed for hydro-morphology assessment. The first simplified ("s") assessment of streams focuses on small- and medium-sized watercourses (Matoušková, 2008; MŽP ČR, 2009). The second extended ("e") method is hydro-ecological monitoring according to Langhammer (2014). In the simplified methodology, data on the channel and floodplain is captured separately; in each case, hydro-morphological criteria are recorded as separate indicators. The assessment of the channel makes use of four criteria and 17 indicators, whereas three criteria and six indicators are used for the floodplain (MŽP ČR, 2009). Following the detailed methodology ("*Metodika monitoringu hydromorfologických*", HEM), data is recorded separately for the channel, extended bank and floodplain on the basis of 18 parameters (Langhammer, 2014).

Our analysis of the individual German and Czech parameters and indicators shows that individual hydro-morphological assessment parameters can be used to identify potentially occurring damage mechanisms and vulnerable infrastructure. For example, the presence of a bank wall (D: EP 5.2, CZ: Indicator 3.4 (s) and 12 (UBR), respectively) can, on the one hand, be assessed as an artificial structure in terms of water ecology; on the other hand, we also understand the bank wall as a flood protection device which is associated with a damage potential.

Therefore, in the following, we make use of the parameters identified in the German and Czech evaluation systems at the three considered spatial scales. However, the method is also transferable to other countries (see Belletti et al., 2015; Gostner, 2019; Tomšová, 2013). Other examples of survey methods include the Austrian *Habitat Survey*, the British *River habitat survey* (RHS, EA, 2003), the French *Système d'Évaluation de la Qualité du Milieu Physique* (SEQ, Rebillard, 2001), the Slovenian *Hydro-morphological River Survey and Assessment* (Lehotský, 2006), or the Chinese *Urban stream morphology method* (USM, Xia, Zhu, Xin, & Li, 2010).

## 3 | METHOD: MULTI-SCALE VULNERABILITY ASSESSMENT OF WATERCOURSES

### 3.1 | General

With HyVAC, we assess stream vulnerability using a multi-scale method that combines both qualitative and quantitative forms of assessment. At the macroscale, vulnerabilities between different watercourses are compared by means of qualitative classification. At the mesoscale, the vulnerability of watercourse sections is assessed quantitatively. This builds on the microscale quantitative assessment of vulnerabilities of the individual impact areas within the sections.

### 3.2 | Macroscale: Types of watercourses

Flood or heavy rainfall hazards generally arise in catchments with high relief energy and large areas of sealed or only slightly effective retention areas (e.g., Beckers et al., 2013; Yigzaw, Hossain, & Kalyanapu, 2013). Damage results, in particular, from dynamized flooding processes where streambeds are more steeply inclined (Wharton, 1992). Therefore, we identified the slope of the valley bottom and the channel cross-section (as a measure of discharge) as key influencing variables. According to the Gaukler-Manning-Strickler formula, these parameters also determine the flow velocity:

$$v_m = k_{st} R^{\frac{2}{3}} I^{\frac{1}{2}} \tag{1}$$

where $v_m$ is mean flow velocity in m/s, $k_{st}$ the coefficient of channel roughness in $m^{1/3}$/s, $R$ the hydraulic radius and $I$ the bottom line slope (∼bed slope) in %.

In this context, straightened watercourse sections with high bed slope in intensively used and populated or urban landscapes have a particularly high damage potential (Bornschein & Pohl, 2018; Hartmann, Jílková, & Schanze, 2018; Jordan, Annable, Watson, & Sen, 2010). Accordingly, hydraulic stress on streams varies with the watercourse size and adjacent land use (Brierley & Fryirs, 2005; Buffington & Montgomery, 2013; Buraas et al., 2014; Knighton, 1999; Newson, Clark, Sear, & Brookes, 1998; Vocal Ferencevic & Ashmore, 2011; Wharton, 1992). While runoff dynamics are particularly pronounced in the catchments of small mountain streams albeit with lower absolute flows, enormous damage can occur on mid-mountain streams due to the higher absolute discharge rates and associated larger flow pulses (Bjerklie, 2007; Bryndal, Franczak, Kroczak, Cabaj, & Kołodziej, 2017). For this purpose, Knighton (1999), for example, described a method to estimate the erosion dynamics of streams as a function of their catchment size, stream length and width. This approach was later adopted and expanded by a number of authors to calculate the (specific) stream power (Buraas et al., 2014; MacBroom et al., 2017; Vocal Ferencevic & Ashmore, 2011).

This stream power seems to be a suitable measure of the impact intensity since the water body and catchment size are integrated via the discharge volume. The variable can be calculated as:

$$\omega = \frac{\gamma Q S_e}{w} \tag{2}$$

where $\omega$ is the specific stream power in W/m$^2$, $\gamma$ the specific weight of water in g/cm$^3$, $Q$ the discharge in m$^3$/s, $S_e$ the bed slope in m/m and $w$ the channel width in meters. Referring to the German and

**TABLE 1** Classification of potential hydraulic vulnerability based on stream types according to Pottgiesser (2018) for Germany and Kujanová et al. (2016) for the Czech Republic. Valley floor slope and size class were taken from the respective watercourse profiles (D) and method descriptions (CZ)

| Eco-region | Type of watercourse | | Class | Valley floor slope [%] | Slope class | Discharge class | Watercourse type-specific vulnerability (WTSV index) |
|---|---|---|---|---|---|---|---|
| Germany | | | | | | | |
| 4 Alps | 1 | Watercourses of the Alps | Stream/ river | 0.6–10 | 5 | 2–3 | Very high |
| | 2 | Watercourses of the alpine foothills | Stream/ river | >0.05 | 1 | 2–3 | Low |
| | 3 | Watercourses of young moraine of the alpine foothills | Stream/ river | 1–4 | 5 | 2–3 | Very high |
| | 4 | Large rivers of the alpine foothills | Large river | >0.2 | 2 | 4 | High |
| 9 central highlands | 5 | Coarse material-rich, siliceous low mountain streams | Stream | 1–5 | 5 | 2 | Very high |
| | 5.1. | Fine material-rich, siliceous low mountain streams | Stream | 0.4–5 | 5 | 2 | Very high |
| | 6 | Fine material-rich, carbonate low mountain streams | Stream | 0.4–3 | 4 | 2 | High |
| | 9 | Siliciclastic, fine- to coarse material-rich low mountain rivers | River | 0.2–0.6 | 3 | 3 | High |
| | 9.2. | Large rivers of the low mountain range | Large river | ≈0.3 | 2 | 4 | High |
| 14 central lowlands | 14 | Sand-dominated lowland streams | Stream | 0.2–0.7 | 3 | 2 | Medium |
| | 15 | Sand- and clay-dominated lowland rivers | River | ≈0.02–0.2 | 1 | 3 | Medium |
| | 16 | Gravel-dominated lowland streams | Stream | 0.3–25 | 4 | 2 | High |
| | 17 | Gravel-dominated lowland rivers | River | 0.05–0.15 | 1 | 3 | Medium |
| | 18 | Loess-loam dominated lowland streams | Stream | 0.2–12 | 3 | 2 | Medium |
| | 20 | Sand embossed main rivers | Main river | 0.007–0.1 | 1 | 5 | High |
| Independent types | 11 | Organic streams | Stream | 0.05–1.5 | 1 | 2 | Very low |
| | 19 | Small lowland streams | Small stream | >0.2 | 2 | 1 | Very low |
| Czech Republic (A-G: GRC-groups of river characteristics) | | | | | | | |
| 9 central highlands | A1 | Channel with naturally low sinuosity and steep valley floor slope | Stream/ river | 0.50–≥1.80 | 3–5 | 2–3 | Medium – Very high |
| | A2 | Channel with naturally low sinuosity and medium valley floor slope | Stream | ≥1.80 | 4–5 | 2 | High – Very high |
| | B | High-altitude channel with high sinuosity | Stream | <0.5–≥1.80 | 1–5 | 2 | Very low – Very high |
| | C1 | | Large river | <0.5 | 1–2 | 4 | Medium – High |

(Continues)

**TABLE 1** (Continued)

| Eco-region | Type of watercourse | | Class | Valley floor slope [%] | Slope class | Discharge class | Watercourse type-specific vulnerability (WTSV index) |
|---|---|---|---|---|---|---|---|
| | | Low-altitude channel with high sinuosity and low valley floor slope | | | | | |
| | C2 | Mid-altitude channel with high sinuosity and low valley floor slope | River | <0.5 | 1–2 | 3 | Medium |
| | C3 | Low-altitude channel with high sinuosity and medium valley floor slope | Stream | 0.50–1.79 | 3 | 2 | Medium |
| | C4 | Mid-altitude channel with high sinuosity and medium valley floor slope | Stream | 0.50–1.79 | 3 | 2 | Medium |
| | D | Low-altitude channel with steep valley floor slope | Stream | ≥1.80 | 4–5 | 2 | Very high |
| | E | Mid-altitude channel with high sinuosity and steep valley floor slope | Stream | ≥1.80 | 4–5 | 2 | Very high |
| | F | Probably modified channel: Low- to mid-altitude, low sinuosity and low valley floor slope | Large river | <0.5 | 1–2 | 4 | High |
| | G | Potentially modified channel: Low- to mid-altitude, low sinuosity and medium valley floor slope | Stream/ river | 0.50–1.79 | 3–5 | 2–3 | Medium – Very high |

Czech case studies, we classified the respective stream types (Kujanová et al., 2016; Kujanová & Matoušková, 2017; Matoušková, 2008; Pottgiesser, 2018) by their typical mean valley floor slope. Based on the characteristics of the mean slope, we derived five slope classes with specific threshold values. Considering their size and designation, we also divided the watercourses into five classes: small streams, streams, rivers, large rivers and main rivers. Based on this systematization, potential type-specific impact intensities on watercourses could be derived for a large-scale overview (Table 1). The resulting index "watercourse type-specific vulnerability" (WTSV index) represents a first evaluation step in our methodology.

## 3.3 | Mesoscale: Section classification

A further spatial specification of watercourses is needed to characterize stream vulnerability at the mesoscale. Here, there are two main factors governing the vulnerability of watercourse sections: (i) the resistance of the construction types in the riverbed and on the riverbanks as a function of the structural condition; and (ii) the way the watercourse section is designed and integrated into the surroundings. The focus of the mesoscale analysis is thus on the interaction of structures or construction types of the channel with immediately adjacent structures in the floodplain as well as the specific channel design. To enable this assessment at mesoscale, we considered previous analyses of flood events (e.g., De Kok & Grossmann, 2010; Diakakis et al., 2019; Hajdukiewicz et al., 2016; Kundzewicz, Hirabayashi, & Kanae, 2010; LfULG, 2004; LfULG, 2015; Marchi et al., 2016). In this way, we could identify areas in and around the watercourse at risk of damage due to the presence of certain structures (Figure 2). In the following, we summarize and describe these structures under the term "damage-relevant boundary conditions" (A). In a second analytical substep (B), we show the potentially available databases.

By dividing critical areas into punctual, linear and planar boundary conditions, it is possible to classify punctual structures, those structures that run linearly along the watercourse or spatial structures in the watercourse environment. Due to the highly heterogeneous design of the riverbed and banks (which are permanently stressed areas), these sub-areas were subject to a separate object-specific investigation (see microscale). Consequently, our focus here is not on

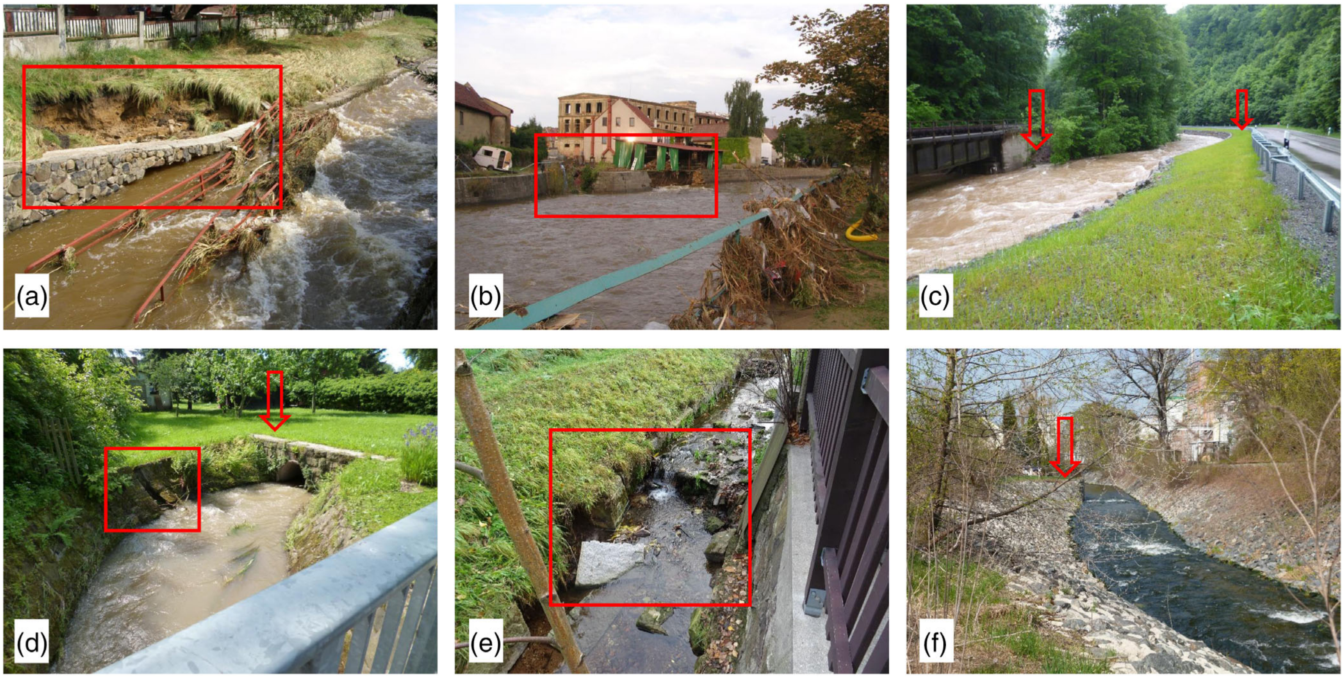


**FIGURE 2** Damaged areas (red rectangle) and areas of potential damage (red arrow) due to the presence of damage-relevant boundary conditions. (a) Overflow and backflow of a bank wall due to inadequately resistant bank conditions. (picture: Daniel Baránek, license: CC BY-SA 4.0, Source: Wikimedia Commons), (b) Damage to bank wall on impact slope with inflowing tributary watercourse and single building on bank (picture: Daniel Baránek, license: CC BY-SA 4.0, Source: Wikimedia Commons), (c) areas of potential damage at road embankment and railway crossing (image: Garack, 2013), (d) damaged area at the baffle slope in front of a pipe, area of potential damage on the adjacent private garden in case of overflow (image: Garack, 2013), (e) damaged area after a bed fall (image: Garack, 2017), (f) area of potential damage due to change in cross-section, geometry transition and change of construction type (Image: Garack, 2013) [Color figure can be viewed at wileyonlinelibrary.com]

the construction types themselves, but on the shape of the watercourse section and its interactions with the adjacent surroundings.

*(A) Damage-relevant boundary conditions*

Punctual boundary conditions represent punctual structural discontinuities in the watercourse where turbulent flow processes occur. In particular, structures used to cross the watercourse such as bridges or culverts are potential bottlenecks where entanglement phenomena, scouring, and damage to adjacent structures can arise (De Cicco et al., 2018; Hajdukiewicz et al., 2016; Johnson, Gleason, & Hey, 1999; Langhammer, 2010; Ruiz-Villanueva et al., 2013). Typical transverse structures in the watercourse are slides, ramps, falls, or weirs. During flooding, the sudden acceleration of the water often causes damage to a transverse structure as well as to the adjacent infrastructure. In addition, special flow stresses on the stream bed or banks found at the estuaries of smaller streams can result in damage to bed or bank areas (Montgomery & Buffington, 1993, MacBroom 2017). Due to these potentially occurring damage mechanisms, we integrated "transverse and crossing structures" and the "mouth of tributaries" as punctual boundary conditions.

To identify linear structures, we used event analyses as well as the results of an extended literature review of model investigations. Thereby, the in-channel flow direction could be highlighted as a particular influencing variable (e.g., Song et al., 2018). Furthermore, several authors have shown that the condition and use of the riverbanks, in particular, influences the resistance of each section to hydraulic impacts (Bridge & Jarvis, 1977, Jin, Steffler, & Hicks, 1990, Miller, 1995, Wharton, 1995, Khatua & Patra, 2007, Terrier, Robinson, Shiono, Paquier, & Ishigaki, 2010, Buraas et al., 2014, Ghobadian, Tabar, & Koochak, 2016, MacBroom 2017). From this, we derived the linear boundary conditions "channel geometry", "special bank pressures" and "location in the channel". If stabilization structures are necessary, they must be introduced into the channel in a hydraulically favorable way. Transitional areas exist at the intersection of different forms of stabilization and when channel geometries change (e.g., from trapezoidal profile to natural profile). Such areas are subject to particularly high hydrodynamic stresses; if not properly designed or maintained, damage mechanisms can be enhanced, resulting in damage during flood events (Wharton, 1992, Hajdukiewicz et al., 2016, MacBroom 2017). Because of these relationships, we incorporate the linear boundary conditions of "construction changes" and "geometry transitions" when assessing the vulnerability of sections. Backwater areas are formed by a sudden change in bedline slopes, such as caused by transverse structures. During flooding, considerable sediment mobilization or sediment accumulation can occur here (Hajdukiewicz et al., 2016; Wicherski, Dethier, & Ouimet, 2017). As such artificially intensified flood potential can also damage the watercourse, these "backwater areas" must be taken into account as a linear damage-relevant boundary condition. In order to prevent damaging processes, it is important that regular and especially ecologically-oriented

**TABLE 2** Damage-relevant punctual, linear and planar boundary conditions at watercourses identical for Germany and Czech Republic (white background); German method (light grey background); Czech method; (s), simple; (e), extended, (dark grey background); SP, single parameter; RS, remote-sensing; m, meters

| Boundary condition | Database | Vulnerability class of the watercourse section due to the specification of a boundary condition | | | | |
|---|---|---|---|---|---|---|
| | | 1 – Very low | 2 – Low | 3 – Medium | 4 – High | 5 – Very high |
| Transverse structures and crossings | SP 2.1, 2.2, 4.5 count and specification | 0 | 1 | 2 | 3 to 4 | More than 4 |
| (transverse) | | 0 | Bed fall (<0.1 m), bottom threshold | Bed fall 0.1–0.3 m, smooth and rough sliding | Bed fall >0.3–1.0 m, bed fall with partial ramp, smooth and rough ramp | Bed fall >1.0 m, bed fall with fish passage or, bypass channel, dam, reservoir, pipes |
| (crossing) | | 0 | No morphological pressure | Nat. Bank, interrupted | Channel narrowed | Nat. Bank, interrupted and channel narrowed |
| | 4.2, 3.1 (s) | 0 | 1 | 2 to 3 | 4 to 5 | More than 5 |
| | 11-PPK (e), 6-UDN | 0 | Sliding / ramp | Bed fall <0,3 m | Weir/ bed fall >0.3–1.0 m | Bed fall >1.0 m, culvert, piping, reservoir |
| Mouth of tributaries | GIS count | 0 | 1 | 2 | 3 to 4 | More than 4 |
| Location in the channel | SP 1.1 | Point bar bank | Transition to the point bar bank | Parallel to flow | Transition to the undercut bank | Undercut bank |
| Channel geometry | SP 4.1 | Natural section | Approximately natural section | Trapeze-profile / double trapeze-profile | v-profile / box profile | Eroded profile / technical standard profile decaying |
| | 2.1, 3.1, 3.2 (s) | Natural section | - | Trapeze-profile, simple and combined | Box profile, trough profile | Eroded profile/ decaying profile |
| Geometry transitions | RS or map, count | 0 | 1 | 2 | 3 to 4 | More than 4 |
| Construction changes | SP 3.3, 5.2 count | 0 | 1 | 2 | 3 to 4 | More than 4 |
| | 3.4/3.5 (s) 6-UDN (e) | 0 | 1 | 2 | 3 to 4 | More than 4 |
| Backwater [m] | SP 2.3 | 0 | <10 m | 10 to 50 m | >50 to 75 m | >75 to 100 m |
| | 4.1 (s) | 0 | - | Partially | - | Completely |
| Special bank pressures | SP 5.01, DOP | None | Drains, vegetation waste | Sink and surge, wave impact | Erosion, trampling damage | Building rubble, household waste, |
| | Floodplain: 1.1, 1.2 (s) 10-OHR, 17-BMK (e) | - | Drains | - | Erosion and deposits over 5 m | - |
| Maintenance | | Regular | - | On demand | - | None |
| Land use | SP 6.1 /land use (GIS) | Woodland, native, typical meadow biotopes | Greenland, woodland, non-native | Fallow, park, green | Dense development, arable land, special crops | Development with open areas |
| | | | | Anthropogenic with natural | Arable land, special crops | Single building, land |

**TABLE 2** (Continued)

| Boundary condition | Database | Vulnerability class of the watercourse section due to the specification of a boundary condition | | | | |
|---|---|---|---|---|---|---|
| | | 1 – Very low | 2 – Low | 3 – Medium | 4 – High | 5 – Very high |
| | Floodplain: 3.1, 3.2 (s) 15-VNI (e) floodplain | Woodland, native, typical meadow biotopes | Greenland, woodland, non-native, pasture | elements, succession, park, green | | development, mining, industry |
| Harmful land features | SP 6.3 / land use (GIS) | None | Fishpond, retention basins | Paved traffic surfaces, digging holes, flood alleviation construction | Sewage treatment plant, storage yards, sports facilities | Dumps, waste dumps / farmhouse/ single buildings/ non-paved traffic surfaces |
| | Floodplain: 3.1, 3.2 (s) 14-VPZ (e) <50 m | None | Greenland, woodland, non-native, rocky wall, woodland, native, pond | Anthropogenic with natural elements, succession, park, green, railway(16-pin) | Arable land, special crops | Single building, land development, mining, industry |

watercourse maintenance be carried out (Moore & Rutherfurd, 2017). Watercourse maintenance includes, among a number of other measures, the care and maintenance of infrastructures and the riparian corridor to avoid potential damage during flood events (e.g., Mikuś et al., 2016). Accordingly, we include an evaluation of the respective "maintenance" as a linear boundary condition in our methodology to assess vulnerability.

Processes within the channel are not solely responsible for damage to channel infrastructures. In the case of unfavorable overflow conditions, land use alongside the watercourse can affect the vulnerability of the watercourse section. Thus we can say that sections are more or less vulnerable depending on their specific integration with the surrounding built environment (e.g., McBride et al., 2007). Our methodology takes account of the development of infiltrations or backwash and the resulting restrictions on the stability of infrastructures in the channel (see Figure 2). In particular, we represent these aspects by the planar boundary conditions "land use" and "harmful land features".

*(B) Databases*

To obtain potential parameters to assess the above-mentioned damage-relevant boundary conditions, we used general characteristics of the watercourse section (remote-sensing/watercourse network) and specific characteristics of individual parameters of the watercourses in Germany and the Czech Republic (Langhammer, 2014; LANUV NRW, 2012; MŽP CR, 2009). Next, we interpreted the characteristics of selected individual parameters to determine whether their spatial occurrence could result in damage processes during a flood event. Some features such as the "location in the channel" or the "mouth of tributaries" can be taken from remote-sensing data, geo-information systems or detected with the help of aerial photographs (see Langhammer, 2014). Table 2 shows the general classification of punctual, linear and planar boundary conditions within the relevant databases according to the respective characteristics of the German and Czech methodologies. The indicators that are potentially available for the simplified (s) and the extended (e) Czech detection method are listed for certain boundary conditions. For unspecified boundary conditions, the coverage method is considered identical for both countries. Regarding the German method, it should be mentioned that only structures whose distance is assessed as "low" have been included in the calculation, considering SP 6.3.

## 3.4 | Microscale: Construction types

Based on the mesoscale observation in sections, we conducted the microscale assessment of the vulnerability of watercourses at the object level. Within a watercourse section, there may be different types of bed or bank protection. While these are subject to the same hydrodynamic pressures in the event of flooding, they will present different levels of resistance due to their diverse types of construction. In order to characterize the behavior of construction types under certain impact situations, the authors prepared (A) an overview of construction types and databases, and then (B) an evaluation of the resistance of the construction types.

*(A) Construction types and databases*

Based on a comprehensive literature review of construction types in channel hydraulics, we found a huge diversity of possible bank and bed protection. However, there is a lack of detailed information on susceptibility to damage during flooding. For this reason, we grouped individual types of construction and examined information on the stress limits of the subordinate groups. Basically, it is possible to distinguish between solid construction types, fill construction types,

**TABLE 3** Classification of construction types into resistance classes based on the German and Czech detection methods

| Single parameter D | Indicator//parameter CZ (s): Simple method (e): Extended method | Resistance | Source |
|---|---|---|---|
| EP 3.3 bed protection | 3.6 bed attachments (s), 6-UDN bed condition (e) | | Magilligan, 1992, LfU, 1996, Oplatka, 1998, Knighton, 1999, Gerstgraser 2000a & 2000b, Schillinger, 2001, SMUL, 2005, Julian & Torres, 2006, Nachtnebel, 2008, Feldmann, 2009, MŽP CR, 2009, Krapesch, Hauer, & Habersack, 2011, LANUV NRW, 2012, Sin, Thornton, Cox, & Abt, 2012, Vocal Ferencevic & Ashmore, 2011, Buraas et al., 2014, Langhammer, 2014, EFIB, 2015, Marchi et al., 2016, MacBroom 2017 |
| No protection | Unpaved (s), unchanged (e) | - | |
| - | Bed threshold / sole bar (s) | 4 – High | |
| Riprap | Riprap (e) | 4 – High | |
| Artificial bed, paving | Continuously paved (s), concrete, stone paving (e) | 5 – Very high | |
| EP 5.2 Bank protection | 3.4, 3.5 6 Bank attachments (s), 12-UDN Bank structure (e) | | |
| No protection | Unpaved (s), unchanged (e) | - | |
| Sheet-piling | - | 5 – Very high | |
| Concrete, wall, jointed, masonry | Natural stone paving, concrete blocks, slabs, walls (s), paving in concrete, concrete slabs, concrete profiles (e) | 5 – Very high | |
| Bio-engineered protection | (local) biological alteration, willow mesh, semi-vegetated attachment, (s), attached with trees/ willow fences, vegetation blocks with grass (e) | 4 – High | |
| Cobbles, quarrystones, non-jointed | Cobbles, vegetated cobbles, slope base protection (s). | 4 – High | |
| Riprap | Gabions (s/e)/greened (s), riprap (e) | 4 – High | |
| Training works | - | 4 – High | |
| Wood protection | Wood constructions (s) | 3 – Middle | |
| Lawn on the embankment | Shallow embankment (s), bank vegetated with grass (e). | 2 – Low | |
| Groynes | - | 2 – Low | |
| Dumped protection | Free combinations, building waste (s), decayed construction, bed material (e) | 1 – Very low | |

near-natural construction types, as well as combined construction types (bio-engineering). The authors pursued the idea of using previously existing parameters from the hydro-morphological survey protocol (see Section 2.2) to derive a suitable classification of construction types. The classification is thus based on the German and Czech recording methods (Langhammer, 2014, LANUV NRW, 2012, MŽP CR, 2009). On the German side, we used the individual parameters "3.3 - bed protection" and "5.2 - bank protection" for the bed and bank areas (Table 3). On the Czech side, we identified the suitable indicators "3.4 - bank protection left", "3.5 - bank protection right" and "3.6 - bed protection" (simplified methodology) as well as "6-UDN" and "12-UBR" (extended methodology). Making use of 21 classes (MŽP CR, 2009), the simplified methodology differentiates between significantly more potential types of bank and bed protection than the German approach, which uses 14 classes. Table 3 shows the classification of the construction types as derived by the authors.

*(B) Resistance to impact factors*

In the next step, we characterized the resistance of the construction types on the basis of hydrodynamic impact variables. For this purpose, we investigated correlations between damage mechanisms and the prevailing flow situations or impact variables from the literature (Jirka & Lang, 2009; Kreibich et al., 2009; Sabrowski, 2008; Stotts et al., 2015; Suaznabar et al., 2017). The studies by Baryshnikov (2006), Feldmann (2009), Kryzanowski, Mikoš, Šušteršič, Ukrainczyk, and Planinc (2012), and Froehlich (2013) looked at how resistant masonry or concrete structures are to individual impact variables. On this basis, we determined the resistance of the concrete and masonry construction types (see Table 3). Other authors such as Zeh (2007), Anstead, Boar, and Tovey (2012), Afzalimehr, Moradian, Gallichand, and Sui (2016), Recking, Piton, Montabonnet, Posi, and Evette (2019), or Rey et al. (2019) have assessed the response of bio-engineering construction types and near-natural construction types to individual impact variables. In Stephan and Gutknecht (2002), Green (2005), Rhee, Woo, Kwon, and Ahn (2008), EFIB (2015), and BAW (2018), further information on near-natural riparian features such as reed beds, riparian scrub, or woody galleries can be found, which find application in the Czech survey methodology. We summarized these bio-engineered and nature-based construction types before assessing them in terms of their resistance (see Table 3). Compilations of the resistance of different types of structure based on the respective impact variables are also given by Florineth (1993), LfU (1996), Schiechtl and Stern (1997), Oplatka (1998), Bollrich (2013), and Patt, Jürging, and Kraus (2018). These compilations are also integrated into our derivations. In Table 3, the construction types identified on the German and Czech sides are classified in terms of their resistance. Table 4 shows the various classes of resistance used here.

**TABLE 4** Impact variables used to classify the resistance of construction types

| Impact variable | Unit | Resistance class 1 – Very low | 2 – Low | 3 – Medium | 4 – High | 5 – Very high | Source |
|---|---|---|---|---|---|---|---|
| Flow velocity | [m/s] | 0.1–1.0 | >1.0–2.0 | >2.0–3.0 | >3.0–4.0 | >5.0 | Magilligan, 1992, LfU, 1996, Oplatka, 1998, Knighton, 1999, Gerstgraser 2000a & 2000b, Schillinger, 2001, SMUL, 2005, Julian & Torres, 2006, Nachtnebel, 2008, Feldmann, 2009, Krapesch et al., 2011, Sin et al., 2012, Vocal Ferencevic & Ashmore, 2011, Buraas et al., 2014, Song et al. 2018, EFIB, 2015, Marchi et al., 2016, MacBroom 2017 |
| Shear stress | [N/m$^2$] | 1–75 | >75–150 | >150–200 | >200–400 | >400 | |
| Stream power | [W/m$^2$] | 1–75 | >75–300 | >300–600 | >600–1,600 | >1,600 | |

Based on a further literature screening (Davis & Harden, 2014; Gerstgraser, 2000a & 2000b; Hopkinson & Wynn-Thompson, 2016; Klösch et al., 2018; Kolb, 1979; Magilligan, 1992; Park, Kim, Park, Jo, & Kang, 2016; Sin et al., 2012), we identified flow velocity and shear stress to be governing impact variables. A number of articles also rely on the impact variables of absolute and specific stream power presented earlier in Section 3.2. These studies describe how flood events affect stream hydro-morphology and ecology (Anderson, Rizzo, Huston, & Dewoolkar, 2017; Bizzi & Lerner, 2015; Hajdukiewicz et al., 2016; Hickin & Nanson, 1984; Knighton, 1999; Krapesch et al., 2011; Lague, 2014; Magilligan, 1992; Marchi et al., 2016; Miller, 1990; Thompson & Croke, 2013; Vocal Ferencevic & Ashmore, 2011). In this context, some individual studies have considered the interdependencies of flow velocity, shear stress, and stream power (Dubinski & Wohl, 2013; Soar, Wallerstein, & Thorne, 2017). For example, Soar et al. (2017) defined the product of flow velocity and shear stress as "specific stream power". We have integrated this relationship and thus the impact based on stream power into our HyVAC assessment methodology. In summary, the HyVAC method is thus based on the three impact variables of *flow velocity*, *shear stress* and *stream power*, which can be used to classify the resistance of different types of constructions to hydrodynamic pressures in watercourses. In general, we use threshold analysis to identify significant change signals in resistance. Table 4 shows the associated literature references and the resulting ranges of impact magnitudes and assigned classes of resistance.

As previously pointed out, the current condition of a watercourse also contributes to the development of damage processes (Hauer et al., 2010; MacBroom et al., 2017; Moore & Rutherfurd, 2017; Müller, 2010). Studies such as those by Rickard (2009), Hauer et al. (2010), and Spörel (2012), have shown which damage patterns can lead to which damage mechanisms. In addition, Rudolf-Miklau, Suda, and Sicher (2007) designed a method to assess the structural condition of torrent obstructions. Further, Moore and Rutherfurd (2017) identified neuralgic stress areas such as mortar joints. McBroom et al. (2017) also envisioned the introduction of so-called "structure damage codes" for streams. We follow these approaches by assuming that resistance decreases as a function of the structural condition of bed and bank construction types. Accordingly, vulnerability at the microscale level is assessed by classifying the watercourse condition.

Table 5 gives an overview of potential forms of damage of the various construction types, grouped into condition classes. Here we describe damage patterns of technical as well as technical-biological bank and bed construction types (see LfU, 1998), which can be assigned to the respective condition class by means of visual assessment (McBroom et al. 2017). While condition class "1" describes a perfect state, class "5" is assigned to construction types that are almost completely damaged and can offer minimal or no resistance to flood events. A special feature with regard to condition assessment is the simplified assessment method in the Czech Republic (MŽP CR, 2009). Here the indicator 3.8 ("condition of the pavements") is used to record characteristics during mapping that are ignored in the German method.

**TABLE 5** Classification of the structural condition of construction types based on condition classes, including extent of damage and verbal description (indicator description 3.8 from Czech method in brackets); pictures: 1: Garack, 2013, 2: Garack 2018, 3: Garack 2018, 4: Garack 2017, 5: Daniel Baránek, license: CC BY-SA 4.0, Source: Wikimedia Commons [Color table can be viewed at wileyonlinelibrary.com]

| Condition class | Extent of damage | Picture | Description of technical construction | Description of bio-engineering |
|---|---|---|---|---|
| 1 | Intact, undamaged |  | No visible superficial loss of substance, no weathering, spalling, erosion or abrasion phenomena (3.8: Visible, not overgrown) | No undesirable erosion phenomena on bio-engineering (3.8: Bio-engineering) |
| 2 | Superficial damage |  | Surface erosion, cracking, punctual mechanical damage, washout of joint material, weathering, exposed reinforcement, reduced bed resistance due to depressions (3.8: Partially vegetated) | Incipient undesirable erosion, feathering of timber structures/visible erosion on bio-engineering, self-regulation |
| 3 | Substantial damage |  | Isolated removal of structural elements, larger cracks, frequent cracks, lack of grout, missing stones, major spalls, potential impairment of load-bearing capacity, undesirable scouring of the bed, exposed construction embedment in the watercourse and lateral embedment. (3.8: Silted up, vegetated). | Less than 50% of timber structures destroyed, live structures with erosion and incipient loss of substance (woody plants), fraying and breakage of timbers, subsidence, deformation and landslides, self-regulation partially limited |
| 4 | Serious damage |  | Significant removal of parts of the construction and/or mechanical damage of up to 50% of the construction, absence of masonry parts, impairment of stability, serious scouring of otherwise attached bed | Severe damage to timber structures, bio-engineering with erosion and loss of substance (woody plants), deformation, slippage and lack of slope base protection, slope failure, self-regulation severely limited |
| 5 | Major damage to complete destruction |  | Heavy erosion of parts of the construction, predominant to complete loss of the construction body, mechanical foundation failure to be expected, urgent restoration of stability (3.8: Destroyed after flood) | Predominant loss of timber construction/ bio-engineering, urgent measures needed due to lack of self-regulation |

**TABLE 6** Vulnerability of construction types derived from the resistance classes and condition classes shown in Tables 4 and 5

| | | Condition class of construction (Table 5) | | | | |
|---|---|---|---|---|---|---|
| Vulnerability of construction ($V_c$) | | 1 | 2 | 3 | 4 | 5 |
| Resistance class of construction (Table 4) | 5 | 1 | 2 | 3 | 4 | 5 |
| | 4 | 2 | 3 | 4 | 5 | 5 |
| | 3 | 3 | 4 | 5 | 5 | 5 |
| | 2 | 4 | 5 | 5 | 5 | 5 |
| | 1 | 5 | 5 | 5 | 5 | 5 |

We determined the vulnerability of bed and bank construction types by overlaying resistance (see Table 4) and structural condition (see Table 5) in the form of an evaluation matrix (Table 6) in order to integrate the effects of the maintenance status of the watercourse (see, for example, Müller, 2010 or MacBroom et al., 2017).

## 3.5 | HyVAC methodological framework and calculation method

### 3.5.1 | Methodological framework

Figure 3 summarizes the methodological framework for determining the vulnerability of watercourses to flooding at the three spatial scales described. Regarding the macroscale classification of ecoregions, it is already evident that on the German side, three ecoregions influence the vulnerability assessment, whereas on the Czech side almost the entire national territory is assigned to the region "Central Highlands".

Table 7 summarizes the relevant assessment parameters at the three spatial scales with the respective influences on the vulnerability of watercourses (derived by impact analysis). The assessment was initially carried out separately in the form of a qualitative assessment at the macroscale and a quantitative assessment at the mesoscale and microscale. After integrating the quantitative assessments at these last two scales, the result was combined with the qualitative assessment specific to the type of watercourse. In so doing, we are able to take these characteristics into account when deriving suitable adaptation measures with the help of the index "watercourse type-specific vulnerability" (WTSV index, see Table 1). The application of our HyVAC method to the German and Czech case studies will now be described in the following sections.

### 3.5.2 | Quantitative calculation method across scales

We determine the vulnerability of the watercourse section $V_S$ by combining the vulnerabilities of the watercourse bed and the left and right bank, taking into account the boundary conditions, according to Equation (3):

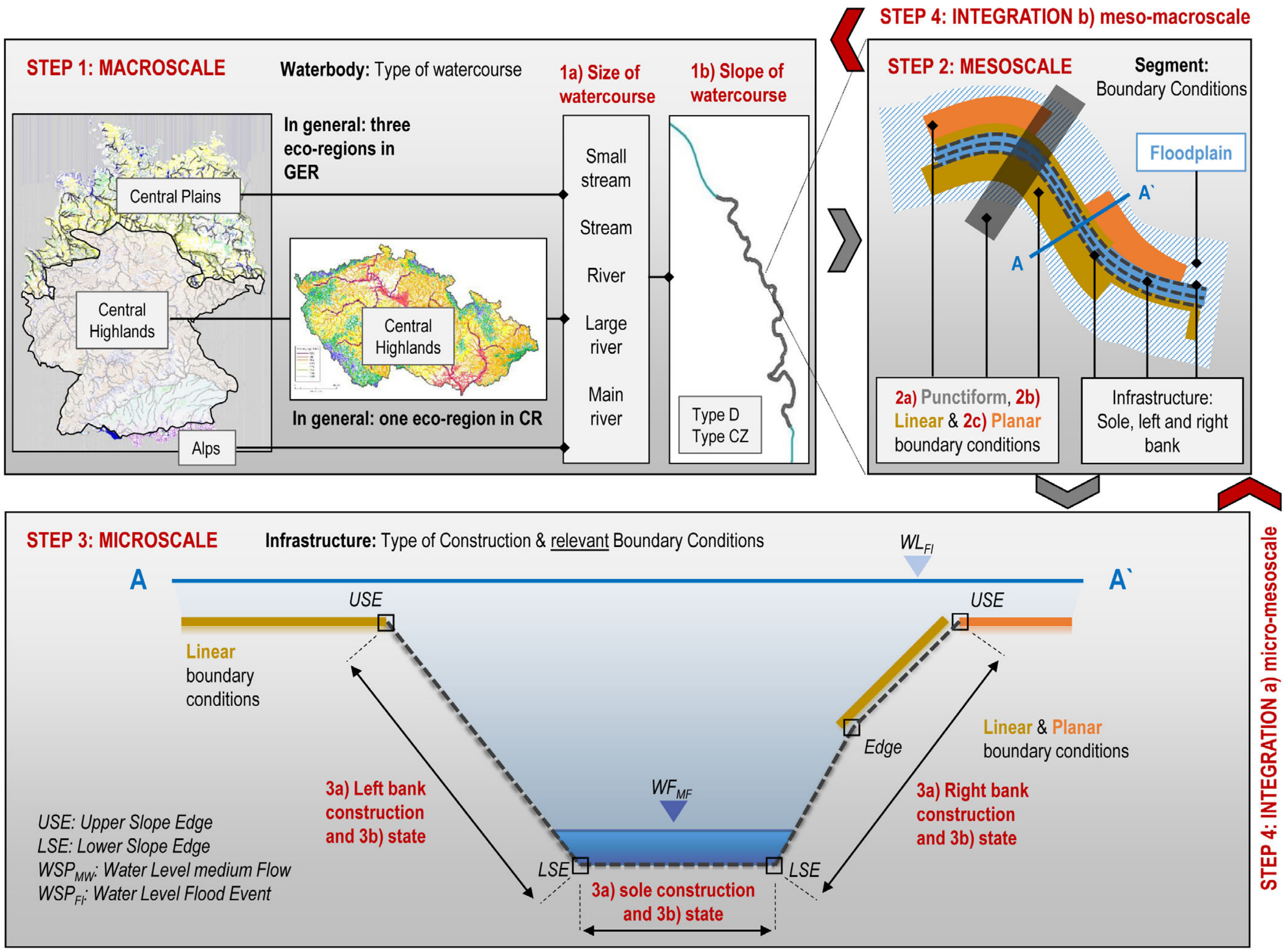


**FIGURE 3** Methodological framework and visualization of the three spatial scales used to assess the vulnerability of watercourses [Color figure can be viewed at wileyonlinelibrary.com]

**TABLE 7** Comparison of watercourse characteristics for hydro-morphological assessment and assessment of flood-induced vulnerability of watercourses (impact and parameters): qualitative assessment (macroscale) and quantitative assessment (mesoscale and microscale)

| Scale | Feature of the watercourse | Hydro-morphologic significance | Impact on vulnerability | Assessment parameters |
|---|---|---|---|---|
| Macro –regional | Ecoregion | Typology | Slope class and discharge class | Size and valley floor slope |
| | Watercourse type | Assessment references | Slope class and discharge class | Size and valley floor slope |
| | Catchment area | Typology | Slope class and discharge class | Watercourse vulnerability class |
| Meso –local | Transverse and crossing structures | Barriers to migration, interruption of ecological continuity | Punctual boundary condition | Count and specification |
| | Mouth of tributaries | External habitation and disturbance | Punctual boundary condition | Count |
| | Location in the channel | Habitats | Linear boundary condition | Specification |
| | Channel geometry | Channel development, structural diversity | Linear boundary condition | Specification |
| | Geometry transitions | Channel development, structural diversity | Linear boundary condition | Count |
| | Construction changes | Structural diversity, refuge | Linear boundary condition | Count |
| | Backwater | Harmful parameters (flow, plugging) | Linear boundary condition | Specification |
| | Special bank pressures | Harmful parameters (artificial, harmful deposits). | Linear boundary condition | Specification |
| | Maintenance | Structural diversity | Linear boundary condition | Specification |
| | Land use | Corridor of development | Planar boundary condition | Specification |
| | Harmful land features | Harmful parameters, influences on habitats | Planar boundary condition | Specification |
| Micro –object | Bed protection, bank protection (left and right) | Flood control infrastructure | Resistance | Type |
| | Structural condition | Potential refuges and niches for flora and fauna | Reduction of resistance | Specification |

$$V_s = \frac{\sum V_{IA}}{3} = \frac{V_{bed} + V_{bank\_l} + V_{bank\_r}}{3} \quad (3)$$

with,

$V$ … vulnerability.

$S$ … section of the watercourse.

$IA$ … impact area (bed, left bank, right bank).

The respective impact of the boundary conditions is taken into account for assessing vulnerability in the watercourse section. The characteristics in Table 2 are used to evaluate a boundary condition. In addition, the boundary conditions are assigned to the area of impact in the channel, that is, whether harmful effects on the bank or bed construction are to be assessed ("bed", "respective banks"; see Table 8). Therefore, the vulnerabilities of the two influencing variables of the immediate impact area ($IA$) and the

**TABLE 8** Impact areas of boundary conditions

| Boundary condition | Impact areas |
|---|---|
| $Pu_1$ – Transverse and crossing structures | Bed & bank |
| $Pu_2$ – Mouth of tributaries | Respective banks |
| $L_1$ – Location in the channel | Respective banks |
| $L_2$ – Channel geometry | Banks |
| $L_3$ – Geometry transitions | Bed, banks |
| $L_4$ – Construction changes | Bed, respective banks |
| $L_5$ – Backwater | Bed |
| $L_6$ – Special bank pressures | Respective banks |
| $L_7$ – Maintenance | Bed & bank |
| $Pl_1$ – Land use | Respective banks |
| $Pl_2$ – Harmful land features | Respective banks |

additional boundary conditions ($BC$) are calculated according to Equation (4):

$$V_{IA} = \frac{V_{IA} + V_{BC}}{2} \text{ if } V_{BC} > V_{IA} \text{ or } V_{IA} = V_{IA} \text{ if } V_{BC} \leq V_{IA} \tag{4}$$

with,

$BC$ … boundary conditions.

The influence of the damage-relevant punctual, linear and planar boundary conditions is integrated with different weighting when determining the vulnerability (see Section 3.3, Table 2). It should be noted that not all boundary conditions influence all three impact areas (see Table 8). For example, the backwater areas ($L_5$) only influence the bed and not the banks. This is expressed by an influential factor in Equation (5). In the case of $L_5$, for example, the influential factor is equal to 1 for the calculation of the bed and zero for the calculation of the banks:

$$V_{BC} = \frac{\sum k_i \times w_b \times V_b}{\sum k_i \times w_b} \tag{5}$$

with,

$b$ … boundary condition (Punctual, Planar, Linear:

$b = Pu_1, Pu_2, Pl_1, Pl_2, L_1, L_2, L_3, L_4, L_5, L_6, L_7$).

$k_i$ … influential factor (boundary condition influences impact area: $k_i = 1$; no influence $k_i = 0$).

$w_b$ … weighting factor (moderate influence of boundary condition: $w_b = 1$; strong influence: $w_b = 2$).

On the watercourse banks, all boundary conditions can have a damage-relevant effect, with the exception of $L_5$ (backwater areas), so that $k_{i,L5} = 0$ applies here. The boundary conditions $Pu_1$, $L_3$, $L_4$, $L_5$ and $L_7$ can potentially increase the damage to the watercourse bed so that the influential factor $k_i$ is set to 1 in these cases. The boundary conditions of transverse and crossing structures ($P_1$), the location in the water body ($L_1$) and the channel geometry ($L_2$) have a particularly strong effect and are therefore included in the above Equation (4) with a weighting factor $w_b$ of 2.

The vulnerability of the impact area of the watercourse section, which is included in Equation (3) at the mesoscale, is determined by combining the vulnerabilities of individual construction types within this section, which are determined individually at the microscale. The integration is carried out using a worst-case approach according to Equation (6). This means that the construction type with the highest vulnerability primarily determines the aggregated vulnerability of the respective impact area.

$$V_{IA} = \max(V_{C,1}, V_{C,2}, \ldots, V_{C,n}) \tag{6}$$

with,

$C_n$ … construction type.

$n$ … number of different construction types in the impact area.

#### 3.5.3 | Integration of quantitative and qualitative assessment method

To integrate the quantitative assessment results into the qualitative assessment of the macroscale watercourse type-specific vulnerability, we combine $V_s$ (Equation (3)) and WTSV (Table 1). On this basis, conclusions can be drawn on the extent of reconstruction and adaptation measures in terms of flood damage prevention for potentially similarly assessed vulnerabilities of watercourse sections in different watercourse types. For example, the reconstruction of a bank wall in a larger watercourse (very high WTSV index) is a major undertaking under extreme hydraulic pressures. In contrast, less robust construction methods can be used in small lowland streams (low WTSV index). Consequently, the damage potential in watercourses with a higher WTSV index is also higher. The schematic comparison of $V_s$ and WTSV is shown in Figure 4, where red areas indicate major adaptation measures and blue areas represent less extensive adaptation measures.

## 4 | APPLICATION AND TRANSFERABILITY OF HYVAC METHOD USING CASE STUDIES

### 4.1 | Case study areas in Germany and the Czech Republic

As part of the transnational INTERREG VA research project "STRIMA II" on Saxon-Czech flood risk management, a comparison was undertaken of methods and case studies in these two countries. In each case, small and medium-sized watercourses (10–1,000 km$^2$ catchment area) were studied. In Germany, the focus was on a medium-sized watercourse, namely the Müglitz in the Eastern Ore Mountains (*Osterzgebirge*), which in its upper reaches also runs a few kilometers through Czechia. On the Czech side, the small town of Frýdlant in the Liberec district was chosen for the study due to its tendency to suffer flooding (most recently, in 2010 and 2011). Here the Řasnice, a small watercourse, was the object of investigation (Figure 5).

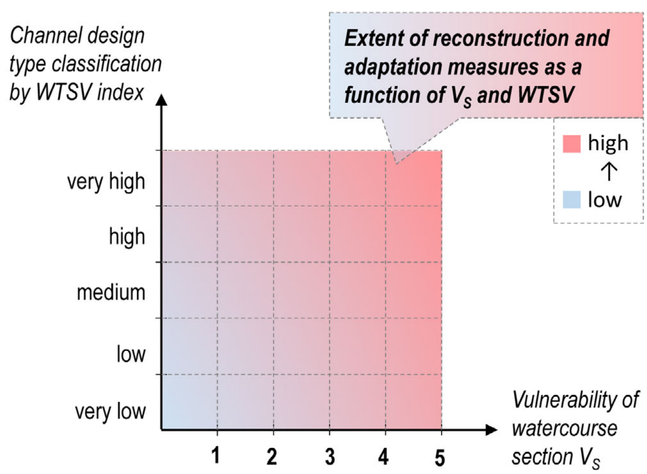


**FIGURE 4** Derivation of the extent of reconstruction and adaptation measures by integrating quantitative and qualitative assessment [Color figure can be viewed at wileyonlinelibrary.com]

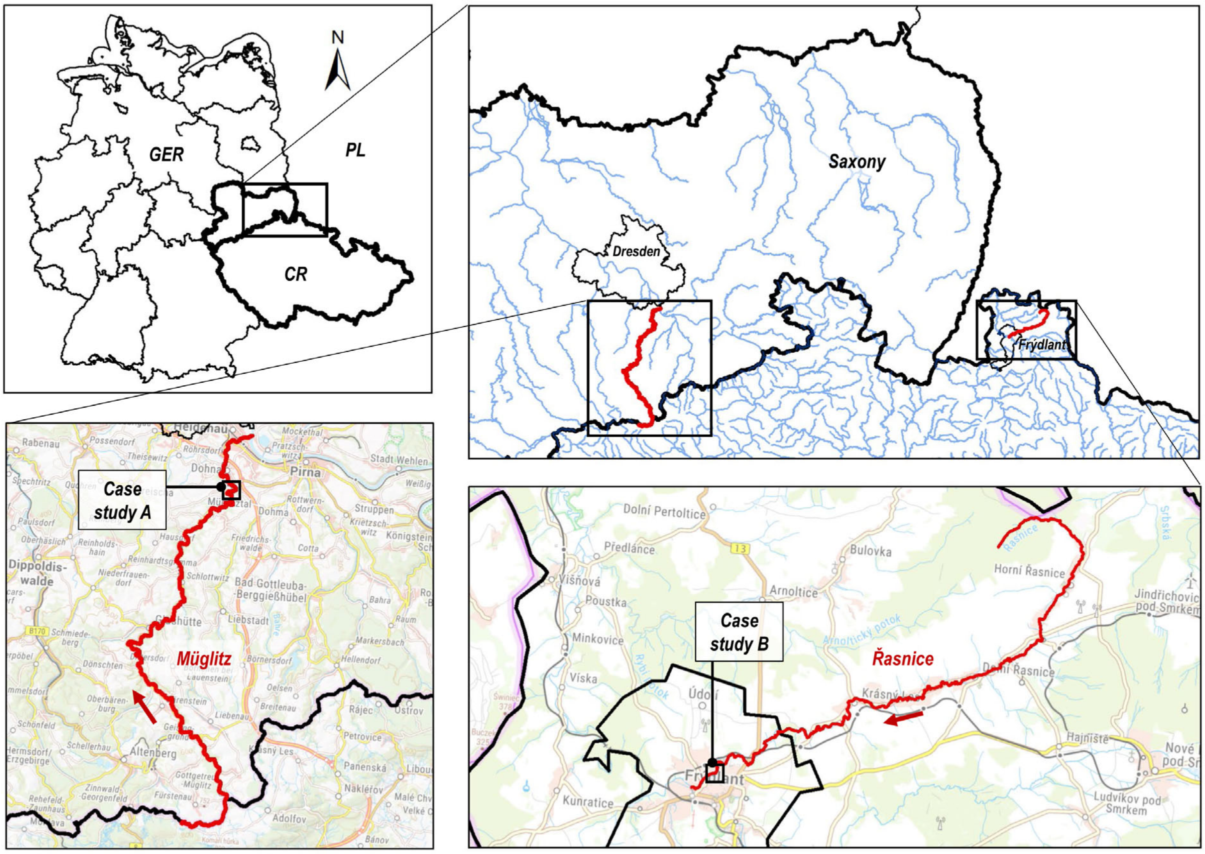


FIGURE 5 Location of the case study areas (data basis: river network: ZABAGED® Geobasis, administrative boundaries: Federal Agency for Cartography and Geodesy Germany, Saxon State Office for Environment, Agriculture and Geology & ZABAGED® Geobasis Data Topographic Map: WMS TopPlusOpen) [Color figure can be viewed at wileyonlinelibrary.com]

In this section, the theoretical-methodological principles of the previous chapters will be employed to confirm not only their applicability but also further possibilities of transferability (Section 4.4). In order to illustrate the special characteristics of medium-sized and small rivers, the Müglitz and Řasnice are subject to an in-depth investigation.

The Müglitz rises in the Czech Eastern Ore Mountains, where it is known as "Mohelnice". It runs for 49 km to the north before draining into the Elbe in the town of Heidenau, southeast of Dresden. The 209 km$^2$ catchment area has a typical highland character with forested steep slopes as well as agricultural use on the moderately steep uplands and hilltops. Accordingly, a steep flood hydrograph is formed during heavy precipitation events, whereby the high average bottom slope (1.4%) leads to particularly dynamic runoff processes in the valley. There is historical evidence of extreme flood events occurring in 1897, 1927, 1957, and more recently in 2002, each of which claimed human lives (Garack, 2013). In 2002, the villages of Glashütte, Schlottwitz and Weesenstein were particularly badly hit. Here we select one section of the watercourse in the village of Weesenstein as our object of investigation in order to identify the relevant influencing variables for assessing vulnerability.

Rising in the foothills of the Jizera Mountains in the German-Polish-Czech border region, the Řasnice flows into the Smědá River at the small town Frýdlant after a flow length of 16.3 km. With a catchment area of 32.3 km$^2$, the Řasnice runs from northeast to southwest and has a mean bottom gradient of 0.99%. The flood events of 2010 and 2011 were particularly destructive in Frýdlant, with major damage also occurring along the course of the Řasnice (see Table 2). The current vulnerability will be assessed on the basis of an exemplary section.

## 4.2 | Application of the HyVAC method: Qualitative vulnerability assessment of watercourses at the macroscale

To assess vulnerability at the macroscale, the Müglitz and the Řasnice are classified according to Table 1. In Table 9, in addition to a general overview, we present the assessment approaches applied to these watercourses. In order to compare the two river sections at a macroscale level of vulnerability, it is crucial to know the watercourse type of the Müglitz and Řasnice and their vulnerability classes as specified in Table 1. According to Table 1 and Table 9, the Müglitz can be assigned a "very high" watercourse type-specific vulnerability (type 5); the Řasnice, on the other hand, is a watercourse type C4 and thus has a "medium" watercourse type-specific vulnerability. To distinguish these watercourses, the vulnerability of the water body section can be specified with the help of the WTSV index (vh: very high, h: high,

**TABLE 9** Vulnerability of watercourse types in Germany/Czechia and WTSV index of the case study watercourses

| Types (D, CR) | | Discharge class 1 | 2 | 3 | 4 | 5 | WTSV index | | Type Müglitz | Řasnice |
|---|---|---|---|---|---|---|---|---|---|---|
| Slope class | 1 | - | 2/11; B | 2/15/17; C2 | C1/F | 10/20 | 1 | Very low | | |
| | 2 | 19 | B | C2 | 9.2; C1/F | - | 2 | Low | | |
| | 3 | A1 | 14/18; A1/B/C3/C4/G | 9; A1/G | - | - | 3 | Medium | | C4 |
| | 4 | A1 | 6/16; A1/A2/B/D/E/G | A1/G | - | - | 4 | High | | |
| | 5 | 5; A1 | 3/5/5.1/1; A1/A2/B/D/E/G | 3/1;A1/G | - | - | 5 | Very high | 5 | |

m: medium, l: low, vl: very low). In the following, the vulnerability of each water section is determined according to Equations (4)–(6).

## 4.3 | Application of the HyVAC method: Quantitative vulnerability assessment of watercourse sections at the micro−/meso-scale

### 4.3.1 | Calculation path

Unfortunately, no data was available for Czech rivers at the time of data collection. Therefore, the mapping was based on the survey methodology used in Germany. Of course, this aids comparability of the collected parameters as the same categories are thus applied in both countries. The application of the HyVAC method requires a stepwise approach: first, the essential parameters (e. g. from LfULG 2016) are determined at the individual scale levels and then integrated step by step using the calculation rule described in Section 3.5.2 before transferring them to the next scale in each case according to Section 3.5.3. Figure 6 illustrates the step-by-step determination of the vulnerability of an impact area in a watercourse section.

### 4.3.2 | Watercourse type-specific vulnerability

The assessment methodology begins with step 1, namely the quantitative determination of the watercourse type-specific vulnerability (WTSV index, see Section 3.2, Figure 3 and Section 4.4, Figure 6), which is calculated from the slope class (step 1a) and the discharge class (step 1b). The investigated section of the Müglitz has a slope class of 5 and a discharge class of 2. Using the evaluation matrix in Table 9 gives a WTSV index of "very high". For the Řasnice, a slope class of 3 and a discharge class of 2 give a WTSV index of "medium". Accordingly, the section of the Müglitz shows a very high damage potential while the section of the Řasnice has a medium damage potential.

### 4.3.3 | Vulnerability due to damage-relevant boundary conditions

In step 2, the potentially damage-relevant boundary conditions at the considered watercourse sections are classified according to Table 2 in Section 3.3 (see also Figures 3 and 6). The assessment is carried out separately for each impact area (watercourse bed and banks). Table 10 shows the results of the classification of the various boundary conditions on the three impact areas in the watercourse sections of the Müglitz and Řasnice.

The vulnerability classes due to damage-relevant boundary conditions are derived from these values. For this, the identified damage-relevant boundary conditions are weighted according to their importance and combined separately into an aggregated value for each of the three impact areas using Equation (5). Equation (7) illustrates this procedure for the left bank of the Müglitz:

$$V_{BC}=\frac{\sum k_i \times w_b \times V_b}{\sum k_i \times w_b} =\frac{2\times3+1\times1+1\times5+1\times3+2\times4+2\times3+1\times2+1\times2+1\times1+1\times1}{2+1+1+1+2+2+1+1+1+1+1} =\frac{35}{13}=2.69 \tag{7}$$

with,
$w_b$ … weighting factor of boundary conditions. b.
$V_b$ … vulnerability due to boundary conditions.
$b$ … boundary condition (Punctual, Planar, Linear: $b = Pu_1, Pu_2, Pl_1, Pl_2, L_1, L_2, L_3, L_4, L_5, L_6, L_7$).

(influential factor $k_i = 1$ in all cases shown and therefore omitted here)

Calculation of the vulnerabilities due to the boundary conditions gave a value of 2.15 for the right bank of the Müglitz and 2.00 for the bed, respectively. In an analogous way, the vulnerabilities due to the boundary conditions for the Řasnice were determined as 2.33 for the bed, 2.31 for the left bank and 3.15 for the right bank.

### 4.3.4 | Vulnerability of construction types in the impact areas (watercourse bed and banks)

In step 3a of the assessment methodology (see Figures 3 and 6), the resistance of the construction types in the watercourse section to be investigated is determined under the assumption that the construction is in perfect condition. Here also the assessment is carried out separately for each impact area, namely the watercourse bed and banks. The resistance classes of the construction types were assigned to the construction types found in the watercourse sections using the

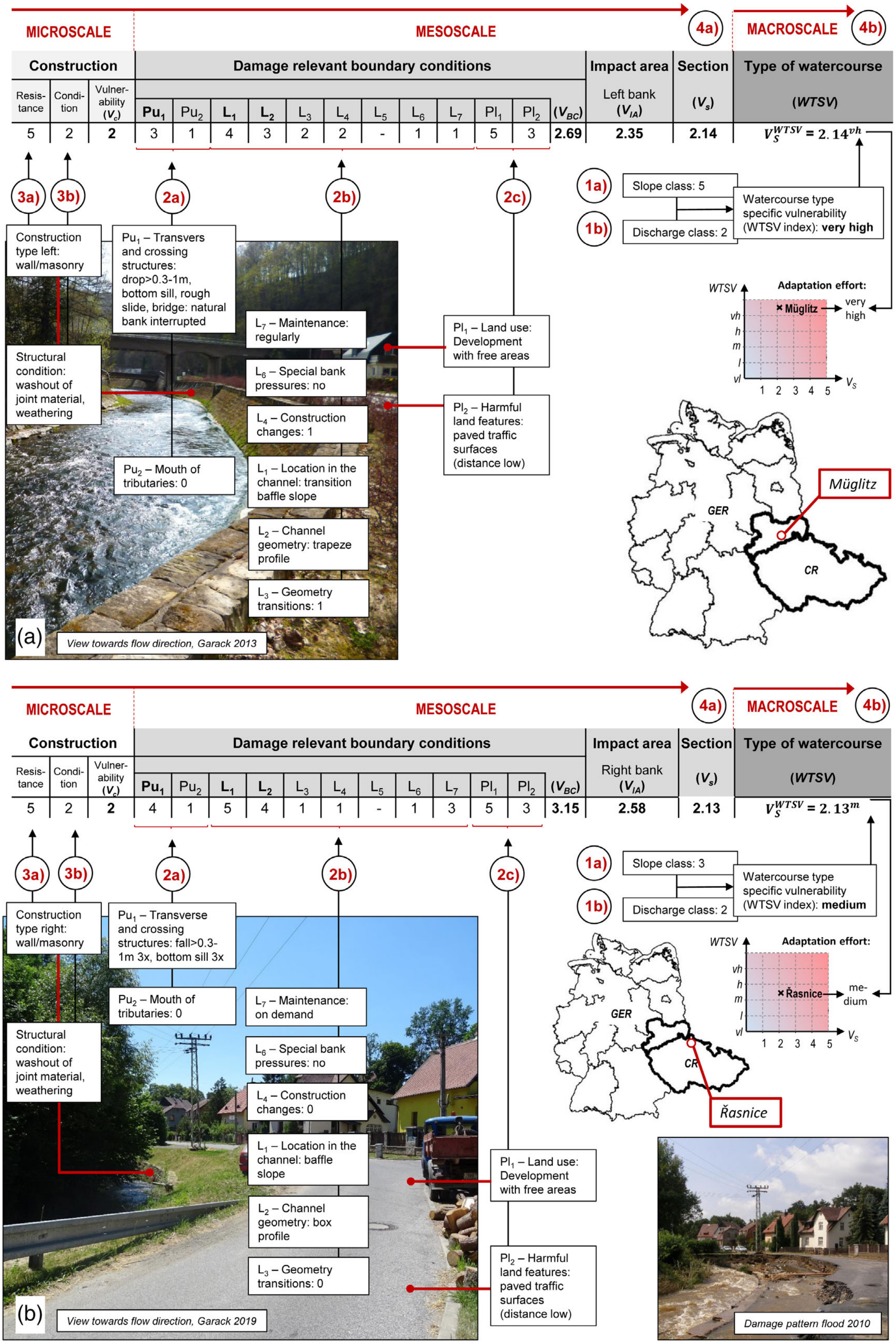


**FIGURE 6** Schematic illustration of the calculation steps for the quantitative assessment of a watercourse section using the case studies of (a) impact area: left bank of the Müglitz and (b) impact area: right bank of the Řasnice [Color figure can be viewed at wileyonlinelibrary.com]

**TABLE 10** Section-specific assignment of damage-relevant boundary conditions for the Müglitz and the Řasnice (values in bold are used in the following exemplary calculations)

| | Section Müglitz | | | Section Řasnice | | |
|---|---|---|---|---|---|---|
| Boundary condition | Bed | Left bank | Right bank | Bed | Left bank | Right bank |
| $Pu_1$ – Transverse & crossing structures | 3 | 3 | 3 | 4 | 4 | 4 |
| $Pu_2$ – Mouth of tributaries | - | 1 | 1 | - | 1 | 1 |
| $L_1$ – Location in the channel | - | 4 | 2 | - | 1 | 5 |
| $L_2$ – Channel geometry | - | 3 | 4 | - | 4 | 4 |
| $L_3$ – Geometry transitions | 2 | 2 | 2 | 1 | 1 | 1 |
| $L_4$ – Construction changes | 2 | 2 | 2 | 1 | 1 | 1 |
| $L_5$ – Backwater | 1 | - | - | 1 | - | - |
| $L_6$ – Special bank pressures | - | 1 | 1 | - | 1 | 1 |
| $L_7$ – Maintenance | 1 | 1 | 1 | 3 | 3 | 3 |
| $Pl_1$ – Land use | - | 5 | 2 | - | 4 | 5 |
| $Pl_2$ – Harmful land features | - | 3 | 1 | - | 1 | 3 |

hydro-morphological assessment method of Germany (LANUV NRW, 2012, see Sections 3.3 and 3.4). For the left bank of the Müglitz, a masonry construction was found in the investigated watercourse section, which was assigned to resistance class 5 according to Section 3.4, Tables 3 and 7. The same value of 5 was determined for the right walled bank of the Řasnice.

In order to move from resistance to an assessment of the vulnerability of the construction types, the structural condition of the protection construction types must be examined in the following step. Therefore, in step 3b, the structural conditions are classified according to the scheme shown in Table 5 (see Section 3.4). For the example of the Müglitz, the wall of the left bank of the watercourse shows superficial damage. The masonry structure was thus assigned to condition class 2 according to Table 5. The right walled bank of the Řasnice was assigned to the same class.

Using the evaluation matrix (Table 6) to complete step 3, the combined parameters of resistance class 5 and condition class 2 of the vulnerability of constructions ($V_c$) on the left bank of the Müglitz give a value of 2 for this masonry construction. Since this one construction type is predominant in the selected section, it automatically determines the impact area of the left bank over the entire watercourse section. Applied to Equation (6), the aggregated vulnerability is thus simply:

$$V_{bank,l} = \max(V_{C,1}) = max(V_{\text{masonry wall}}) = \max(2) = 2 \tag{8}$$

Evaluations carried out in an analogous manner of the construction types and their structural conditions on the bed of the Müglitz as well as its right bank also led to a classification in vulnerability class 2. For the section of the Řasnice in the Czech Republic under consideration, the method also gave a vulnerability class 2 for both banks, whereas the bed was assigned to class 1.

### 4.3.5 | Vulnerability of impact areas integrating microscale and mesoscale assessment

Following on from steps 2 and 3 of the quantitative assessment, the integration is carried out across the micro-and mesoscale (see Figures 3 and 6). In step 4a, a comparison is made for each impact area to identify whether the determined vulnerability resulting from the boundary conditions is greater than the initially determined vulnerability of the construction types on their own. Equation (4) is used to determine the vulnerability in the respective extended impact areas. If the previously determined values for the left bank of the Müglitz are inserted, we get Equation (9) (in this case $V_{BC,bank,l} > V_{bank,l}$), leading to the result depicted in Figure 6a.

$$V_{bank,l,e} = \frac{V_{bank,l} + V_{BC,bank,l}}{2} = \frac{2 + 2.69}{2} = 2.35 \tag{9}$$

For the other impact areas of the Müglitz and also the Řasnice, the vulnerability due to the boundary conditions is higher than the originally determined vulnerability of the construction types, thus leading to a higher vulnerability when considering the extended impact area. The vulnerability of the bed of the Müglitz in the investigated watercourse section is 2.00 and that of the right bank 2.08, taking into account the (extended) impact area. In the same manner, values of 2.58 for the right bank (see Figure 6b), 2.15 for the left bank and 1.67 for the bed were determined for the investigated section of the Řasnice.

In step 4a, we determine the vulnerability of the watercourse section. For this purpose, the calculated vulnerabilities of the different impact areas at the mesoscale are combined into an average value according to Equation (3). For the Müglitz, the vulnerability of the investigated watercourse section is calculated as follows:

$$V_s = \frac{\sum V_{IA,e}}{3} = \frac{V_{bed,e} + V_{bank\_l,e} + V_{bank\_r,e}}{3} = \frac{2.00 + 2.35 + 2.08}{3} = 2.14 \quad (10)$$

Similarly, the vulnerability of the investigated section of the Řasnice is 2.13, a slightly lower value than for the Müglitz.

### 4.4 | Application of the HyVAC method: Combination of qualitative and quantitative assessment across scales

In the last step 4b (see Figures 3 and 6), the numerical results of the quantitative assessment are combined with the qualitative assessment at the macroscale (WTSV index). Although the sections of the Müglitz ($V_s = 2.14$) and the Řasnice ($V_s = 2.13$) show almost identical vulnerability values from the quantitative assessment, differentiation is necessary due to the diverse watercourse types (Section 4.2). Each type is associated with particular dynamics and a typical discharge pattern of the watercourse in which the section is located. For this reason, the WTSV index (such as $vh$ = very high and $m$ = medium) must be specified in order to determine the final vulnerability. This gives final values for the vulnerability of the watercourse sections of $V_S^{WTSV} = 2.14^{vh}$ for the Müglitz and $V_S^{WTSV} = 2.13^{m}$ for the Řasnice. The difference becomes especially clear if the calculation is only applied to the impact areas according to Figure 6. The bank walls in a watercourse type with "very high type-specific vulnerability" must thus be designed with significantly greater strength – despite the lower absolute value of 2.35 – compared to a watercourse with medium type-specific vulnerability, such as Řasnice with a value of 2.58.

From these calculations, it is possible to derive qualitative suggestions regarding the type and extent of adaptation measures in the channel, for example, the bank dimensions and bed protection or adaptations to the discharge profile to reflect typical discharges (see Section 3.5.3). For our example, this means that despite very similar values for $V_s$, more robust adaptation measures are required in the Müglitz because of the very high WTSV than in the Řasnice, which only has a medium WTSV. Thus both in Germany and in the Czech Republic, the descriptions of the watercourse types provide valuable additional information.

### 4.5 | Transferability of the HyVAC method

Based on the investigated case studies, the German and Czech methods for assessing the hydro-morphology of watercourses can be judged highly suitable for assessing flood-induced vulnerability. Regarding the transferability of the two methods, it was found that while they use fundamentally similar approaches, there are differences in the three spatial scales. At the macroscale, the German watercourse classification appears more detailed and differentiated, a fact also reflected in the naming of the stream types (which make reference to the substrate and local geology). On the other hand, the eco-regional diversity in the Czech case (mainly "central highlands") does not compare to that on the German side ("lowland", "central highlands", "Alps"); this implies a higher diversity of watercourse types in Germany. At the level of the highlands, the two countries show comparable types of watercourses. However, the ranges of gradient and discharge classes appear somewhat coarser on the Czech side, which is also evident in the watercourse classification (Table 1).

At the mesoscale, the two national methods are comparable and well suited to assessing the vulnerability of watercourse sections (see Table 2). Here, the specificity of the "simplified" and "extended" methods on the Czech side is clearly an advantage. For the boundary condition $P_1$, however, it would be useful to have a classification of bridges and culverts comparable to that of the German method. The same applies to the "harmful" parameter of the German method ("Harmful land features"), as this would enable an improved derivation of damage processes occurring in the channel (concerning $L_6$). Regarding land use, the Czech methodology could be refined by defining and recording the distances of structures from the channel (small/medium/large) ($Pl_1$ and $Pl_2$). In the methodology we have presented, only structures whose distance is assessed as "small" are included in the calculation. Further, in Germany, a distinction is made between unpaved and paved traffic areas, which is also relevant to the likelihood of erosion in the case of overflow.

At the microscale, it is important to highlight the more differentiated Czech methodology, which allows a particularly detailed recording of construction types on the bed and banks, even though the types "sheet-piling", "training works" and "groyne" are missing (see Table 3). Another positive aspect of the Czech survey methodology is the obligatory assessment of the condition of bank and bed constructions, which in the context of watercourse maintenance not only shows the relevance of potential damage but also gives an estimate of the required maintenance. For more detailed comparisons of hydro-morphological survey methods, please also refer to the work of Belletti et al. (2015) or Kampa and Bussettini (2018). The problem of missing data on the hydro-morphology of the Řasnice could be compensated on the Czech side by an independent subdivision into 100-m sections and on-site mapping according to the German survey methodology. Here, the authors were able to draw on their own extensive mapping experience. During the survey, it became apparent that a further subdivision of construction types, following the simplified Czech survey method, would help specify the degree of obstruction (damage potential) in urban watercourses. If necessary, these findings should be taken into account in a revision of the German survey method.

## 5 | CONCLUSIONS AND FUTURE RESEARCH

The investigations undertaken in this study confirm the suitability of deriving damage-relevant parameters from data on the hydro-morphological condition of watercourses. Based on a comparison of

German and Czech data acquisition methods, we were able to show which parameters are relevant at the macro-, meso-and micro-scale.

At the macroscale, the ecoregion, catchment size and associated length of watercourses are of particular importance in the international context. Studies by Knighton (1999), Vocal Ferencevic and Ashmore (2011) or MacBroom et al. (2017) have developed more in-depth approaches for this, suggesting an additional subdivision of water bodies into upper, middle and lower reaches with regard to their susceptibility to damage (derived from erosion behavior). This approach can be further explored in future research using the methodology presented here.

At mesoscale, the damage-inducing effect of punctual, linear and planar structures in the channel and in the floodplain should be viewed as a further object of research. Overlays with hydrodynamic modeling could pinpoint potential damage areas depending on the probability of flooding. For this purpose, the presented methodology provides a broad overview of potentially damage-relevant boundary conditions, which can also be assessed as damaging from an ecological perspective. Based on these interrelationships, integrative approaches in river basin management can be advanced by utilizing our HyVAC method.

At the microscale of construction types, object-specific characteristics are particularly significant in the development of flood damage. The approach presented in the HyVAC method for the classification of individual design variants is largely based on incomplete datasets regarding critical load limits of impact variables (flow velocity, shear stress and stream power) of construction types during floods. Due to the worldwide use of such construction types and design variants, further results from field studies or laboratory investigations would be of great interest (see Bjerklie, 2007, MacBroom et al., 2017).

The presented methods also offer the possibility of an even smaller-scale estimation of the damage potential based on the recording of channel dimensions. This approach could be refined in the future through the complementary use of remote-sensing data (see Bjerklie, 2007). The construction types themselves can also make an additional contribution to resistance due to their typical flow-relevant surface properties. For each construction type, the surface roughness is a key influencing factor for flow conditions, shear stress, and flow velocities (micro-and macro-roughness, see Hurson & Biron, 2019). Here the classification of surface roughness could provide more details on the erosion and abrasion resistance of differently shaped streams, as the processes determining flow resistance are dependent on the roughness scale (Carey, Stone, Norman, & Shilton, 2015; Sabrowski, 2008). Furthermore, the material bonding within each structure is a critical factor in the development of damage mechanisms. To assess impact resistance to entrained sediments, debris, and alluvium, it is necessary to consider the type of material composite of the construction types. Accordingly, assumptions could be made on impact resistance in terms of how strong the impulse must be to dislodge individual elements from the structure (see McBride et al., 2007; Suaznabar et al., 2017). In this context, the duration of certain flow stresses is also relevant. Again, more research is needed on the resistance of structures as a function of their design as well as on the applied flow forces and durations.

As an indication of potentially stressed areas of watercourses, the macroscale classification of watercourse types according to the presented HyVAC method can be usefully applied since certain design features can be derived from construction types and adjacent land use. Thus, in the example of the Müglitz, particularly robust construction types with large armoring stones are to be preferred due to the vulnerability of this type of watercourse, whereas in the example of the Řasnice, it is clear that excessively massive armoring is unnecessary, even if robust construction types are needed along certain sections. This example shows the application-oriented character of our methodology, whereby, on the basis of the presented scales, suitable levels of action and planning are addressed in each case. Furthermore, the interdisciplinary approach adopted here is intended to once again highlight the potential of existing databases for synergetic research.

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## DATA AVAILABILITY STATEMENT

Excel calculations that support the findings of this study presented in the charts are available from the corresponding author upon reasonable request.

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