Received: 28 January 2022 | Revised: 25 April 2022 | Accepted: 11 May 2022
DOI: 10.1002/wat2.1605

OVERVIEW

WIREs WATER WILEY

# High groundwater levels: Processes, consequences, and management

**Bernhard Becker**[1,2] | **Frank Reichel**[3] | **Daniel Bachmann**[4] | **Reinhard Schinke**[5]

[1]Deltares, Delft, The Netherlands
[2]RWTH Aachen University, Aachen, Germany
[3]Emschergenossenschaft, Essen, Germany
[4]University of applied sciences Magdeburg-Stendal, Magdeburg, Germany
[5]Leibniz Institute of Ecological Urban and Regional Development, Dresden, Germany

**Correspondence**
Bernhard Becker, Deltares, Delft, The Netherlands.
Email: bernhard.becker@deltares.nl

**Edited by:** Thomas Hartmann, Associate Editor, Nigel Wright, Senior Editor and Wendy Jepson, Editor-in-Chief

**Abstract**

In recent years, the issue of high groundwater levels has caught attention. Unfavorable consequences of high groundwater levels are especially damage to buildings, infrastructure, and the environment. Processes that lead to high groundwater levels are hydrological (heavy or extended rainfall and flood events), or anthropogenic (reduced groundwater extractions, interaction with sewer networks, hydraulic engineering measures, structural interventions in the water balance, and mining activities). Several different map products have been prepared for the information of inhabitants and for planning purposes, and also methods for damage and risk analysis related to high groundwater levels have been developed. Groundwater management measures and structural measures are available to reduce the risk related to high groundwater levels. An operational management system could be combined from existing components, but operational forecasting systems for high groundwater levels are—different to flood forecasting systems—not yet common practice. A better understanding of the processes and the development of integrated approaches for modeling, design, planning, forecasting, and warning, as well as improvement of interdisciplinary collaboration between different organizations, are recommendations for the future.

This article is categorized under:

- Engineering Water > Engineering Water
- Water and Life > Conservation, Management, and Awareness
- Science of Water > Hydrological Processes
- Science of Water > Water Extremes

KEYWORDS

flood risk, groundwater flooding, groundwater management, high groundwater level, subsurface flood

# 1 | INTRODUCTION

Fluvial and pluvial floods are among the most severe natural disasters worldwide. Consequences to economy, people, and ecology are well-known, very obvious, and therefore investigated for several decades. However, the phenomenon of high groundwater levels, e. g. as a result of long-lasting precipitation or river floods, is often neglected, because of its invisible character. In recent years, the issue of high groundwater levels—defined as a groundwater level that is higher than the usual level—has caught attention, especially in Germany, the United Kingdom, and Canada. Flood events in the Elbe river (Germany) in August 2002 and 2013 caused groundwater levels rise in the vicinity of the water course (Sommer & Ullrich, 2004). In addition to flood damage, the rising groundwater affected basements of buildings and caused further damage (Kreibich & Thieken, 2008; Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012). Abboud et al. (2018) report about a flood event in Alberta (Canada), where high river stages during the flood period propagated into the adjacent permeable alluvial aquifers.

Specific evaluations of the proportion of groundwater-related damage to overall flood damage are rarely found in the literature. With reference to the Elbe flood event of 2002 in Germany and the buildings owned by the Free State of Saxony, the groundwater-related losses comprise about 16% of overall flood losses (Huber et al., 2003; Sommer et al., 2009). This is comparable to values available for the 1999 flood event in the Bern district (Switzerland), where 23% of losses were caused by groundwater (FOWG, 2004). In both examples, the rising groundwater was caused by fluvial floods. The term "subsurface flood" (B. P. J. Becker, 2010; B. P. J. Becker et al., 2015) has been suggested to describe this phenomenon.

While groundwater remains basically in the underground during subsurface flood events, in some locations in England and Wales the groundwater emerged at the surface during the winters in 2000/2001 and 2001/2002 after prolonged extreme rainfall in a specific geological setting of chalk aquifers (Cobby et al., 2009). The term "groundwater flooding" refers in this case to an inundation, which originates from groundwater and the water levels rise above the ground surface. In a conceptual extension of the term, Abboud et al., 2018 define groundwater flooding as an inundation of subsurface structures, which means that the groundwater level not necessarily rises to the ground surface, which is not flooding in a closer sense. The references from above show that different terms have been used for similar phenomena. In the following, we will use the term "high groundwater level".

Beside hydrological processes (rainfall and floods), high groundwater levels may occur by anthropogenic processes. In many densely populated areas of the world, wells are operated for water supply. Pumping water from a well lowers the water table in the vicinity of the well. In principle, groundwater extractions reduce the risk of damage due to high groundwater levels. If the groundwater extractions decrease, the groundwater table rises again. Rising groundwater tables due to reduced groundwater abstractions have been reported for a number of cities throughout the world (Brassington, 1990; BWK, 2022). Another example of anthropogenic processes relates to the sealing of the leaky sewer system in the Ruhr region (Germany). After sealing, the sewer no longer acts as an unintended drainage system. The groundwater levels would increase to the natural groundwater levels if the sealing had been done without compensating groundwater management measures. River training measures, constructions of weirs and dykes, rainwater infiltration, or mining activities can also change the groundwater situation and lead to high groundwater levels.

To provide a holistic view of the main aspects of dealing with high groundwater levels, this article covers a review of essential hydrological and anthropogenic processes with their consequences. In addition, planning tools and measures for risk mitigation are addressed to complete the overview.

# 2 | PROCESSES AND CONSEQUENCES

## 2.1 | Outline

High groundwater levels can originate from hydrological and from anthropogenic processes. Adverse consequences result from these processes when changes affect human uses and/or the environment itself. Hydrological processes refer to natural groundwater recharge and river–aquifer interactions. High groundwater levels that originate from hydrological processes are usually limited in their temporal duration. Anthropogenically induced high groundwater levels are often related to (i) interactions between sewer networks and groundwater, (ii) reduced groundwater abstraction, or (iii) hydraulic engineering interventions. The anthropogenic processes usually have, if no countermeasures are taken, a long-term or permanent effect.

## 2.2 | Hydrological processes

### 2.2.1 | Pluvial origin of high groundwater levels: Groundwater recharge

Groundwater recharge is the portion of precipitation that enters the aquifer from the land surface. During storm events, the groundwater recharge can increase: on the one hand, as a result of the high amount of rainfall itself, and on the other hand, as a result of ponded conditions that let infiltrate more water into the soil than during moderate rainfall events. Consequently, the groundwater level can rise quickly. Hydrological, hydrogeological, and pedological conditions as well as the initial moisture content determine how the groundwater level develops during a storm event. Storm events often occur locally and the duration is then limited to hours or a few days. The groundwater level rise and fall can happen in a nearly similar time scale.

Not only storm events, but also long periods of intensive rainfall can let the groundwater level to rise. An example is given in Figure 1: a precipitation of more than 200 mm in August 2010 (1) and a wet period starting with 95 mm in November 2010 resulted in a groundwater level rise of more than 1.0 m in the period from December 2010 until April 2011. A wet summer period between May and August 2014 (2) caused a groundwater level rise, not before June 2014, the ongoing rainfall caused another groundwater level rise by 1.2 m during the period from January to February 2015. The groundwater level reacts to long periods of above-average rainfall with a delay, it can take weeks or months until the effect of rainfall is visible in the groundwater observations. Because the groundwater rises slowly, the rising of the groundwater level often takes place unnoticed and thus is often encountered unprepared.

### 2.2.2 | Fluvial origin of high groundwater levels: River–aquifer interaction

Most large rivers in Europe are gaining rivers; this means that the groundwater flow is directed towards the river as base flow. Under normal conditions and under low flow conditions, the river drains the catchment. During a flood event, the river stage rises, and the groundwater flow direction temporarily changes such that water flows from the river towards the aquifer (Figure 2). This results in a temporary groundwater level rise in the vicinity of the river bank. When the water level goes down again to normal conditions after the flood event, the water that has been stored in the

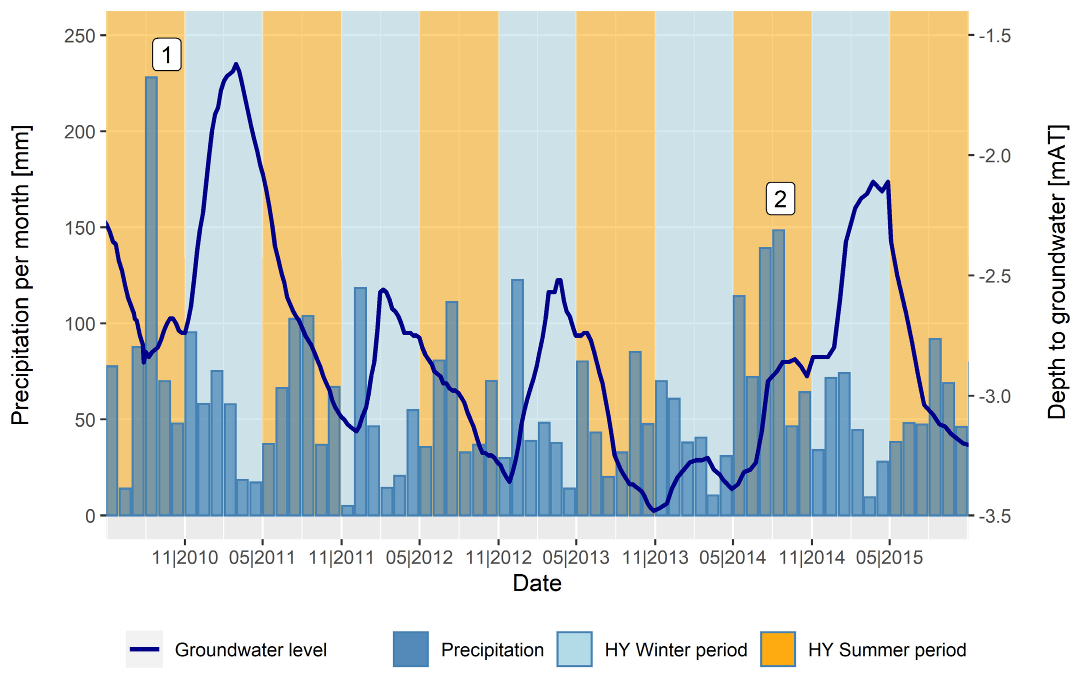


FIGURE 1 Precipitation and depth to groundwater for the observation point St. Tönis (Germany, North Rhine-Westphalia; BWK, 2022, modified). HY, Hydrological year; mAT, Meter above the terrain. Data sources: Meteostat (2021) and MUNLV-NRW (2019)

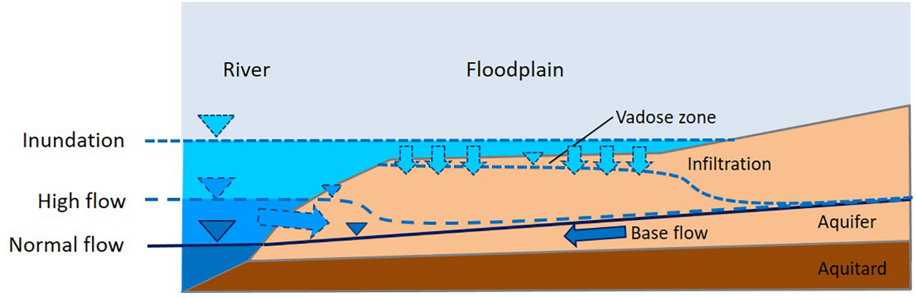


**FIGURE 2** Schematic illustration of bank storage and infiltration process during high flow and inundation

banks returns to the river. This process is called bank storage (Pinder & Sauer, 1971). Water exchange takes place as saturated flow through the wetted perimeter within the river bank.

If the river level rises further such that the river exceeds the bankful stage, water infiltrates from the inundated area vertically through the vadose zone (Figure 2). The interface area for river–aquifer interaction becomes much larger in this case. Furthermore, water moves much faster on the land surface than on the subsurface. This brings water further towards the hinterland. Consequently, water infiltration from an inundated area can contribute significantly to the groundwater level rise during a flood event (see also B. P. J. Becker, 2010; Sächsisches Landesamt für Umwelt und Geologie, 2003).

The water exchange between river and aquifer via bank storage and infiltration through the vadose zone depends on the duration of the flood event, the peak, and the shape of the flood wave as well as on the hydraulic conductivity and storage properties (confined, unconfined conditions) of the aquifer (B. P. J. Becker et al., 2015; Ubell, 1987). As mentioned already in the introduction, groundwater level rise from fluvial origin has been observed in connection with some recent major flood events. Central issues of flood-induced high groundwater levels are the following:

- The subsurface component of a flood occurs at unexpected locations, namely, in the surrounding flood plains and (far) behind dikes.
- Groundwater levels rise with delay. When the flood event is already declining, the groundwater level can still rise (B. P. J. Becker, 2010)
- High groundwater levels last longer than the flood event. While the river stage decreases from its peak to normal conditions within a couple of days, it can take several months until groundwater levels reach normal levels after a flood event (Sächsisches Landesamt für Umwelt und Geologie, 2003).

## 2.3 | Anthropogenic processes

### 2.3.1 | Sealing of sewer networks

If a sewer system is leaky, groundwater can either flow into the sewer system or sewer water can flow into the aquifer. The flow direction depends on the potential difference between groundwater and sewer water levels. Studies in Dresden (Karpf, 2012; Karpf & Krebs, 2011) have shown that the typical flow rates for the direction from the sewer into the aquifer are one to two orders of magnitude lower than the rates of groundwater flow into the sewer. With respect to high groundwater levels caused by sealing of the sewer system, only the case of groundwater flowing into the sewer is of relevance. Groundwater gets into the sewer system through leakages in manholes, public sewers, and private underground pipes if the leaks are located below the groundwater level. Most leakages are caused by cracks, shard fragments, and damaged connections. Apart from diffuse groundwater flow through leakages in the sewer system, unapproved drainage connections are another source of groundwater infiltration. This results in groundwater lowering in the surroundings.

Laws in many countries require that leaky sewer pipes must be sealed. However, after sealing the sewer pipes they no longer serve as receiving waters for the groundwater. Without building additional capacities to absorb and discharge groundwater, the groundwater level may rise in areas close to the sealed sewer pipes (Figure 3).

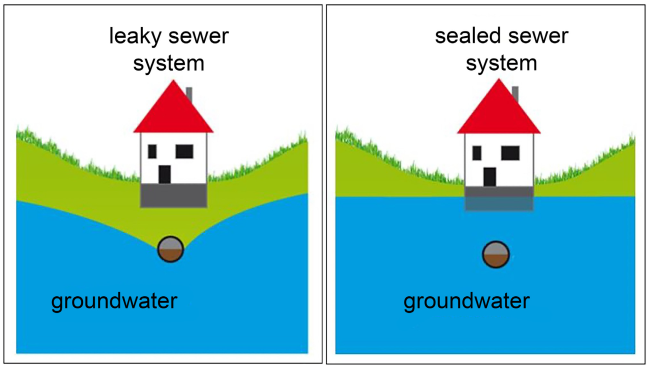


FIGURE 3 *Left*: Groundwater lowering by a leaky sewer system, *right*: groundwater rise after sealing the sewer system (Emschergenossenschaft)

The amount of groundwater flow into the sewer system, and consequently, the effect on the groundwater table, depends on the permeability coefficient of the aquifer, the hydraulic gradient between the groundwater and sewer water level, and the size of the interface area. Studies have demonstrated that large parts of the sewer system in the Ruhr region (Germany) act as unintended receiving waters for groundwater (Emschergenossenschaft, 2017) and keep the groundwater level artificially low. The infiltration of groundwater into the sewer system adds up to about 33 Mio $m^3$/a in the operational area (865 $km^2$) of the responsible water authority (Reichel, 2009).

The location of significant interactions between groundwater and sewer system can be detected with the help of groundwater flow models. The models can also be used to estimate how much the groundwater level will rise after sealing the sewer system (Reichel & Getta, 2008).

A leaky sewer network can also aggravate the effects of a subsurface flood (Section 2.2). Sommer et al., 2008 point out that the sewer network distributes flood water that has entered the sewer network from the surface to areas that were initially not affected by flooding. Backwater effects in the sewer network can change the flow conditions from gravity flow to pressurized pipe flow. This can lead to an increased infiltration of sewer water into the groundwater and this way contribute to a groundwater level rise. Abboud et al. (2018) report that during the Alberta subsurface flood event groundwater entered the sewer network through leaks, and from the sewers the water found its way into the basement of buildings. During the Elbe flood of 2002, groundwater also entered Dresden's sewer network through leaks (Sommer et al., 2008, 2009).

### 2.3.2 | Reduced groundwater extractions

In the course of industrialization, the need for drinking water and process water has risen sharply, accompanied by an intensive extraction of groundwater. In the range of the resulting massive groundwater depression, people got used to the lowered groundwater levels and now perceive them as natural.

If groundwater extractions reduce, the groundwater level rises. A reduction in the groundwater extractions can be caused by water savings that arise from increased environmental awareness, improved production processes, or by the fact that mining, industrial and commercial sites close or move away from the urban areas. The city of Berlin (Germany), for example, covers 100% of its drinking and industrial water supply from groundwater resources within the city limits. Until 1990, the groundwater withdrawal increased continuously, but starting with 1990, private households reduced the drinking water demand and several small enterprises closed. Currently, the public water supply company only extracts half the amount of 1989. Consequently, the groundwater level is now higher than it used to be. Numerous buildings that were designed for the lower groundwater levels must now be protected individually against groundwater (Monninkhoff et al., 2022; Senatsverwaltung für Umwelt, Verkehr und Klimaschutz, 2018). In the city of Delft (the Netherlands), a large industrial site has had a water right to extract 13.5 Million $m^3$ per year since 1996. In the year 2007, the company announced plans to reduce the groundwater extraction. Studies have been carried out to assess the impact of the reduced extraction (Roelofsen et al., 2008, 2018). According to the studies, the reduced extraction will lead to a significant rise in the groundwater table, accompanied by heave of the soil, if carried out as planned. Currently, the reduction of the groundwater extraction is ongoing and accompanied by monitoring and countermeasures. The case has already had an impact on the water legislation in the Netherlands: not only for the right to extract water but also for the reduction of groundwater extractions permission from the water authority is required. Other cases where the reduction of groundwater abstraction leads to a groundwater level rise are reported by Brassington (1990).

Note that reduction of groundwater extractions is not a general trend but limited locally. Instead of rising groundwater levels, many regions are coping with decreasing groundwater levels as a result of the over-exploitation of groundwater resources. Examples can be found in South Asia, South India, Northern China, the Middle East, Australia, Spain, and the United States (Giordano, 2009). Decreasing groundwater levels can even lead to land subsidence. As shown for the city of Jakarta, land subsidence can increase the risk of flooding (Bakr, 2015; Deltares, 2016), but high groundwater levels in particular are usually a minor concern in such circumstances.

### 2.3.3 | Special cases

In addition to the previously described effects, high groundwater levels can also occur as a result of water management measures, hydraulic engineering measures, structural interventions in the water balance, and mining activities.

Water management measures and hydraulic engineering measures that lead to an increase in groundwater level include reconstruction or renaturation measures on water courses and the construction of weirs and dams. The groundwater level rises along with the surface water level in the adjacent water course. Another measure that can lead to high groundwater levels is rainwater infiltration. The groundwater level rises due to an increased artificial groundwater recharge.

The withdrawal of rock material by underground mining (e.g., hard coal mining) causes a subsidence of the terrain surface. This can lead to a reduced depth to groundwater. However, this effect is only an apparent groundwater rise, since the groundwater level does not rise, but remains the same; it can even fall due to mine drainage measures. The depth to groundwater decreases if the terrain surface subsides more than the groundwater level and the terrain surface approaches the groundwater table. For the sake of completeness, it should be mentioned that subsidence of the terrain surface as a result of underground mining does not necessarily reduce the depth to groundwater. Depending on the ratio of the terrain subsidence to the change in groundwater level, it is also possible that the depth to groundwater remains the same or even increases after terrain subsidence has taken place.

In the case of open-pit mining (e.g., lignite mining), the mine drainage is the main driver of the subsidence. In certain soil types, processes like soil consolidation and creep can lead to irreversible subsidence (B. Becker & Rohe, 2018). This can become a problem after the end of mine operations. The groundwater level rises with the ceasing of mine drainage and the subsidence due to the mine drainage can finally result in a lower depth to groundwater than in the premining state.

## 2.4 | Consequences

Changing groundwater levels that exceed seasonal trends can affect a variety of uses and leads often to adverse consequences for humans and the environment. High groundwater levels, which we address here, can stress especially

- the built environment with buildings, infrastructures, and sewage systems in case of insufficient structural resistance (e.g., Kreibich & Thieken, 2008; Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012),
- the nature with (adverse) changes to ecosystems and biotopes,
- the agriculture and forestry due to reduced plant growth (Deng & Bailey, 2020; Luckner et al., 2002),
- the underground with changes of affected soil/aquifer properties, including the consequences of an increasing piezometric head in confined aquifer areas (the increasing water pressure on a low permeable topsoil can cause ruptures or uncontrolled, concentrated leakages—especially behind flood protection measures (Julínek et al., 2020)), and
- the quality of subsoil and groundwater itself due to contact with natural and anthropogenic pollutions, which includes saltwater intrusions (Deng & Bailey, 2020) and (bio-)chemical interactions with waste deposits and contaminated sites (Getta et al., 2004).

The resulting consequences can be differentiated—comparable to floods—in terms of direct damage (with physical water contact) and indirect damage (without water contact), which include both monetary and nonmonetary values. Moreover, it can be further differentiated by primary damage that occurs during the specific situation as well as secondary damage that occurs subsequently in terms of time and causality (DWA, 2008; Smith & Ward, 1998).

From an economic perspective, the focus is often on direct damage that can be assessed in monetary terms. Direct damage results, for example, from the cost of refurbishment, structural reinforcement, and protection as well as from yield losses in agriculture. In the case of permanent changes in the groundwater situation, permanent costs can also be incurred like the costs for drainage measures.

With the view of high groundwater levels and their consequences, it is not only the amplitude of groundwater levels that have to be considered but also the duration of the event. The temporal component ranges here from

- short-term (days to weeks, to few months, e.g., as a result of heavy precipitation events and river floods) and long-lasting (months to years, e.g., as a result of exceptionally precipitation-intensive months, seasons, or years) to
- permanent changes
  - due to termination/reduction of groundwater management, which may result from reduced water demand or cessation of mining dewatering,
  - sea-level rise in coastal areas, as well as
  - due to river engineering measures such as the construction of weirs.

The emphasis in analyzing and managing such risks is depending on specific issues, but often it is on damage to residential and nonresidential buildings with their high economic losses. Figure 4 gives an overview of damage types, damage patterns as well as causes of damage related to buildings (Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012). Water and moisture damage as the first damage type already occurs with the entry of groundwater into the building. Even in such cases, it usually requires an appropriate and professional refurbishment or structural protection to avoid consequential damage, including mold formation. In the case of corresponding exposure, the latter can lead to health problems that should not be underestimated.

High groundwater levels can change load-bearing behavior as the second damage type. Main cause is the change or especially the increase in hydrostatic pressure on building components and/or on the entire building. In addition, the

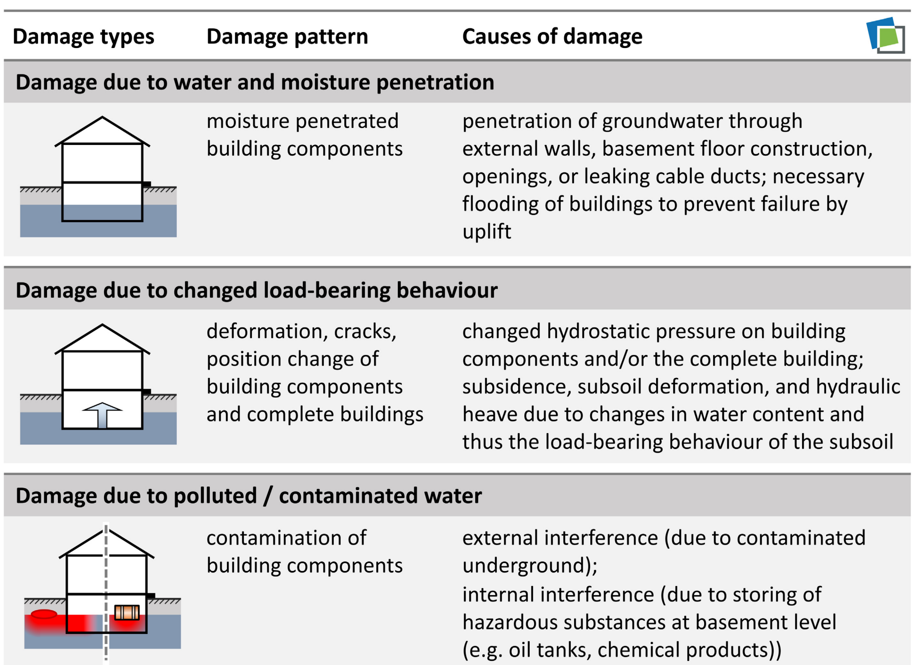


FIGURE 4 Building-related damage types, damage patterns, and their causes (Schinke, Neubert, Hennersdorf, & Gruhler, 2012, modified)

water can modify the load-bearing properties of the foundation soil (e.g., softening of an underlying cohesive soil material).

Damage due to pollution and contamination as the third damage type emerge from internal and external interferences. The external interferences may be caused by contaminants in the subsoil that are mobilized by rising groundwater levels. Internal impairments are usually caused by improper storage of substances hazardous to water. Typical examples are floating heating oil tanks, although in many countries buoyancy protection is required for the tanks by law.

In summary of the three building-related damage types, water and moisture damage occur most frequently due to the specific mechanisms of action; damage due to altered load-bearing properties and due to polluted water is observed much less frequently (Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012).

## 3 | PLANNING TOOLS

### 3.1 | Hazard maps for fluvial high groundwater levels

A flood hazard map highlights areas that can be affected by flooding. Flood hazard maps are a common means to make people aware of flood-related dangers worldwide. In order to follow the EU flood risk management (European Commision, 2007), in many European countries flood hazard maps have been created that show inundation areas for a certain probability of occurrence (average return intervals, e.g., 100 or 200 years). It includes inundation areas originating from groundwater, but the corresponding hazard maps for the subsurface are not required by the Directive 2007/60/EC (European Commision, 2007), the Water Framework Directive (2000/60/EC), or the Groundwater Directive (2006/118/EC). Nevertheless, several cities have already considered hazard maps for fluvial high groundwater levels as relevant for their flood risk management concept. The purpose of such a hazard map is to inform and sensitize those affected, but also to support planning and adaptation processes related to high groundwater levels. The most important information of such a hazard map is the expected minimal depth to groundwater. Figures 5 and 6 show examples for Cologne and Dresden, respectively. The development of the maps implies serious challenges, especially due to the long process chain as well as the focus on rare events and conditions. The hazard map for Cologne (Figure 5) has been generated with the help of numerical modeling, and the map for Dresden has been derived by analyzing historic events.

A connection between hazards related to high groundwater levels and the structural design of buildings form maps with the weather-related expected highest groundwater level. These values provide a crucial basis for deriving design

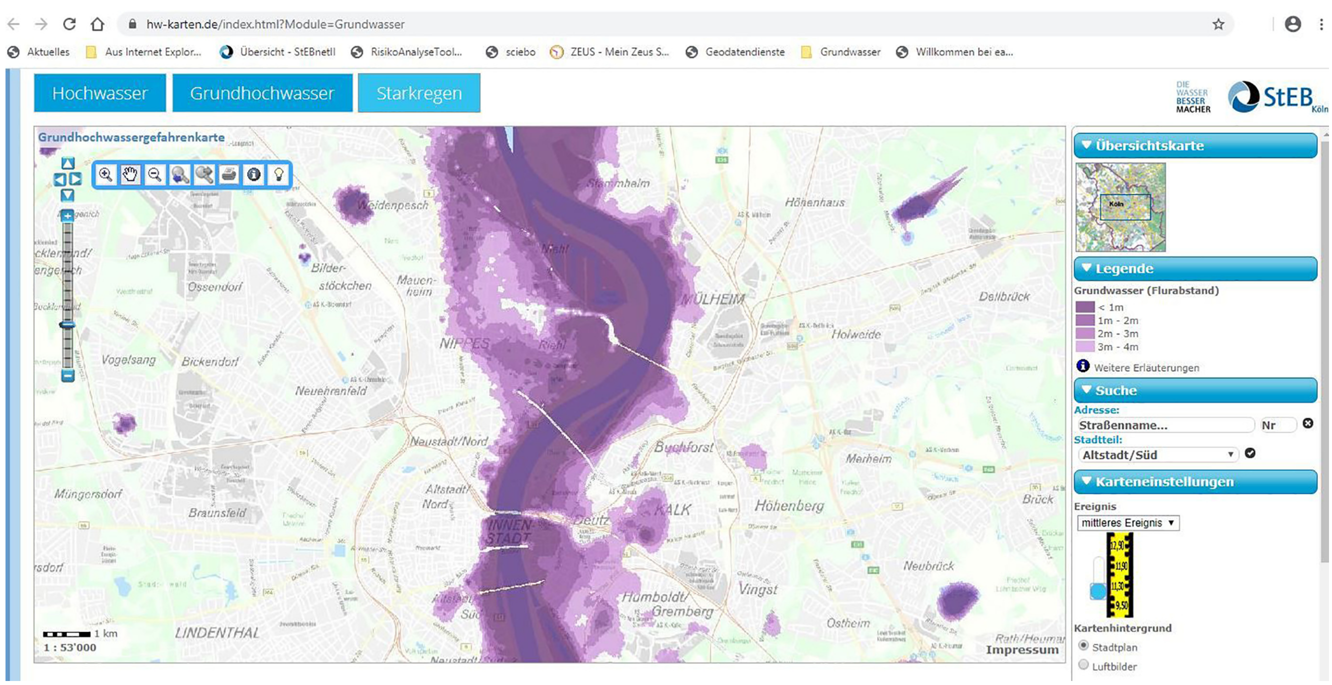


FIGURE 5 Subsurface flood hazard map for Cologne (www.steb-koeln.de). Purple shading indicates the depth to groundwater (Stadtentwässerungsbetriebe Köln, 2018)

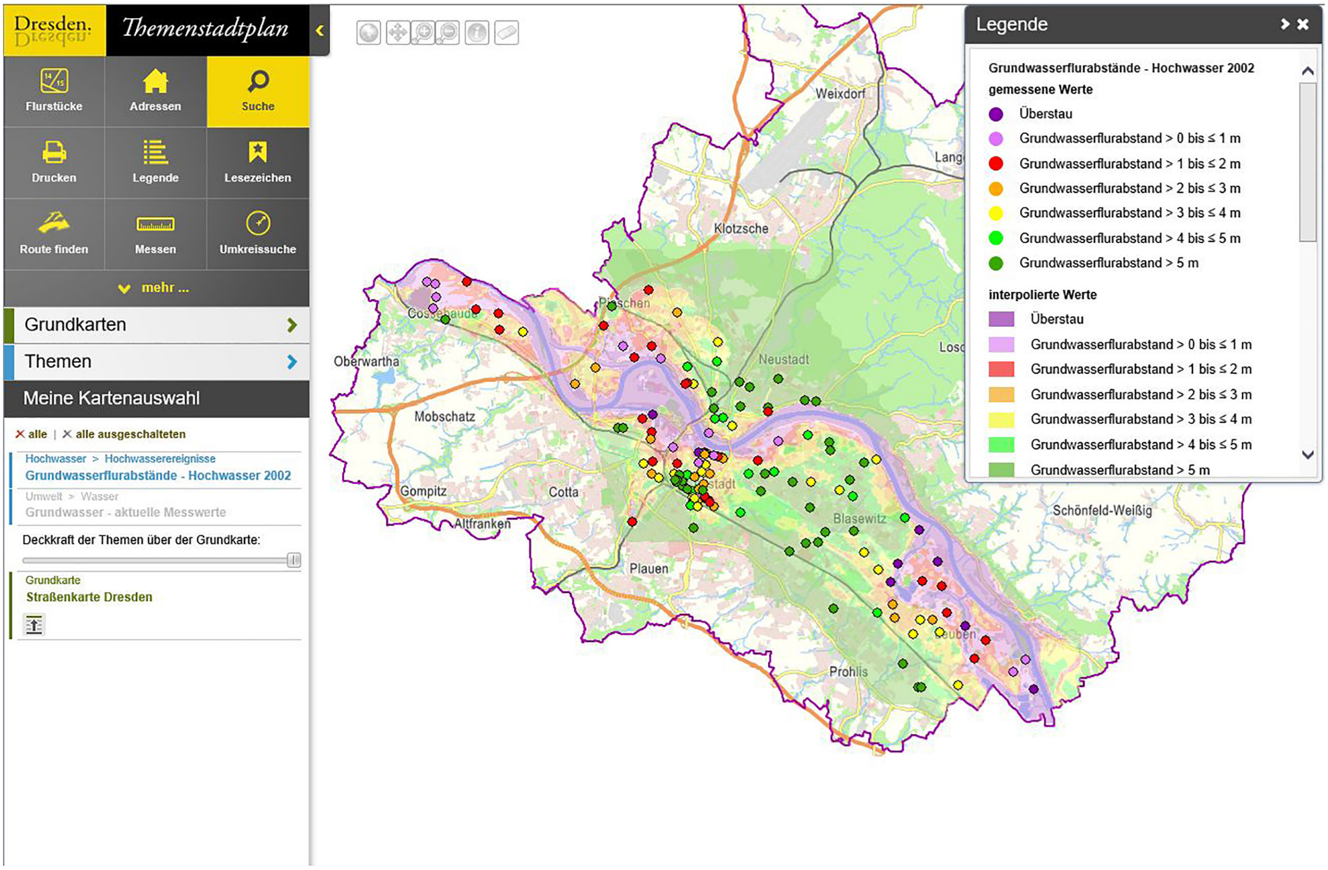


FIGURE 6 Minimal depth to groundwater during and after the historic flood event 2002 in Dresden, synoptic (Stadt Dresden, 2019)

groundwater levels. The design groundwater level itself is an important parameter for the determination of load assumptions and for the design of waterproofing measures on buildings. Examples of maps with the expected highest groundwater level can be found in BWK (2022). Like hazard maps for high groundwater levels, the generation of such maps comes with serious challenges, but in addition to the long process chain and the focus on rare events and conditions, these maps need a higher level of detail.

## 3.2 | Indication map for areas potentially affected by high groundwater levels

An indication map shows areas that are potentially affected by high groundwater levels. It has a larger extent than the hazard maps that have been introduced in the previous Section 3.1, is not focused on a river section, and is not limited to the fluvial origin of high groundwater levels. Due to the larger scale and the different processes that are incorporated, the indication map only shows areas that are potentially affected by low depth to groundwater. The indication map supports spatial planners, building owners, architects, and construction experts within their planning process, but also interested residents belong to the target audience. Figure 7 shows the indication map on areas that are potentially affected by depth to groundwater less than 3 m for the Free State of Bavaria (Germany). The method to generate such a map is described in BWK (2022).

## 3.3 | Damage and risk analysis

High groundwater levels become an issue when they cause damage. In such cases, a systematic investigation of the event and its consequences represents an essential task in dealing with the incurred damage and the resulting future

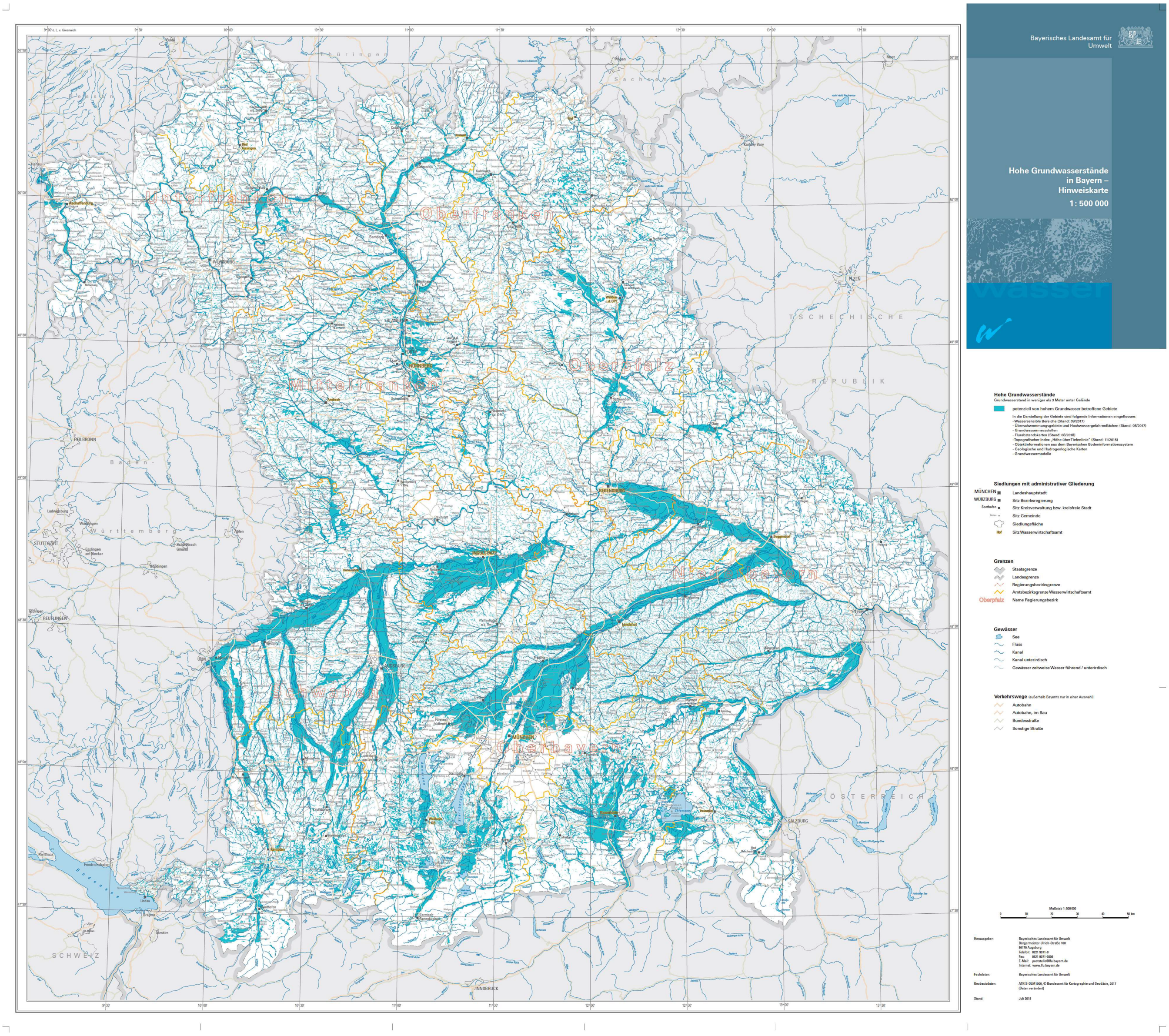


FIGURE 7 Indication map of areas that are potentially affected by high groundwater levels for the Free State of Bavaria (Germany; Bayerisches Landesamt für Umwelt, 2018; BWK, 2022)

risks. In the same way, these analyses also serve as a decisive basis for the targeted selection and implementation of appropriate precautionary and damage mitigation measures.

In our complex world—with the pursued, holistic, cross-scale view on multiple hazards including the consideration of divergent interests and conflicting goals—there is accordingly a need for detailed and comprehensive approaches and tools to evaluate the potential risk, to compare different variants, and to optimize solutions in order to reduce negative consequences of hazards. Various methods and approaches are known for estimation of flood damage, for calculation of current and future flood risks, as well as for evaluation of intended precaution and mitigation measures. This is the result of intensive research in this field, which has arisen mainly from the need in dealing with the flood events of the recent past and their immense losses.

The approaches used for this are characterized by different methods (e.g., bottom-up and top-down approaches; empirical and synthetic approaches), which usually focus on different spatial scales and issues. In contrast to floods, the modeling of damage due to high groundwater levels is rarely performed or completely neglected. It is mainly a consequence of the more complex damage mechanisms and the long chain of effects, which have to be considered in the estimation of damage and risks due to high groundwater levels. Moreover, the extent of damage from high groundwater levels is secondary to that of flood damage (Section 1).

However, damage and risk analyses due to high groundwater levels focus not only on flood-induced events. Especially, the anthropogenic and climate change-induced effects on groundwater levels require appropriate tools to derive potential damage and to investigate the effect of protection and adaptation concepts. The challenges for the approaches to determine damage to buildings and to the entire building stock of an investigation area refer to the detection of essential cause–effect relationships, the required and comprehensive data mining, appropriate characterization of subterranean building components as well as desired high spatial and contextual resolution for the results of the analyses. Against this backdrop, synthetic approaches and impact analysis have decisive advantages, so that some essential basic features for such a methodology are emphasized here. The principles are provided by the synthetic model approach called HOWAD for determining damage to buildings due to floods (Neubert et al., 2016) and GRUWAD for determining damage due to high groundwater levels (Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012). The model approach was applied in a multitude of regionally specific case studies, particularly in Germany, but also in the United Kingdom, Spain, and the Czech Republic (Golz et al., 2015; Neubert et al., 2016; Schinke et al., 2016; Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012).

The conceptual approach follows the SPRC concept (Source–Pathway–Receptor–Consequences Concept), which clarifies the fundamental cause–effect relationships in risk research. Figure 8 illustrates the schematic structure of the overall approach with the three input modules, the calculation tool, and the modeling results. With a focus on groundwater issues, the hazard (source, pathway) is usually described by the results of groundwater flow modeling or coupled simulation systems. This includes comprehensive scenario and variant analyses—taking into account different probabilities of occurrence where applicable—to characterize the potential range of impacts and, in particular, to map both the effects of area-related protection and adaptation strategies as well as individual flood precaution measures on selected buildings. In the case of flood-induced high groundwater levels, the minimal depth to groundwater, related to a specified duration during and after the (potential) event, has emerged as an important outcome and transfer parameter,

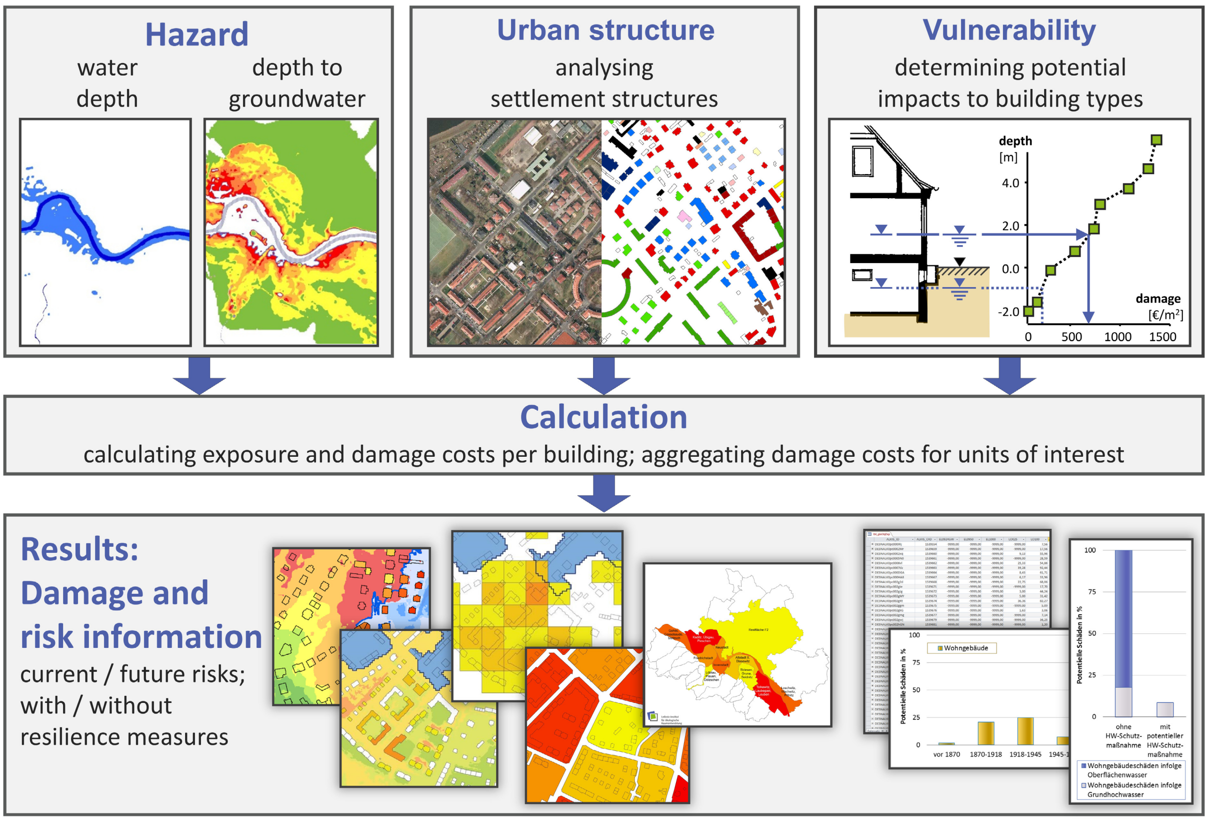


FIGURE 8 Model approach calculating damage and risks due to floods and high groundwater levels considering the effects of resilience measures (Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012, modified)

which can be illustrated in synoptic maps, shown in Figures 5 and 6 (Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012).

To ensure a high spatial and contextual resolution in damage and risk modeling, corresponding methods are required that allow a detailed characterization of the receptor "buildings" in terms of settlement structure and its vulnerability. This is ensured here by differentiating the building stock using a building typology and the synthetic analyses of type-correlating depth damage functions.

The overall objective of the building typology is on an appropriate grouping of buildings that are characterized by similar structural properties and lead to similar damage behavior. When differentiating by the construction period and structure type, buildings are grouped together that are comparable in terms of size, structural design, spatial pattern, and building materials (see Schinke, Neubert, Hennersdorf, Stodolny, et al., 2012). These structural characteristics determine the vulnerability as a result of various impacts, such as those caused by high groundwater levels.

Determining the vulnerability of relevant building types, it requires corresponding, well-founded depth-damage functions. Illustrating the method to derivate synthetic functions, the procedure relies on a type-specific identification, selection, and detailed analyses of characteristic buildings with a focus on geometry, spatial pattern, building construction, and building services. The decisive basis are subjected to a virtual flooding of the buildings in stages that allows an impact-related specification of damage patterns—differentiated according to the three damage types highlighted in Figure 4—as well as a step-by-step derivation of repair technics, and the calculation of refurbishment costs. The value pairs from depth to (ground) water and the refurbishment costs mark the fixed points of the depth-damage function. With view of the overall procedure, the analyses are thus comparable to compressed damage appraisals based on engineering analysis.

Any geographic information system or other spatial data analysis tool that evaluates the three elements of input data—hazard, urban structure, and vulnerability—can then be used to calculate the damage and risk information. The calculations carried out at the building level, which is a special feature of methodology and allows a wide range of interpretations (Figure 8).

# 4 | RISK MITIGATION

## 4.1 | Groundwater management

Nearly half the world's population relies on groundwater as their primary source of drinking water (Morris et al., 2003). Wells are typically used to extract groundwater for water supply, but they are also frequently used to drain mining sites or to protect urban infrastructure and construction sites from groundwater. Besides wells, the following structures are available as groundwater management measures for groundwater drainage:

- artificial canals (drainage canals and ditches),
- modified natural water courses, and
- drainage pipes.

These measures can be applied individually, but it can make sense to combine different measures. For all groundwater management measures, sufficient discharge capacity must be foreseen in the receiving water, and backflow protection has to be provided at the discharge point. In most countries, the discharge of water is subject to legal regulations. The individual measures are described in the following.

Watercourses and artificial canals drain the aquifer they cut in and convey the drainage water either under gravity flow or with the help of pumping stations. The water level in the watercourse or canal determines the groundwater level in the adjacent aquifer (see also Figure 2).

Natural water courses can be modified to increase their drainage capacity. By deepening or widening the watercourse, the drainage effect can be increased if the surface water level decreases accordingly. In the catchment of the Emscher (Ruhr region, Germany) groundwater drainage with modified natural water courses has been used for more than 100 years to compensate for the subsidence effects on groundwater caused by mining activities (Section 2.3).

The construction of artificial drainage canals and ditches is another possibility for groundwater drainage. Canals must be cut into the aquifer that is to be drained. Artificial canals are typical for plains and have shaped the landscapes in the lowlands of Flanders, the Netherlands, and Northern Germany on a large scale, but canals and ditches can also be applied on a local scale (BWK, 2022).

Natural watercourses and artificial canals require sufficient space. For ecological reasons and due to a lack of space in urban areas, they usually only have shallow cutting depths. The use of natural watercourses and artificial canals for groundwater drainage is therefore limited to groundwater level targets close to the surface.

Wells can be used for deep drainage targets and they do not occupy much space. A vertical filter well extracts groundwater with a submersible motor pump (well pump), which is installed in a vertical borehole with a stable filter. Wells create a punctiform drainage effect, but only when the pump operates, so the operation of wells comes with operational costs. To control the groundwater level in a large area, multiple wells are usually grouped as well-galleries. Wells can be operated permanently or temporarily. The permanent operation can be necessary to compensate for reduced groundwater extractions; in most cases, it will be possible to use the wells that have originally been installed for the groundwater abstractions, as done in Delft (Section 2.3). Temporarily usage of wells applies mainly to avoid high groundwater levels due to pluvial or fluvial origin. Wells can be installed to protect single buildings (for two example projects that have been realized in the aftermath of the flood event 2002 in Dresden (Gutt & Zschätzsch, 2013; Huber et al., 2003), but also on a larger scale. Horizontal filter wells consist of multiple horizontal boreholes around a central manhole. The boreholes are stabilized with filter pipes and mineral filter beds. Horizontal filter wells are much more expensive than vertical filter wells. They are suitable for shallow, very productive aquifers from which large amounts of water must be withdrawn. Under operating conditions horizontal filter wells have advantages over vertical filter wells: they usually have a longer operating time than vertical wells due to the low filter velocity, the low risk of mixing groundwater from different sources with different geochemical properties, and the low susceptibility to iron precipitation (ochering).

Drainage pipes are perforated pipes. They are used where the groundwater must be permanently lowered and if the groundwater drainage by wells is economically inefficient due to a low permeability of the aquifer. Drainage pipes are underground infrastructure. Like open waters, they drain in a linear shape, but drainages do not require open space. Usually, drainage pipes are only partially filled with water. The water level in the drainage is not controllable and is determined by the properties of the drainage (diameter, gradient). Like for open waters, the groundwater level adjusts to the water level in the drainage pipe. Drainage pipes can also be designed as deep-lying, completely water-filled drains with a controllable water level. The water level is controlled by pipe sockets that can be adjusted in height (Emschergenossenschaft, 2017). The pipe sockets are open at the top so that the water can flow freely into the manhole. The water-filled operation reduces the chemical precipitation of iron in the drainage, which is a great advantage in operation compared to partly filled drainage pipes. In the core zone of the Ruhr region (Germany) the water authority operates a network of water-filled drainages. Figure 9 shows the picture of a construction site where a drainage pipe is installed next to the sewer pipe. The drainage pipe will be used to control the groundwater level after the sealing of the sewer network and compensates for the unintended draining effect of the formerly leaky sewer (see also Section 2.3 and Figure 3).

FIGURE 9 Drainage pipe being installed next to a reconstructed sewer pipe (Emschergenossenschaft)

## 4.2 | Structural measures preventing damage to buildings

In the light of the building-related damage types and damage patterns caused by high groundwater levels, this section focuses on structural measures that aim at reducing potential damage and improving the resilience of the built environment. It requires first an adequate analysis of hazards, damage, and risks associated with high groundwater levels as well as a prognosis of their future development. In this context, the use of damage and risk analysis with a high spatial and contextual resolution, highlighted in Section 3.3, is an appropriate method to reflect the possible consequences, specify the challenges in dealing with high groundwater levels, as well as to characterize the effects of area-related measures and building-related mitigation measures. Considering all long-term aspects of the natural and anthropogenic changes including reduced groundwater extractions, this is useful to derive the design groundwater level and to determine the structural measures on buildings based on it. Against this background, it is advisable to consider all preventive measures already during the planning of new buildings, as they are easier, more effective, and cheaper to implement.

Three precautionary strategies are pursued with the structural measures on buildings, which are also known for flood prevention:

- dry proofing,
- wet proofing, and
- avoidance.

Figure 10 illustrates these three strategies related to high groundwater levels. In this context, it is important to consider the temporal component of the impact, which ranges—in contrast to floods—from short-term to long-term, to permanent changes (Section 2.4).

The strategy of *dry proofing* aims to improve the resistance of buildings. The focus is therefore on sealing constructions that prevent the (ground-) water penetration into the building. Examples are tub constructions known as white tank (water-impermeable reinforced-concrete construction), black tubs (bituminous or plastic sealing materials), or brown tubs (building seals made of bentonite or other clay minerals with a high swelling capacity). A subsequent increase in the groundwater-related resistance of buildings is usually complex. Main reasons are the limited accessibility of the sealing levels/sealing surfaces and the high requirements of tightness (hydrostatic pressure). In principle, methods and technologies can be used which allow sealing on the outside (e.g., by injection curtain for sealing) or on the inside of the building envelope in contact with the ground (e.g., by means of an inner tube with sufficient buoyancy protection). Furthermore, it is also necessary to prevent vertical capillary water transport in the wall cross-section (e.g., by mechanical methods or injection methods).

The strategy of *wet proofing* is primarily geared to short-term impacts and is used when the water penetration cannot be safely prevented. The aim is to reduce potential damage by adapting the building construction, relocating building services, and inventory as well as reducing high-value use in the basement. It includes specific solutions—such as emergency flooding or an implementation of superimposed loads—that prevent building structures from overloading or floating. In case of groundwater-related hazard, the storage of substances hazardous to water, the use of oil heating systems, and the storage of heating oil should be avoided from the basement as a matter of principle even if the elements have a security system.

The strategy of *avoidance* focuses on a relocation of vulnerable elements out of hazard zones and it is easier to consider in the design phase of new building. Here, even eliminating a basement or elevating the entire building can significantly reduce the groundwater exposure. In contrast, this strategy presents some challenges for existing buildings.

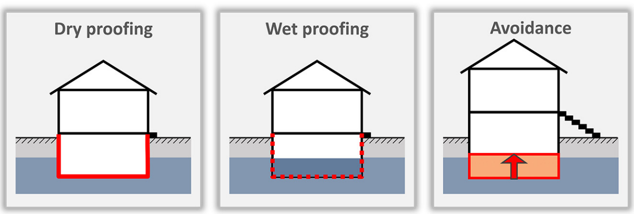


FIGURE 10 Strategies of object-related structural measures to improve the resilience of buildings in case of high groundwater levels (BWK, 2022, modified)

Options include partial or full basement backfilling or house elevation (HyBauTec Wolfanger, 2021; LMBV, 2021). Engineering practice shows that, in principle, both approaches are used and that these are suitable options for areas affected by mining after the cessation of groundwater dewatering. For the sake of completeness, it should be mentioned at this point that object protection can also be realized by groundwater extraction and, if necessary, in combination with a cut-off wall ring. These measures are assigned here to water management (Section 4.1).

## 4.3 | Operational management of fluvial high groundwater levels

In the scope of fluvial and coastal floods, operational flood forecasting is an important element of modern flood risk management (Bachmann et al., 2016; Jain et al., 2018; Pilling et al., 2016). Based on short-term forecasts, warnings are issued, so that appropriate emergency mitigation measures can be implemented, for example, setting sand sack barriers or evacuation measures (Figure 11), which reduces damage to people and assets.

However, flood forecasting systems are currently limited to a short-term prediction of discharges and water levels (in river or at coast). The forecast of high groundwater levels is currently not yet an integral part of most operational flood forecasting systems.

### 4.3.1 | Forecast

Within the scope of high groundwater levels, the objective of an operational system is a short-term forecast of groundwater levels (or the minimum depth to groundwater) in the surrounding of a river (Figure 12). The forecasting chain used to forecast fluvial floods usually consists of a meteorological forecast of, for example, precipitation and temperature, a hydrological forecast of discharge, and a hydrodynamic prediction of water levels in the river. For a forecast of high groundwater levels, an extension of this model chain is required, as shown in Figure 12.

In addition to the current and forecasted water levels in the river, the groundwater level at the beginning of the forecast period (at T0) as an initial condition, the groundwater recharge, and other changes in boundary conditions (e.g., well operations) during the forecast period are important parameters to groundwater models. Existing (online) groundwater monitoring networks provide data to define the initial groundwater levels. Groundwater recharge follows from the meteorological forecast; planning data from major groundwater users support the short-term forecast of groundwater extractions.

Several approaches are available to extend the existing forecasting chain for the forecast of flood levels to a forecast of high groundwater levels:

- *Expert knowledge*: Based on experience, knowledge, and available forecasted information (e.g., flood water levels) high groundwater levels and thus possible hazards are estimated by experts. The advantages of this method are its simplicity and robustness. It provides a fast access to information and a fast adaptability to the forecasted input variables. Disadvantages are the availability of experts and a possible intuitive and subjective assessment of the situation. By its nature, an expert assessment is qualitative.

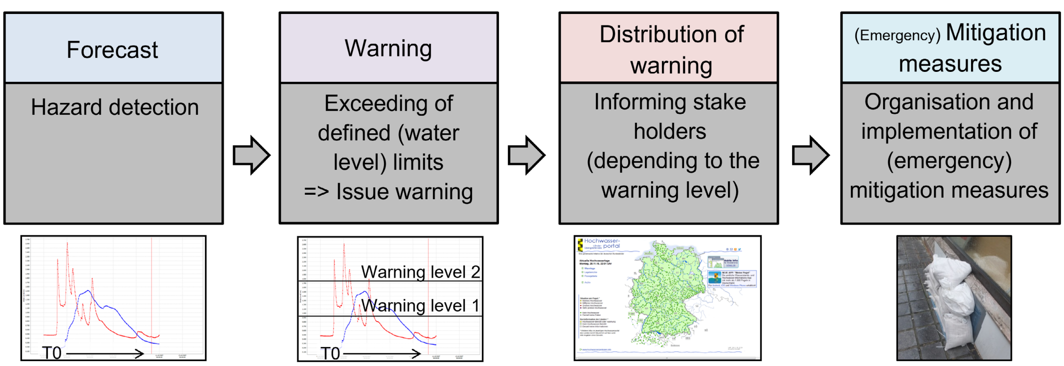


FIGURE 11 From forecast to mitigation measures

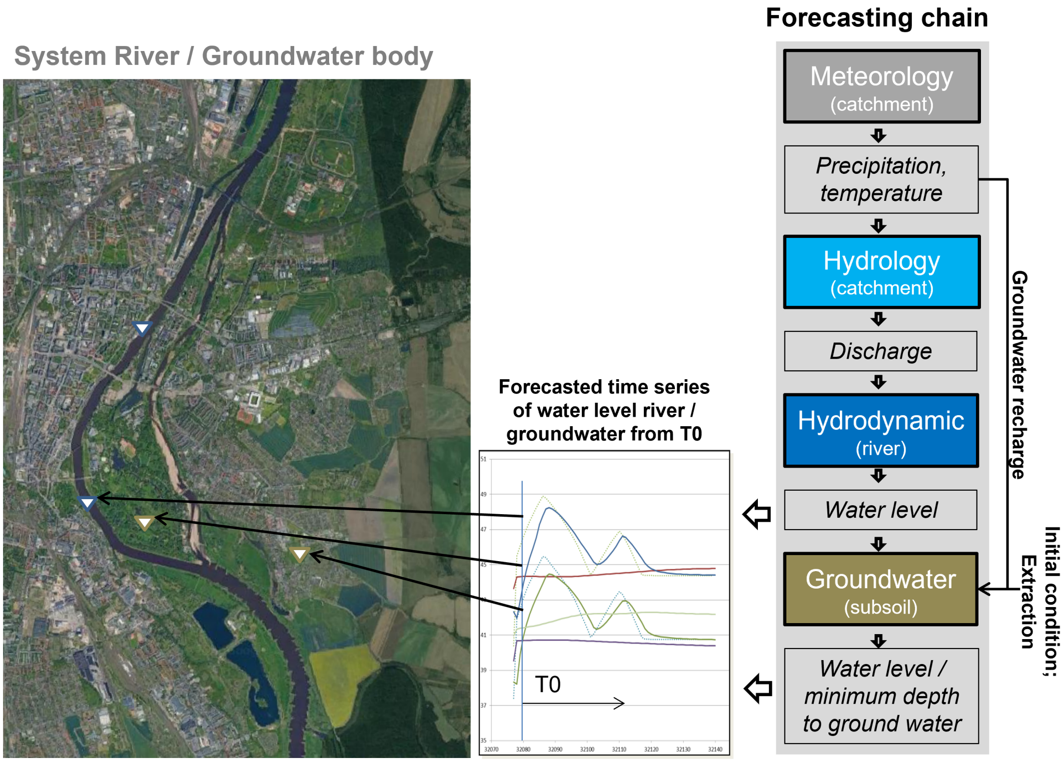


FIGURE 12 Operational short-term forecast of high groundwater levels

- *Precalculated data*: Subsurface flood hazard maps (Figure 5) are precalculated for defined river flood events (e.g., Q50–Q100). These maps serve as the basis for the assessment of risk areas also in the operational case. Advantages of this method are that it is simple, robust, and has a fast access to objectively verified information. Disadvantage of this approach is the reduced adaptability to the predicted conditions: each flood wave, the initial conditions, and the boundary conditions are—in general—different for each event.
- *Model-based forecasting systems*: Numerical–physical groundwater models, statistical models, or models based on artificial intelligence are coupled with the existing forecasting chain and can model high groundwater levels for a short-term forecasting period. Thus, such systems support the identification of risk areas. Coupling of the models (hydrodynamic river–models to groundwater models) can be set up sequentially coupled or coupled on a time-step basis (2010). The advantage of model-based forecasting systems is the provision of objective information based on current initial conditions and forecasted river water levels. Disadvantages are the complexity of these systems and the time required for modeling. However, model simplifications, modern hardware, and existing forecasting platforms, such as Delft-FEWS (Deltares, 2021), can simplify and accelerate the forecasting process.

A combination of these approaches can further contribute to an improvement of the forecasting results.

A prototype of a model-based forecasting system for high groundwater levels is shown in Figure 13 (Bachmann et al., 2014). For the city of Cologne (Germany), an 1D-river model of the Rhine-river was coupled on a parallel time-step basis with two groundwater models representing the surrounding groundwater body (Figure 13, left up). A historical flood event (Figure 13, left bottom) was calculated and its effect on the groundwater levels analyzed (Figure 13, right). This coupled system is ready to be used in a short-term forecast.

### 4.3.2 | Warning and warning distribution

After the forecast of high groundwater levels (hazard detection), the exceedance of defined limits must be transferred into a warning system (Figure 11). The limits are set based on the existing damage potentials in the area. Classical media, such as radio or personal transmission, as well as mobile data transmissions, such as text messages (SMS),

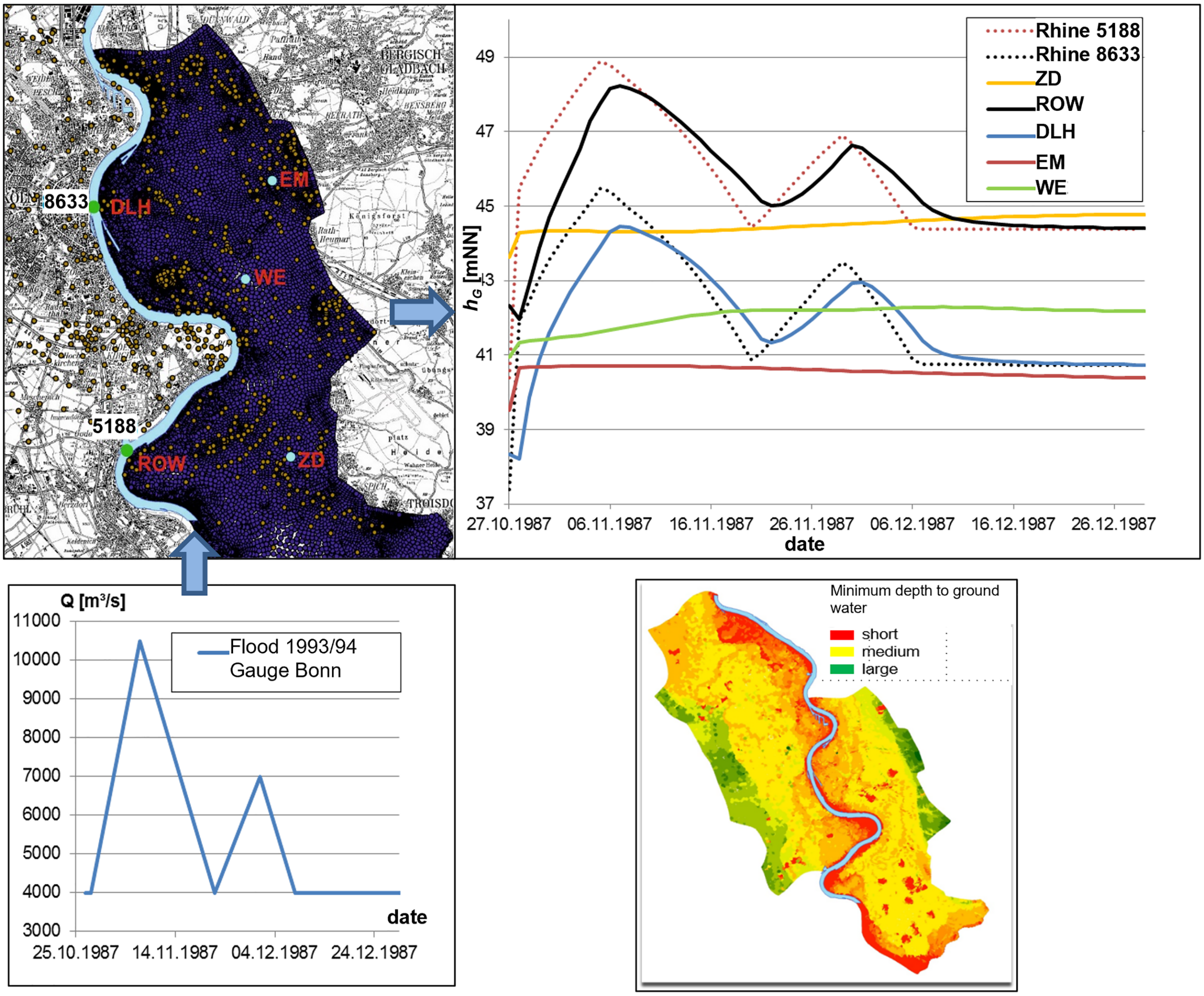


**FIGURE 13** Model results from prototype of a model-based forecasting system for high groundwater levels in the Cologne area (Germany)

e-mail, social media, or smartphone apps can be used for the submission of warnings. As warning recipients, focus groups are potentially affected persons (e.g., residents, parking garage operators, transport companies), first responders (e.g., authorities, civil protection organizations), and crisis managers.

### 4.3.3 | Emergency mitigation measures

In principle, a distinction can be made between planned and emergency mitigation measures. For example, in case of river floods, sandbag protection to prevent the flood spreading or the evacuation of people are considered as emergency mitigation measures.

If the protection level by planned measures, such as structural measures (Section 4.2) or measures of water management (Section 4.1), is not sufficient, the following emergency mitigation measures can be implemented during an event of high groundwater level:

- Emergency securing of endangered objects especially in a basement (e.g., oil tanks),
- Relocation of potentially affected inventory and expensive mobile elements (e.g., cars and valuable goods), and
- Ballasting or controlled flooding to protect the structure of buildings.

## 5 | SUMMARY AND CONCLUSIONS

A high groundwater level is a groundwater level that is higher than the usual level. High groundwater levels come with unfavorable consequences mainly for the built environment with buildings, infrastructures, and sewage systems. It is first from groundwater itself, when the groundwater penetrates basement walls or the basement floor, and second by change of hydrostatic pressure on building components. Third, contaminants can be mobilized under high groundwater levels.

High groundwater levels can originate from hydrological processes or anthropogenic effects. Hydrological processes are increased groundwater recharge due to rainfall and river–aquifer interaction during a flood in a river. Anthropogenic interventions that lead to high groundwater levels are often related to (i) the interaction between sewer network and groundwater, (ii) reduced groundwater abstraction, and (iii) hydraulic engineering measures.

While flood management has accompanied mankind for centuries in some regions, high groundwater levels have received a wider attention only in recent years. To prepare for the negative effects of high groundwater levels, it is thus important to identify the regions that are potentially affected by high groundwater levels and what the potential hazards and risks are. Some planning tools are presented in this article. Hydrological and geological aspects and a changing climate, as well as socio-economic development and the corresponding usage of groundwater, are to be considered.

The fact that there are different processes and that different domains are concerned makes it necessary to improve collaboration between institutions and organizations. Integrated approaches for modeling, design, planning, forecasting, and warning should be developed: those organizations that develop flood risk management concepts and carry out spatial planning should take high groundwater levels into account in their activities and involve the organizations that are responsible for groundwater management. On the other hand, collaboration is also important when existing subsurface infrastructure is modified—in this article, we present the example of sewer pipe sealing—and when the groundwater operations change—for example, when groundwater extractions are reduces. In the end, the interdisciplinary collaboration should aim at coherent risk communication to stakeholders, potentially affected people and institutions, at effective and efficient measures for risk mitigation, and at a sustainable urban and regional planning.

Especially, in the case of fluvial origin, the emergence of high groundwater levels is driven by complex interaction processes between multiple domains: aquifer, river, inundation area, and a sewer network. Abboud et al. (2018) point out that the related scientific literature is still relatively sparse. Developing a better understanding of the processes and their interaction is thus very important. This should also include the problem of low groundwater levels and groundwater quality.

### AUTHOR CONTRIBUTIONS

**Bernhard Becker:** Conceptualization (lead); project administration (lead); visualization (equal); writing – original draft (lead); writing – review and editing (lead). **Frank Reichel:** Visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Reinhard Schinke:** Conceptualization (equal); supervision (lead); visualization (equal); writing – original draft (equal); writing – review and editing (equal). **Daniel Bachmann:** Conceptualization (equal); visualization (equal); writing – original draft (equal); writing – review and editing (equal).

### ACKNOWLEDGMENT

Open Access funding enabled and organized by Projekt DEAL.

### CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

### DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

### ORCID

*Bernhard Becker* https://orcid.org/0000-0001-9831-0792
*Reinhard Schinke* https://orcid.org/0000-0002-6008-1151

### RELATED WIRES ARTICLE

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**How to cite this article:** Becker, B., Reichel, F., Bachmann, D., & Schinke, R. (2022). High groundwater levels: Processes, consequences, and management. *WIREs Water*, *9*(5), e1605. https://doi.org/10.1002/wat2.1605