Quantifying resilience in hydraulic engineering: Floods, flood records, and resilience in urban areas

Reinhard Pohl

Abstract
The design of safe structures and installations is an important issue in hydraulic engineering. In this context, the question arises whether the concept of resilience can provide additional information compared with the (semi-) probabilistic or risk-based analysis to improve the results of the design procedure. In this paper, the integration of resilience aspects into the design is discussed on three levels: First the consideration of resilience as a characteristic of the structure and its members, secondly as a set of multicriterial indicators and thirdly as a numerical value. To illustrate the three resilience approaches three examples are discussed: the qualitative selection of components, reassessment of urban flood resilience on the basis of updated historical flood records and the comparison of resilience values for different hydraulic structures. Considerations on the quantitative description of the resilience of hydraulic structures in flood-prone areas are presented and should open the way to further discussions about the quantification of resilience terms.

This article is categorized under:
Engineering Water > Methods
Engineering Water > Planning Water
Science of Water > Water Extremes

KEYWORDS
design criterion, flood, multicriterial indicators, resilience

1 | INTRODUCTION

For centuries, people have been settling near rivers used as water sources, waterways, and energy sources for water mills. The water brought soil moisture for the crops, and the floods fertilized the fields with fine sediments. On the other hand, many of these settlement areas were at risk of flooding. As a result, these towns and villages in the river valleys were flooded more or less frequently, resulting in damage, loss of property, and fatalities. Furthermore, human activities in and along the rivers changed the flow regime and the exposure of the settlements as well. When using the term “resilience” in relation to flood and flood protection, one should take into account the informative value as well as the meaning of this word, which is increasingly used in many fields of science and technology. Often it does not seem to be completely clear, and one wonders whether this is a vogue term or a keyword (see also Kuhlicke, 2013).
In most cases, “resilience” appears as a property of a process or installation that makes it more resistant to any threats or ensures short recovery times after any impact on a system.

In this respect, the question arises whether resilience can also be a “hard” criterion for the design and dimensioning of flood protection measures or structures? To answer this question, three levels of introducing resilience in hydraulic design are discussed in this paper. Three examples from different fields of hydraulic engineering are presented to show benefits and limits of resilience-based considerations.

## 2 RESILIENCE AS A TECHNICAL TERM

To answer the above question, the term’s different areas of application and the different meanings should be taken into account. Resilience and the demand for resilient objects and processes can be found in many areas: technology, society, nature, and others (Adger, 2000; Kolar, 2011).

The term resilience was originally used to refer to ecosystems in the 1960s (De Bruijn, Buurmanb, Mensa, Dahma, & Klijna, 2017), and it has been used increasingly in the field of civil engineering only within the last two decades (see also, Fekete, Hufschmidt, & Kruse, 2014). The Cambridge Dictionary (2019) defines societal “resilience” as the ability to be again happy, successful, etc. again after a difficult or bad event; for materials it applies that matters and substances have the ability to return to their usual shape after bending, stretching, or pressing; finally for things and processes, in general, it suggests the quality of being able to return quickly to a previous good state after problems. A similar definition is given on Dictionary.com for ecology (“the ability of an ecosystem to return to its original state after a disturbance”), and modified in physics: “the amount of potential energy stored in an elastic material when deformed.”

The technical committees ISO/TC 292 “Security and resilience” and CEN/TC 391 “Protection and security of citizens “drafted the standard EN ISO 22300:2018 including the definition of resilience as the “ability to adapt and adjust to changes in the environment ...”. Zussblatt, Ganin, Fiondella, and Linkov (2017) define resilience as the ability to anticipate and adapt to changing conditions, to survive disruptions and recover quickly from them. According to these definitions, four resilience characteristics can be identified: anticipate (plan/prepare), endure (absorb/buffer), recover (recreate/revive), and evolve (adapt).

While the first mentioned definitions, only focus on the recovery time, the ISO version additionally includes the resistance or buffer capacity of a system. This paper follows the ISO definition.

From the perspective of a hydraulic engineer, the safety of hydraulic structures is essential. The reliability of the structure(s) is ensured when the system is usable, durable and sufficiently load-bearing. Then it can withstand all expected hydraulic—hydrological loads without any impairment of structural safety (DIN 19700-10:2004-07, 2001a; DIN 01055-100:2001-03, 2001; DIN ISO 8930: 1991-03, 2001b). Furthermore, situations with loads (e.g., flood peak, water level) that exceed the design values may occur. In these cases, reserves in the structure can be mobilized in terms of resistance and buffer capacity and finally consumed when the load increases (Figure 1).

A look at the design practice in hydraulic engineering shows that, in the past, often only the water level elevation (h) was used as design value. Later on, additionally the discharge (Q) was used as an additional dimensioning load. This could be determined from a long series of gauge readings or precipitation-runoff models. Usually the highest observed peak discharge was used as design value, often multiplied by a safety factor (e.g., HHQ × 1.5). When the observation series became longer, it was possible to fit distribution functions to the data and to extrapolate peak discharges (DWA, 2012) with a certain probability of exceedance (=1/recurrence period). From this, the failure probability (P) of a dam, weir or flood defense structure can be derived with additional information. With the extension of this probabilistic design by the expected consequences of failure, a risk-based design as well as risk management become possible. The question now is whether this approach can be extended to include resilience and whether this provides additional information and benefits for the design and evaluation process. Mustajoki and Marttunen (2019) extend this existing practice and propose resilience management.

In recent decades, several research fields have been established with the objective of adapting societies to changing requirements caused by natural events (see also Opdyke, Javernick-Will, & Koschmann, 2017). This is also indicated by scientific events, to discuss these issues, such as “Urban Flood” (Paris 2009), “Resilient Cities” (Bonn 2010), “UFRIM” (urban flood risk management; Graz 2011), FloodRisk (Oxford 2008, Rotterdam 2012, Lyon 2016, Budapest 2020) or the scientific decade 2013–2022 of IAHS, under the title “Panta Rhei—Everything Flows.” It is an interesting and important topic to consider the vulnerability development of communities due to natural disasters and the resistance to these challenges including the time to recover after a shock or incident (resilience).
3 RESILIENCE AS A PROPERTY IN THE HYDRAULIC ENGINEERING DESIGN PROCESS

There is a consensus among hydraulic engineers that all structures, parts and components should be designed in such a way that they can absorb the loads even within a certain overload range. This means that a structure should not fail immediately if the loads such as discharge, water level, pressure, and so on have exceeded the design values; it should also be possible to render it usable again after the impact with only a short repair or recovery time. That is important since the design loads are often randomly distributed natural quantities that cause uncertainties in design. However, how can this objective be achieved? The design should be based on resilient principles that can be described for the individual application. This is a descriptive resilience approach (level one in the frame of this paper) that maps properties or attributes for the shapes and functions of structures or structural parts. For spillways, for example, this means that the resilience increases when blockages and malfunctions of machinery can be avoided. While siphons and shaft spillways provide relatively high discharges under pressure, they are at risk of clogging (floating debris, bushes, logs, etc.). Free flow spillways can be surcharged, but gates can become inoperable for several reasons. Hence, the selection of the spillway type may follow this ranking: 4 syphon—3 shaft spillway—2 gated spillway—1 ungated spillway at the dam crest, which is expected to be the most resilient one. It is possible to calculate the stage-discharge-relation for these structures, but it is difficult to quantify the behavior of the different spillway types in the case of clogging and, thus, the resilience (see also Pohl, 2000).

Levees can be equipped with regular overflow sections to avoid the undesired overtopping at random or problematic spots, although this leads to overflow and the loss of the flood protection function. While the design flood may be exceeded, the levee as a structure itself will hopefully be protected from failing.

Example of system properties: Behavior of dams beyond the design loads

In case of floods within the design discharge range, reliable functioning of the spillway and appurtenant works is expected and marked with green in Figure 1. For resilient types of spillways, such as free overflow structures and
concrete dams, sufficient functionality and stability are also expected beyond the design discharge within a certain range, which is shown in yellow and orange in Figure 1. Slight damage may occur in this area and is permissible (in accordance with the German dam standard DIN 19700:11-2004, n.d.), provided the structural stability is guaranteed. These reserves can buffer the extreme loads before the structure fails due to further inflow increases.

## 4 Resilience as a Set of Multicriterial Indicators

A first step toward resilience quantification is to identify indicators (scores, points, dimensions, costs, etc.) that can affect or describe resilience (level two within the frame of this paper). Generally, these values have different units, so it is difficult to summarize them in one representative indicator. In some cases, these indicators are dimensionless, uncertain, qualitative or verbal (e.g., high, medium, and low).

As a consequence of the definitions in Section 2, the recovery time and the resistance to threats or impacts could primarily be considered relevant attributes or indicators. In addition, depending on the area of application, the buffer capacity, the magnitude of the impact, the damage per capita or per gross domestic product (GDP), the number of fatalities, the insurance coverage quota, the availability of relief units (action forces), the experience and degree of organization of aid agencies, the contractors available in the case of emergency, financial and technical resources and more can be included. Once these indicators have been found, they can be evaluated in a single or composite index or in a points system. Furthermore, these indicators may vary from issue to issue and one can trace them individually to describe the degree of resilience.

Marzi et al. (2019) describe measuring disaster resilience as a key to successful disaster risk management and adaptation to climate change. They evaluated a comprehensive disaster resilience index for the whole of Italy using quantitative, indicator-based assessments, including a combination of different performance indicators. Although the meaning of the absolute resulting index value is not clear and requires explanation, it is a good instrument for rankings or prioritizing measures. Mustajoki and Marttunen (2019) present a matrix for evaluating the resilience and sustainability of reservoir operation.

A Pareto-optimization can help finding the best solution with the highest resilience based on multicriterial indicators (as objective function) with different units (Dittmann, Froehlich, Pohl, & Ostrowski, 2009). This optimization improves one characteristic value or indicator without deteriorating another one. Therefore, it offers a set of best solutions that are to be found in the so-called Pareto-front.

### Example of a set of multicriterial indicators: Coping with floods under changing boundary conditions

This example (Level 2) includes three studies that were conducted to compare the flood situation as well as the vulnerability and resilience of the population and property in the flood-prone areas based on multicriterial indicators: The first study is a previous work of the author, in which he describes the historical development of flood resilience in a sample area (Elbe river near Dresden, Germany) using various indicators of resilience (Pohl, 2015). The second study deals with the situation at the Rhône River near Sion (Sitten) in Switzerland (Popp-Walser, 2013). Jongman et al., 2015 published the third study that refers to very densely populated areas near rivers or the coast in South-East Asia.

The description of the hydrological and flood situation of the Elbe near Dresden was based on the flood records from 1501 A.D. until today. Due to obvious inconsistencies and errors in the available official data (LfUUG, 2002), it was necessary to reassess all historical water level and discharge data to obtain consistent series for a more reliable extrapolation of the floods with higher recurrence periods. This was conducted in an extensive process involving historical information (Deutsch & Poertge, 2002; Glaser & Stangl, 2004; Poetzsch, 1784; Schaefer, 1848; Schmidt, 2000; Sturm et al., 2001). The current study referring to this data, examined the history of the river, the terrain, the flow regime and the morphology (Faulhaber, 2000; Nestmann & Buechele, 2002) using 2D hydronumerical models to verify the historical stage-discharge relations (Kirsch & Pohl, 2011; Siglow, 2007). With these updated peak flow series, spanning more than 500 years, hydrological analysis was performed based on the conventional approaches (Dyck, 1980; Maniak, 2016). Figure 2 shows the flooded area in the city of Dresden as an example of the study results: the historical map with the inundation area of the spring flood 1845 (top), the inundation in August 2002 (middle) and the numerically
One of the motivations for this study was a discrepancy between discharges and stages in 2002 and 2013 as compared to 1501 and 1845. With such different “centennial floods,” the question of trends arises. Figure 4 shows a moderate downward trend. However, it is also obvious that the basic population (for the statistical analysis) may have changed due to various human activities on the river and in the watershed. In particular, flood protection measures, such as construction of reservoirs in the entire catchment area in the 20th century, could explain the moderately declining trend.

**Figure 2** Inundation maps for the Elbe River in the city of Dresden. Top: 1845, middle: 2002 (www.dresden.de), bottom: own hydro-numerical calculation with a DTM for 1845 (see also Kirsch & Pohl, 2011). The color scale in the lower map indicates the water-/inundation depth. The actual discharge for historical events such as 1845 was determined by comparing the inundated areas when adjusting the discharges.

**Figure 3** Linear trends of partial series of annual peak discharges over a period of 30 years (black lines) and 50 years (orange lines) respectively and human-made influences.

Recalculated inundation of 1845 (bottom). One of the motivations for this study was a discrepancy between discharges and stages in 2002 and 2013 as compared to 1501 and 1845.
Nevertheless, the peak discharge in 2002 was the highest ever, which represents an all-time record, mathematically speaking, that strongly influences the trend of the partial series (Figure 3). It is not considered an outlier because it was measured using ADCP (acoustic Doppler current profiler).

Therefore, it is difficult to answer the question of a trend due to climate change (see also Bloeschl et al., 2015). Although the trends have increased in recent decades, Figure 3 visualizes that all partial series of the five-decade periods after 1800 show rising trends, while the series over three decades show two rising, three falling and two almost constant trend lines. Despite the use of the same flow data, these deviations, which are only due to mathematics, show the obvious uncertainty due to the limited set of data. Although this cannot be demonstrated clearly and statistically significant, an increase in the flood peaks or a decrease of the return periods cannot be excluded for the Saxon reach of the Elbe River in the future.

As long as humankind can remember, people have built their settlements on rivers. Thus, they were able to benefit from the water supply, the fertile soils, and the agricultural irrigation, the transportation of goods, the generation of hydropower and the inland navigation respectively. However, settling near the river also has a major disadvantage: the risk of inundation, resulting in vulnerability and less resilience. Figure 4 shows some insights into the history of the example area (Saxon capital Dresden in relation to the Elbe River) using selected plans, paintings, and photos.

If we look at many villages along rivers that became towns in the last centuries and finally cities (see upper row of small pictures in Figure 5), a first assessment of the resilience-indicators shows mainly positive developments in three sample areas. The upper part of Figure 5 shows the qualitative history and trend of flood resilience indicators for the city of Dresden (Pohl, 2011). Due to the growth of the city of Dresden, also in the higher-lying areas away from the river, the percentage of the flood-prone area has decreased, which has changed the distribution of the risk (see also di Baldassarre, Kemerink, Kooy, & Brandimarte, 2014). Although the overall risk potential in the possible flooded area increases, the relative hazard normalized to the GDP in this area decreases. This can be looked upon as one indicator of decreasing vulnerability, shorter recovery times, more buffer capacity and ultimately increasing resilience.

An analogous assessment was elaborated for Sion (Sitten) in Switzerland (Popp-Walser, 2013), where the risk was considerably reduced by the third ongoing Rhône correction (1850–2050). The dashed graphs in Figure 5 show that a deterioration of the flood protection situation is avoidable by continuing the correction.

Jongman et al. (2015) also reported a positive development of resilience-related indicators, like normalized flood damage in very densely populated areas in Southeast Asia. However, the observation period of only 20 years in the above-mentioned study seems to be too short, as the discussion of the trends in the example area of the Elbe River has shown. Longer series of data are required to demonstrate a significant increase in resilience for large cities in developing countries. For an exploding population, in a megacity with a comparably low GDP near a large river and only a few
meters above sea level, the trends of the absolute and normalized hazard potential could run along the dashed curves in the lower chart of Figure 5.

This requires further research using long time series and large data sets to ascertain which tendency flood resilience will follow at different places in the world in the future. The author initiated the first steps to verify these assumed curves in Figure 5. However, since the current definitions of resilience are mostly only qualitative, there is a gap on the way to a resilience-based design of flood protection works and measures.

Figure 5 gives some relevant indicators in dealing with floods: the hazard potential in the urban area standardized to the GDP of this area, the potential proportion of the inundated urban area and the GDP-related flood risk.

5 | RESILIENCE AS A QUANTITATIVE DESIGN CRITERION

The above-mentioned considerations use as an indicator of vulnerability and resilience the relationship between flood incident and consequences, and risk ($R = \text{annual damage}$). Thus, the question is whether the resilience can be
quantified and expressed in such a way that it can itself be used as a design criterion? Hence, the first line of approach should be to take into consideration the different definitions of resilience and other related terms given by different authors and used in different areas with resilience considerations, such as technology, environment, and society (Faturechi & Miller-Hooks, 2015; Juepner et al., 2018).

If the probability of failure ($P$) and the associated consequences ($C$) are known, the risk ($R$)

$$R = \frac{P \cdot C}{C}$$

or

$$C = \frac{R}{P},$$

can be calculated. This can be expressed in terms of property damage costs per year or, in case of accidental personal injuries, by using the so-called FN-diagram (fatality number, see also Martin & Pohl, 2014).

The question now arises whether a quantified resilience can replace the existing criteria and indicators mentioned above as a quantitative design value at a higher level of informative value and significance or whether resilience remains merely an attribute for describing the interaction between load and resistance from a certain point of view.

When attempting to quantify resilience by means of a formula (level three within the frame of this paper), the following parameters might be used according to the extended definition: the intensity $I$ of the incident (flood event, shock, e.g., in terms of the inundation depth or the product of depth and flow velocity), the affected area $A$, the duration of the incident $TE$, the consequences $C$ (damage, losses, costs) and the time until the recovery $TR$. A first proposal of an equation could be as follows (see also Pohl, 2011; Figure 6):

$$RE = I^a \cdot A^b \cdot TE^c \cdot \left(\frac{C}{TRe}\right),$$

where $I^a \cdot A^b \cdot TE^c/C$ could be understood as sorption/buffer capacity or resistance. The exponents $a$ to $e$ indicate the possible nonlinearity of the influence of the variables. They are still unknown and must be calibrated when sufficient data is available. This formula describes the resilience of a system as the property to resist any impacts and to bounce back within a reasonable amount of time to recover. The vulnerability could be defined as $VU = 1/RE$.

If flexibility or learning aptitude is also taken into account, this should be done by multiplying by the nominator of Equation (2). The still unknown exponents ($a$ through $e$) indicate that the formula might have nonlinear dependencies.

The link between resilience and risk could be found by inserting the rearranged Equation (1):

$$RE = I^a \cdot A^b \cdot TE^c \cdot P^d \cdot (R^{de} \cdot TRe)$$

FIGURE 6  Emergency management life cycle and timeline with different levels of resilience

Although example calculations with plausible results were performed (Juepner et al., 2018), this approach should only serve as a basis for further discussion. Consideration should be given, whether a normalizing (dimensionless
terms) is possible, how the unknown exponents can be determined and if any other mathematical interlinkage to the quantities probability $P$ and risk $R$ can be found.

The emergency management life cycle (e.g., CIRIA, 2013) and the timeline with different levels of resilience are combined in Figure 6. The flood incident (arrow) is accompanied by operational measures of flood protection (response) and followed by a recovery phase in which the bounce back will hopefully take place or is organized by suitable measures. A mitigation/adaption/adjustment period can help to establish more resistance and more resilience so that the management lifecycle becomes an upwards spiral. In long periods between flood events, it is necessary but not easy (declining line in Figure 6) due to several reasons (money, memory, and other upcoming priorities), to maintain the same qualified level of preparedness and awareness to ensure that measures can cope with the next unexpected extraordinary flood.

An important, but not easily quantifiable issue, which affects the recovery time and the extent of damage in case of flood impacts, is flood awareness and preparedness. Only if those who are involved know the flood risk and are prepared for such events, it will be possible to reduce the damage and the recovery time. Experience shows that, on the one hand, after a severe flood event various technical and nonstructural measures are taken to reduce the risk of future floods. Yet on the other hand, the flood awareness of the residents in a flood-prone area decreases with the duration of a flood-free period. One reason among others is a certain oblivion and human nature to remember good things more than the bad (see also Bornschein & Pohl, 2012). In addition, many people live only a limited time in one place. This implies that, assuming an average period of 20 years of residency, 10 years after a flood event only 50% of the inhabitants of the area in question have personal memories of the event. The graph of the “perceived” flood awareness in Figure 7 shows these effects differentiated for residents, persons responsible and experts and explains a possible temporary decline of the spiral line during the orange period in Figure 6. If it were possible to express awareness by a value (as Figure 7 might suggest), this should be multiplied by the nominator of Equation (2).

Example with a quantitative approach: Identifying different resilience levels

To illustrate the quantification of resilience (Level 3), initially a simple point-based system should be used (large, long [−lasting] = 3, medium = 2, small, short-term = 1). This allows a comparison or ranking among similar object categories (Table 1) by means of Equation (2) with (unknown) exponents and the duration of the incident set to be 1. After a hypothetical failure, due to an extraordinary flood, it would be expected that a bridge would require a longer

![Figure 7](image-url)
reconstruction time when compared to a culvert designed for the mean discharge. In this respect, the culvert could be assigned a higher resilience in this (simplified) case.

A flood-adapted structure (e.g., on piles) would suffer less damages in the event of inundation, which would result in greater resilience. And as mentioned above, a fixed weir ($Q \sim h^{3/2}$) can be overcharged much more than a shaft spillway ($Q \sim h^{1/2}$); so that in the first case, less damages and lower reconstruction costs can be expected after an extraordinarily high discharge.

This first proposal could be further refined by adding variables and exponents in Equation (2).

### 6 CONCLUSION AND OUTLOOK

Resilience can be employed as an indicator or criterion for the design of hydraulic structures. It is applied as an attribute (Level 1), as a set of related indicators (Level 2) and as a quantifiable value within a proposed formula (Level 3).

Experience shows that the first, purely descriptive resilience approach is far-reaching, broad and not sharp and does not allow a precise technical application of resilience required for communication in science and technology (Marg, 2016). The method that uses indicators is more helpful for the design, operation, and inspection of technical works and structures. A full quantification would be the best option for such resilience management, but often not all input data is available or can only be obtained with great effort.

Different types of hydraulic structures react differently to overcharge, which means lower resilience or more resilience. In many cases, this can be described by characteristics from the experience of the experts involved.

In order to estimate the development of communities’ resilience to floods over centuries, reliable data on past flood incidents and reactions is needed to enable extrapolation to the future. Using historical discharge values to describe...
changes in flood resilience over decades and centuries could fill a gap and allow for a more comprehensive look at the topic. To assess the flood resilience of communities the development of the damage potential can be used as an absolute value or normalized with the economic potential until there are standardized quantities for determining the resilience.

For the case study area of the example in Figure 5, the general vulnerability seems to be decreasing as it could be found with the help of characteristic indices. In addition, the relative values of inundation and potential damage appear to be decreasing, which could be seen as increasing resilience. In other parts of the world (especially with an enormous population growth in coastal and river-near areas), other trends than those shown in Figure 5 are to be expected and should be investigated in more detail.

After using stages, discharges, inundation probabilities and risks as design criteria for flood protection, the application of the resilience is considered. In the author's view, this will only succeed if a quantitative definition of resilience can be established in the (near) future. From the above considerations, it can be concluded that further research is needed to achieve this objective. Some further steps have to be taken to yield more precise, more replicable and more reliable quantitative resilience values, among them

- Checking whether all relevant criteria (Levels 1 and 2) or variables (Level 3) are taken into account.
- Checking whether Equation (2) needs the inclusion of more or other variables (Level 3);
- Comparing the results with those from the risk-based design.
- Verification of deviating results.
- Calibration of the exponents in Equation (2) and the weighting of the cause variables (Level 3).
- Applying a large number of case studies (Levels 2 and 3) to compare and prove the results.

CONFLICT OF INTEREST
The author has declared no conflicts of interest for this article.

ORCID
Reinhard Pohl https://orcid.org/0000-0002-7447-9961

RELATED WIRES ARTICLES
Floods and societies: The spatial distribution of water-related disaster risk and its dynamics
Increasing river floods: Fiction or reality?

Further Reading
Brand, F. S., & Jax, K. (2007). Focusing the meaning(s) of resilience: Resilience as a descriptive concept and a boundary object. Ecology and Society, 12(1), 23.
Dictionary.com. (2019). Resilience. New York, NY: Random House Retrieved from https://www.dictionary.com/browse/resilience
Karte des Elbstroms des Koenigreiches Sachsen in 15 Kartenblättern (Lithographie, Massstab 1:12000 mit den Grenzen der Überschwemmung vom 31. Maerz 1845). (1845) Saechsische Landes- und Universitaetsbibliothek, Kartenforum Sachsen, Section IX Dresden von 1850-55 (SLUB/KS 3.gr.2.61, SLUB/DF DK 6) Retrieved from http://fotothek.slub-dresden.de/karten/index.html?/karten/slub-ks.html
Matz, S., & Pohl, C. (2008). Erstellung eines hydraulischen Teilmodells fuer die deutsche Obere Elbe anhand historischer Daten fuer das Sommerhochwasser von 1890. Hennef: DWA (in German). Panta Rhei-IAHS Programme. (2019). Xxxx. Retrieved from https://iahs.info/Commissions--W-Groups/Working-Groups/Panta-Rhei.do
Sharifi, A., Chelleri, L., Fox-Lent, C., Grafakos, S., Pathak, M., Olazabal, M., ... Yamagata, Y. (2017). Conceptualizing dimensions and characteristics of urban resilience: Insights from a co-design process. Sustainability, 9, 1032. https://doi.org/10.3390/su9061032
Steinführer, A., Kuhlicke, C., De Marchi, B., Scolobig, A., Tapsell, S., & Tunstall, S. (2009). Local communities at risk from flooding: Social vulnerability, resilience, and recommendations for flood risk management in Europe. Leipzig: Helmholtz Zentrum fuer Umweltforschung (UFZ).

REFERENCES
Adger, W. N. (2000). Social and ecological resilience: Are they related? Progress in Human Geography, 24(3), 347–364.
Bloeschl, G., Gaál, L., Hall, J., Kiss, A., Komma, J., Nester, T., ... Viglione, A. (2015). Increasing river floods: Fiction or reality? WIREs Water, 2(4), 329–344. https://doi.org/10.1002/wat2.1079
Bornschein, A., & Pohl, R. (2012). Hochwasserbewusstsein 10 Jahre nach dem “Jahrhundertereignis” im Osterzgebirge und an der Elbe (Flood awareness 10 years after the “Centennial Flood” in the Osterzgebirge and on the Elbe River). WasserWirtschaft, 102(7/8), 76–82, ISSN 0043-0978 (in German).
Popp-Walser, C. (2013). *Entwicklung von Hochwasserrisiken unter Berücksichtigung von Verletzlichkeit und Widerstandsfähigkeit (Development of flood risks considering vulnerability and resilience—The example of the Rhone in Valais from 1850 to 2050).* Diplomarbeit, TU Dresden, Fakultät BIW, Professur THM 2013 (in German).

Schaefer, W. (1848). *Chronik der Dresdner Elbbrücke, nebst den Annalen der groessten Elbfluthen von der fruehesten bis auf die neueste Zeit.* Dresden: Verlag von Adler und Dietze (in German).

Schmidt, M. (2000). *Hochwasser und Hochwasserschutz in Deutschland vor 1850—Eine Auswertung alter Karten.* Muenchen: Kommissionsverlag Oldenbourg Industrieverlag. ISBN 3-486-26494-X (in German).

Siglow, A. (2007). *Auswertung von Wasserspiegellagenberechnungen mit historischen Datensätzen fuer die Hochwasseranalyse.* Diplomarbeit, TU Dresden, Fakultät fuer Forst-, Geo- und Hydrowissenschaften, 70 S (in German).

Sturm, K., Glaser, R., Jacobeit, J., Deutsch, M., Brázdil, R., & Pfister, C. (2001). Floods in Central Europe since AD 1500 and their relation to the atmospheric circulation. *Petermanns Geographische Mitteilungen, 148*, 18–27 (in German).

The Cambridge Dictionary. (2019). *Resilience.* Cambridge, England: Cambridge University Press. Retrieved from https://dictionary.cambridge.org/dictionary/english/resilience

Zussblatt, N. P., Ganin, A., Fiondella, L., & Linkov, I. (2017). Resilience and fault tolerance in electrical engineering. In *Chapter in NATO Science for Peace and Security Series C: Environmental Security*. Dordrecht: Springer. ISBN 978-94-024-1123-2. https://doi.org/10.1007/978-94-024-1123-2_16

**How to cite this article:** Pohl R. Quantifying resilience in hydraulic engineering: Floods, flood records, and resilience in urban areas. *WIREs Water*. 2020;7:e1431. https://doi.org/10.1002/wat2.1431