# Data-driven Municipal Resilience Quantification for Extreme Weather Events – Application of Dataspace Functionalities for Disaster Management

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## 1 ABSTRACT

The climate change led to extreme weather events that can cause extensive catastrophes. The consequeneces for urban areas and municipalities have become much more complex and requires an assessment and an increase of their resilience. Reliable information builds the basis for decision maker to be prepared and to get in front of the situation in case of an event occurrence. But the availability and the structure of data sources include also an increasing complexity. This paper presents a developed dataspace concept for a data-driven resilience assessment of urban areas or municipalities. Different sources like social data, infrastructure networks, building models, financial assests as well as weather data are combined for a extensive data analysis. Statistical and stochastic methods are applied to generate an understanding between the cause and the effect with respect to extreme weather events. The data analysis is applied to quantify urban key performance indicators for the disaster management. Examples are the availability, usability or the expected damage. The dataspace concept allows an assessment before, during and after the occurrence of a disruptive event. Single resilience phases, like preparation, prevention, protection, response and recover can be easily characterized. The methodology identifies potential weak spots and increases the coping capacity. Several use-cases for different urban areas and municipalities are presented and underline the applicability. Heavy rain and flood events are exemplary investigated.

Keywords: dataspace, extreme weather, disaster management, resilience, data analysis

## 2 INTRODUCTION

Current hazard situations led to complex crises and catastrophes. A highly technological society that is interwind in global trade has new challenges to cope with such adverse events. The Covid-19 pandemic or certain extreme weather events are exemplary events that have significantly influenced and continue to change the society and the politics [1]. The multi-layered and federal civil protection system in Germany is also confronted with hugh challenges, due to the occurrence of such crises or catastrophes. On example of this is the establischment of methods to decrease consequences, to response as fast as possible or to initiate an effeicient recovery[2].

Thesecircumstances underline the need of an assessment and an increase of municipal resilience. Different information characterizing the municipial resilience, but requires the availability of structured data which is also an complex challenge. The German Federal Office for Civil Protection and Disaster Relief (BBK) calls for "firmly agreed ways of exchanging data and information" which has to be "evaluated and improved" [3].

Based on these aspects, this paper presents a dataspace concept that merges heterogeneous data sources. Statistical and stochastic methods are applied to analyse the merged data and to quantify municipal resilience. Applications exampels show results of the demonstrator to evalute the occurrence of potential extreme weather events. Several use-cases are coordinated with different emergency management and disaster control authorities.

## 3 CONCEPT OF A RESILIENCE DATASPACE

The concept of the datadriven municipal resilience assessment aproach is shown in Figure 1. There are two main components: dataspace functionalities and methods for resilience analysis.

A dataspace is a federeated and open infrastructure for a sovereign data excchange, which is based on comon rules and standards [4]. This concept uses decentral data storage and a demand-oriented integration of data. The guarantee of data sovereignty is a central element of data spaces and they are an innovative digital ecosystsm that enable the open, secure and transparent use of data. They play a key role in the European digital strategy and the expansion of the European data economy [5].

According to Figure 1, connectors are used to combine different data sources. The pipeline transforms the data for the subsequent data analysis. Within a data catalogue, a potential user can extract different information concerning the availability, the format or the soluation of the connected data.

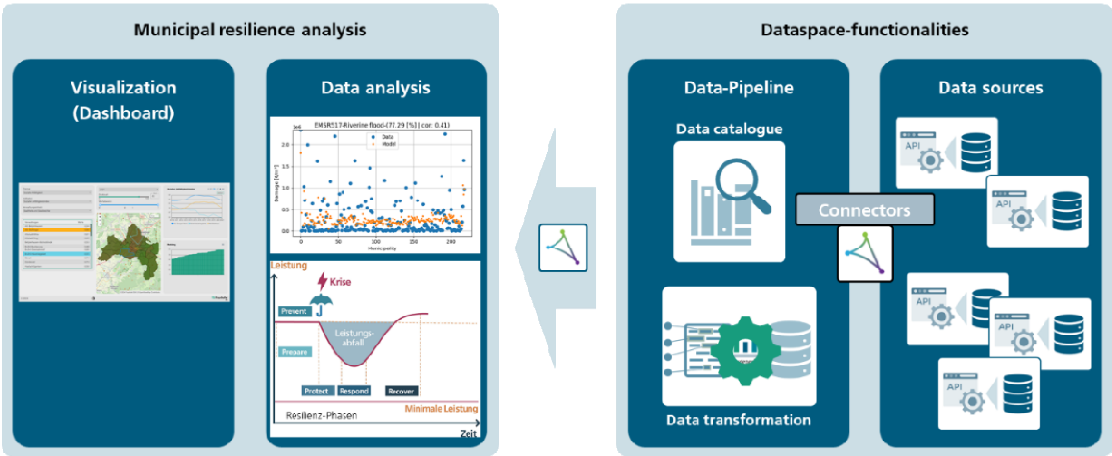


Fig. 1: Overview of single components for the data-driven resilience analysis of regions or municipalities.

The second part of the concept consists the data analysis as basis to derive quantitative resilience measures. Finally, the results are visualized within a dashboard. Different options, like GIS-based results, diagrams or time series are summarized to give a broad understanding and a contribution for municipal decision-makers.

## 4 DATA-DRIVEN RESILIENCE ANALYSIS

The characterization of possible disruptions and the resulting consequences can be quantified and evaluated using classic risk analysis methods [6]. The application of protective measures reduces the expected damage or the probability of occurrence and results in acceptable risks [7]. According to [8], increasing complexity and process dependencies are reasons why the application of risk-reducing measures is not necessarily sufficient. The aspects of resilience provide a holistic, adaptable and interdisciplinary concept to counter unforeseeable disruptions. Also a fast recovery after a disruption is an essential part concerning the prosperity of a society [9] and motivates the assessment and the increase of the municipal resilience. Based on the interdisciplinary application of resilience, several definition of that term are available [8].Within this paper the established definiton of [10] is used which includes five cyclic phases, see the left picture of Fig. 2. Therefore resilience "[…] is the ability to prepare for adverse events, to prevent them if possible, to cope with them, to react and recover as quickly as possible and to adapat to further future events if possible". Adverse events are disasters or change processes with far-reaching consequences that are of human, technical or natural origin.

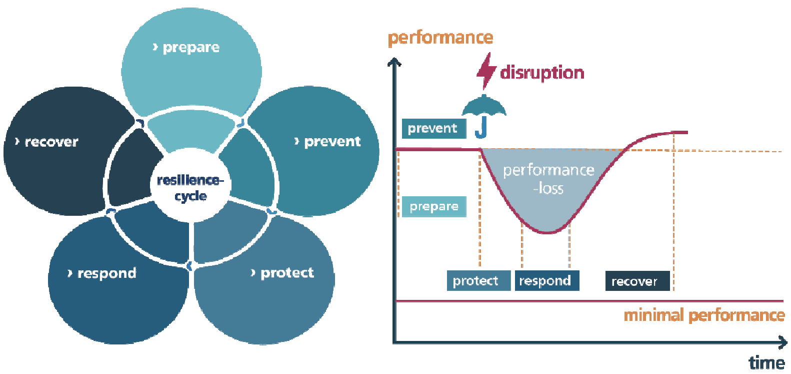


Fig. 2: Cyclic phases for the definition of resilience (left) and their interpretation on a performance-time relation to quantify resilience (right).

According to [11], the resilience of any systems can be measured using a performance-time relationship, as indicated with the right picture of Fig. 2. The five cyclic phases can be projected on this functional relationship before, during and after the disruption. The area in this relation measures the performance loss and indicates a quantitative resilience measure, i.e. the smaller the area, the higher the resilience.

The generalized concept of resilience is applied to the present requirements concerning the assessment of municitpalities subjected to hazards. Fire fighters and municipal decision makers from 12 different German districts and cities were involved in several workshops. They helped with their expert knowledge to identify key performance indicators (KPIs) for a resilience assessment of municipalities. Table 1 summarizes the results in alignment to the use-cases pandemic and extreme weather.

| **KPI** | **Use-case pandemic** | **Use-case extreme weather** |
|---|---|---|
| Affected persons | Number of test/recovered/fatalities | Number of affected persons |
| Coping capacity | Nurse per patient/hospital | Availability first responder<br>Number of applications |
| Availability | Bed occupancy/capacity (hospitals) | Critical infrastructure |
| Robustness | Unemployment | Usability/damage of buildings |
| Economy | Economic damage (direct/indirect) | |

Table 1: Derived performance measures for the municipal resilience assessment in alignment to different use-cases.

The results concerning the municipal resilience assessment in Table 1 are listed according to their priority from the perspective from civil protection. Hence, the first KPI is the number of affected persons. The coping capacity and the availability are separated in dependency of the use-case. The usabiliy of buildings is a further essential KPI for the use-case extreme weather. Finally, economic damage was mentioned but is of lesser importance from a civil protection perspective.

## 5 APPLICATION EXAMPLES

The KPIs in Table 1 formed the basis for the review to data sources and approaches for the quantification of the performance targets. The identified datasources are coupled in alignment to the introduced scheme in Figure 1 for the quantification of single resilience metrics. The needs from the emergency management and first responder builds the basis to derive different use-cases. Subsequent, selected examples are presented to demonstrate the applicability and practical use of the introduced approach. The examples characterize single resilience phases (Figure 2).

### 5.1 Preparation and protection – Weak spot identification before and during the event occurrence

The first application example investigates within a what-if analysis the consequences of a hundred-year flood event. Flood maps [12] are consolidated with information concerning the road network [13, 14], points of interest, fire stations [15], digital buildings models [16]as well as landscape and usage models [17].

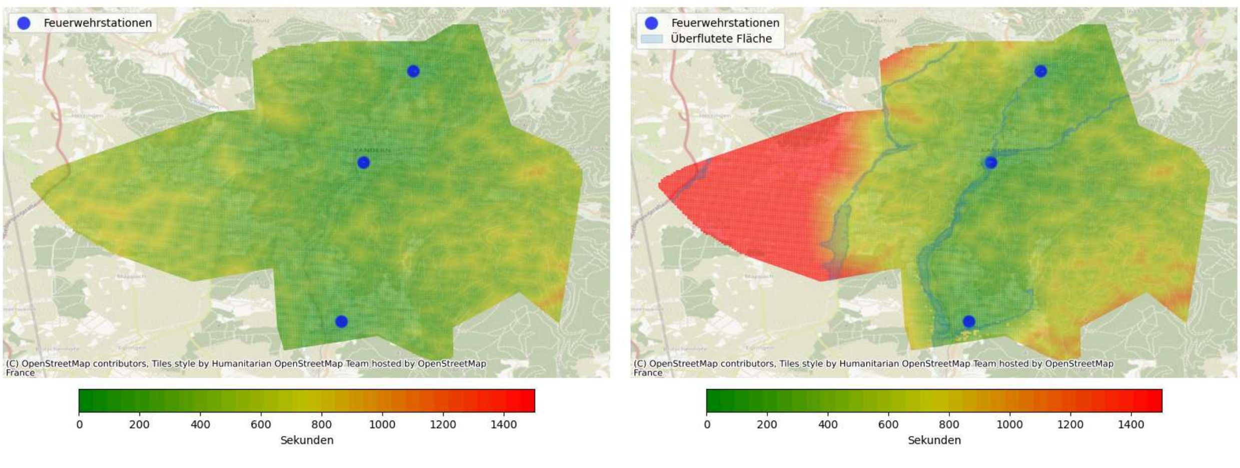


Fig. 3: Availability of all locations within a community with view from fire stations (blue points) before (left) and during (right) a flood event.

In alignment to the identified KPIs form Table 1, the availability of fire stations is calculated. A knot edge model is derived in with respect to the included road network. Afterwards, the travel times from single fire stations to each location in the municipality are calculated and the shortest pathes are identified. Finally, all results are merged and visualized in an isochrone map. The consideration of the flood map identifies blocked roads and influence the availability. The approach visualizes the changes caused by a flood and supports for a preparation in case of an event. The comparison is shown for a community in Baden-Württemberg in Figure 3. In this example, the eastern part of the region is strongly affected in case of a flood event.

The digital building models are applied to identify the number of affected buildings in combination with the flood map. The inclusion of the landscape and usage model helps to assign the buildings to single resilience dimensions according to[11]. Hence, the approach helps to identify, which parts of the municipality are affected. Figure 4 shows the results of the presented application example, the community in Baden-Württemberg, where most of the buildings are assigned to the social part, e.g. residential buildings, followed by technical infrastructure and buildings in the range of industry, sales and services. The resilience dimension organizational, e.g. administrative buildings, have a very small proportion in this example.

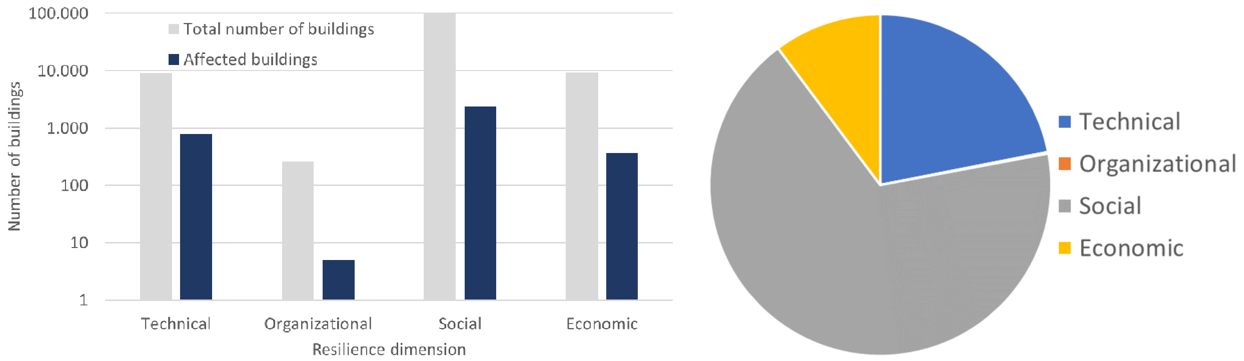


Fig. 4: Identification of affected buildings and the assignment to single resilience dimensions in dependency on the buildings use.

Beside the preparation for a disruptive event, there is also the need for a best practice protection, if an event happens. The next example was developed with a water board from North Rhine-Wesphalia. In case of potential dam failures there is the question what the consequences for the population are and how they can be protected. Figure 5 shows the results from a hydrodynamic simulation [18]. The black dot in the left map identifies the position of the broken dam and the color code indicates the time-dependent flood propagation. The right picture shows the predicted flood level. This information is coupled digital data concerning the road network [13, 14] and population data [19, 20].

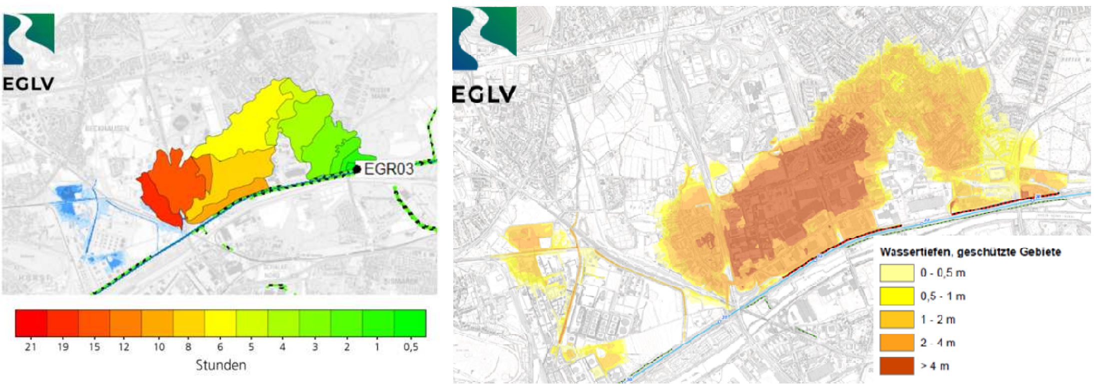


Fig. 5: Hydrodynamic simulation of a dam failure to estimate the flooding in terms of time-dependent propagation (left) and the flood heigt(right) according to [18].

The left picture of Figure 6 shows the static estimation of persons in the affected area. In this example, there are almost 13,00 persons involved. The introduced approach to estimate the availability (Figure 3) is applied with a walking speed and helps to estimate how long does it take to leave the endangered area. The results are currently applied for decision support by the city administration to install a rescue route system.

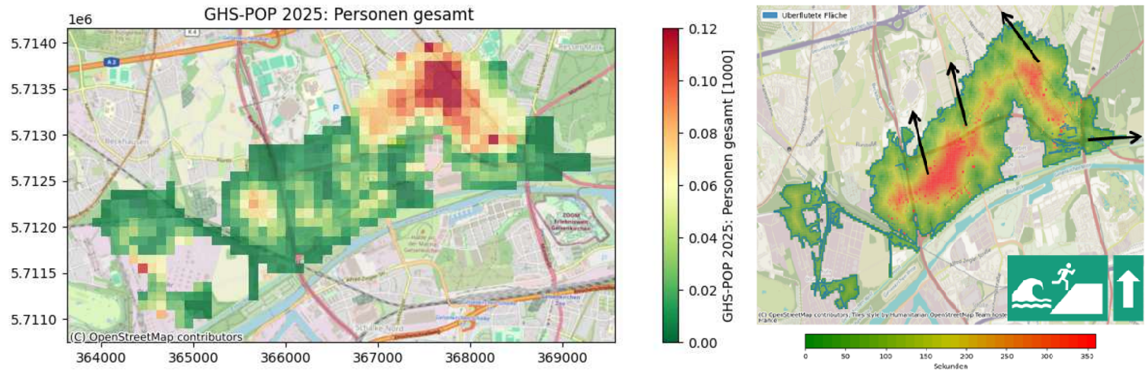


Fig. 6: Estimation the number of affected people (left) and the analysis of rescue pathes (right) in case of a dam failure.

The examples demonstrate that single resilience phases and dimensions are directly addressed with the introduced data-driven approach. The results give decion support for administrative authorities and crisis manager.

## 5.2 Response – Situational awareness after the hazard event occurence

The next example shows how the introduced approach supports after the occurrence of a disruptive event and contributes to the resilience phase "response". The emergency manamangement service (EMS) is a module from the European earth observation programme "Copernicus" [21]. In case of an extreme weather event, satelitte images can be directly requested by first responders. The information of floodes areas of past events are combined with digital terrain model [22] to estimate the flood level as missing information. The consolidation with digitalbuildingmodels[16]helps to identify the number of affected buildings and the development of fragility curves estimate potential building damage. Figure 8 shows the assement of the affected buildings and the corresponding damage that is dependent on the estimated flood height. The example is based on satellite images that were captured during the flood event in the Ahr valley in 2021.

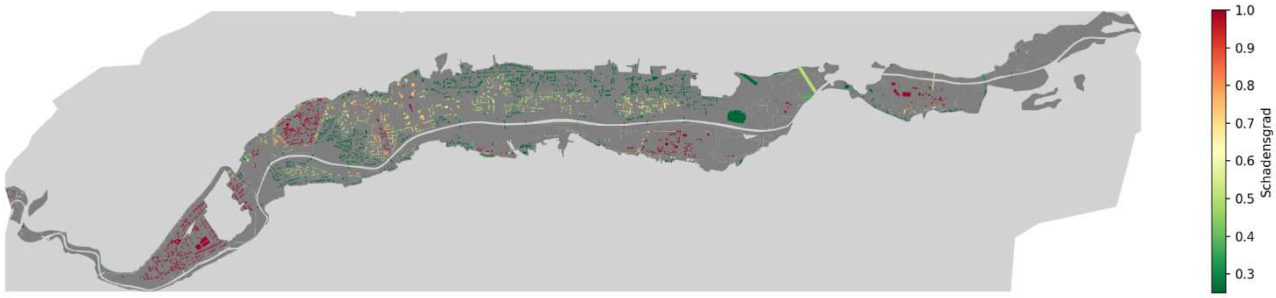


Fig. 7: Estimation of building damage based on the calculated flood height and the digital building models.

This use-case demonstrates the contributin of the introduced approach to generate further information for a situational awareness picture.

## 6 CONCLUSION

This paper introduces a new approach that uses data space functionalities for the resilience assessment of municipalities. Generalized standards of the International Dataspace Association (IDSA) guarantees data sovereignty and data protection. Connectors couple several external data sources and a developed data pipeline transform the digital information for analyses. The results of the data analysis are visualized in a user-friendly dashboard.

Existing solutions needs more effort for the merging of different information and their interpretation. The introduced approach includes efficient algorithms for data consolidation, automated analysis and corresponding visulazation.Different data analysis appraoches helps to identify potential weak spots and contributes for the resilience analysis of communitites or municipalities.

The use of the resilience cycle and the corresponding five phases of preparation, prevention, protection, response and recovery results in a clear definition and adresses all relevant aspects including resilience dimensions and properties.

The application examples demonstrates the applicability for extreme weather events concerning the resilience phases preparation, protection and response. The results are verified in alignment to the needs of municipal decision makers, first responders and crisis manager.

Further work will focus on the validation of the data analysis approach. Examples are verification of flood height estimation and calcultation of expected building damage. The estimation of person density based on static population data. In case of further data with dynamic population data, this data source can be replaced.

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## 8 REFERENCES

1. BMI (2022) Deutsche Strategie zur Stärkung der Resilienz gegenüber Katastrophen: Umsetzung des Sendai Rahmenwerks für Katastrophenvorsorge (2015–2030) – Der Beitrag Deutschlands 2022–2030, Berlin
2. Schmitz J (2021) Warum versagt die administrative Krisenbewältigung so oft?: Die (Hochwassesr)Kastastrophe und das Krisenmanagement, Bonn
3. BBK (2021) Stärkung des Bevölkerungsschutzes durch Neuausrichtung des Bundesamtes für Bevölkerungsschutz und Katastrophenhilfe, Berlin
4. Reiberg, A., Appeld, S., Krämer P, Smolen A (2023) Datentreuhänder, Datenvermittlungsdienste und Gaia-X Hub Deutschland: White Paper 2/2023, München
5. Data Europa Academy (2023) Data spaces: Introducing the concept and relevance in today's world
6. Kaplan S, Garrick BJ (1981) On The Quantitative Definition of Risk. Risk Analysis 1:11–27. https://doi.org/10.1111/j.1539-6924.1981.tb01350.x
7. Hunter PR, Fewtrell L (1986) Acceptable Risk. IEEE Trans Rel 35:348. https://doi.org/10.1109/TR.1986.4335455
8. Hiermaier S, Scharte B, Fischer K (2019) Resilience Engineering: chances and challenges for a comprehensive concept. In: Ruth M, Goessling-Reisemann S (eds) Handbook on Resilience of Socio-Technical Systems. Edward Elgar Publishing
9. Bristow DN (2019) How Spatial and Functional Dependencies between Operations and Infrastructure Leads to Resilient Recovery. J Infrastruct Syst 25. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000490
10. Thoma K (2014) „Resilience-by-Design ": Strategie für die technologischen Zukunftsthemen. Acadech Studie, München
11. Bruneau M, Chang SE, Eguchi RT et al. (2003) A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra 19:733–752. https://doi.org/10.1193/1.1623497
12. Bundesanstalt für Gewässerkunde Geoportal der BfG. https://geoportal.bafg.de/ggina-portal/. Accessed 01 Aug 2024
13. OpenStreetMap. https://www.openstreetmap.org/. Accessed 01 Aug 2024
14. OpenRouteService. https://openrouteservice.org/. Accessed 01 Aug 2024
15. Bundesamt für Kartographie und Geodäsie Points of Interest Bund (POI-Bund). https://gdz.bkg.bund.de/index.php/default/points-of-interest-bund-poi-bund.html. Accessed 07 Aug 2024
16. Bundesamt für Kartographie und Geodäsie 3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE). https://gdz.bkg.bund.de/index.php/default/3d-gebaudemodelle-lod2-deutschland-lod2-de.html. Accessed 01 Aug 2024
17. Bundesamt für Kartographie und Geodäsie Digitales Basis-Landschaftsmodell (Ebenen) (Basis-DLM). https://gdz.bkg.bund.de/index.php/default/digitales-basis-landschaftsmodell-ebenen-basis-dlm-ebenen.html. Accessed 01 Aug 2024
18. Emschergenossenschaft Lippeverband Blaugrünes Leben, wie wir unsere Heimat neu bauen. https://www.eglv.de/. Accessed 06 Mar 2025
19. Statistisches Bundesamt Regionaldatenbank Deutschland. https://www.regionalstatistik.de/genesis/online/. Accessed 01 Aug 2024
20. European Union GHSL – Global Human Settlement Layer: Open and free data and tools for assessing the human presence on the planet. https://human-settlement.emergency.copernicus.eu/. Accessed 01 Aug 2024
21. European Union Copernicus Emergency Management Service. https://emergency.copernicus.eu/. Accessed 01 Aug 2024
22. Bundesamt für Bevölkerungsschutz und Katastrophenhilfe Digitale Geländemodelle. https://gdz.bkg.bund.de/index.php/default/digitale-geodaten/digitale-gelandemodelle.html. Accessed 01 Aug 2024