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Sustainable risk management of trouble spots caused by heavy rainfall events: Citizen Science app and data analytics for residents and authorities

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Abstract. *To address the increasing threat of heavy rainfall events the FloReST (Urban Flood Resilience – Smart Tools) project focuses on the identification and prediction of emergency flow paths in urban areas and enhancing risk management and communication. The project developed a Citizen Science app to document and report pluvial flood risks in urban areas due to the fact that conventional flood protection has so far focused mainly on fluvial hazards. The population is involved in sustainable risk minimisation through the active use of the app and local risk awareness. Additionally, the app includes educational functions through a user guidance on categorizing pluvial hazards and taking preventive measures. The app is complemented by a Geo Data Warehouse, which enables authorities to analyse and visualise the data transmitted by users via customisable dashboards. Although there are still some technical limitations, such as limited offline functionality and inaccuracies in the use of Global Navigation Satellite Systems, these may be addressed in future research. Thanks to its open-source design, the system remains scalable and can be adapted to other regions worldwide. Overall, the Citizen Science app and Geo Data Warehouse form an innovative, participatory tool that improves the resilience of cities to climate change through inclusive, data-driven risk management.*

1 Introduction

Heavy rainfall events and flood disasters have increased in frequency and intensity in recent years (Deumlich and Gericke, 2020). Because of climate change this trend will continue to intensify in the coming years and decades, causing numerous material and human losses.

Floods, such as those in the Ahr Valley in 2021, have shown that warning the population in time is a crucial factor, especially in pluvial events. To mitigate this factor, continuous research is being conducted on better forecasting methods and the communication of various alert chains is being improved.

The Water Extreme Events (WaX) program of the German Federal Ministry of Research, Technology and Space (BMFTR) is also dedicated to these tasks. The funding line includes 12 projects focusing on water-related topics. One of these projects is the "Urban Flood Resilience – Smart Tools (FloReST)" project. As part of this project, various smart tools are being developed

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to improve risk management in heavy rainfall events. The focus is on identifying and predicting flow paths in urban areas and the resulting risk management.

Risk management includes a wide range of measures aimed at mitigating problematic areas within these flow paths that may pose dangers during heavy rainfall events. These include, for example, clogged drains, grates, and sieves that can no longer absorb water masses during a strong runoff, causing the water to flow elsewhere.

Identifying such problematic areas requires a high level of local knowledge. Many citizens are familiar with how their neighbourhood behaves during heavy rainfall events and possess detailed knowledge about runoff behaviour on their own property and in adjacent public spaces. This valuable knowledge often resides with residents who have observed and even documented their surroundings during past events. Since responsibility for public spaces lies with the respective municipalities, establishing a communication chain between these knowledgeable locals and decision-makers is essential.

This knowledge is particularly valuable for researchers and municipalities in preventing heavy rainfall events. The involvement of citizens in research projects through Citizen Science (CS) has been established for several years and is increasingly being used in civil projects.

The goal is to provide local knowledge to researchers and municipalities to enable efficient and effective risk management. Communication with citizens also plays a crucial role in this process. Participation fosters greater tolerance and acceptance of implemented measures among those affected.

This participatory process shall be implemented in the form of a mobile application (app) for Android smartphones. The app should allow citizens to report problematic areas directly, including both the exact location and a description of the issue. Researchers or municipalities can analyse the data according to their risk management strategies and use it for implementing measures. With this tool we aim to investigate how the citizen science method in heavy rainfall prevention can be technically implemented and tested as a contribution to sustainable flood management.

The paper begins with a literature review on the topics of risk management in flood scenarios, citizen science, and appropriate technical solutions (Section 2). This is followed by a description of the methods (Section 3) used and a detailed presentation of the results (Section 4). The discussion section explains the advantages of the citizen science method regarding the management of emergency drainage routes, as well as the challenges and limitations of the method (Section 5). Section 6 concludes with a summary of the work.

2 Literature Review

2.1 Risk management for floods and heavy rainfall

Flood events are not unusual on rivers and larger water bodies in Germany. People live with the regular rise and fall of water levels and are usually able to deal with occasional moderate floods with confidence and resilience. Floods that originate from watercourses are the result of long-term rainfall or the occurrence of melting snow are referred to as fluvial phenomena.

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Unlike fluvial events, which are usually easy to predict, so-called pluvial events usually occur spontaneously and without sufficiently long predictions or annual intervals. Pluvial floods are characterised by the fact that they can occur independently of a watercourse and are usually caused by heavy rainfall in a short period of time and in a small area (Kutschker and Glade, 2016).

The poor predictability and short warning times of these events make good prevention and risk management even more important.

One of the most important findings in risk management is that people are more likely to implement measures if they are personally (directly or indirectly) affected by an event. Affectedness is primarily controlled by the occurrence of emotions in those affected. The stronger the emotion the higher the likelihood of a reaction (Netzel et al., 2021).

How people perceive their personal risk is also crucial. A distinction should be made between global and personal risk perception. If people perceive a global risk, such as climate change itself, this only rarely leads to them taking protective measures. However, if people are personally affected and experience the associated emotions, such as in the case of a heavy rainfall event as a result of climate change, they are more likely to take precautionary measures (Netzel et al., 2021).

This realisation brings risk management to a small-scale level that must take local conditions into account (Rosenzweig et al., 2018). The probability of measures being implemented is only high if people are addressed directly. The level of education and knowledge of the people targeted are crucial here. People with a higher level of education and a higher level of knowledge about heavy rainfall and runoff processes are more likely to implement appropriate measures (Netzel et al., 2021).

Risk management therefore has both an educational task and an obligation to address people's emotions to implement the best possible precautionary measures.

Due to the so far poor spatial predictability and the non-periodic occurrence of pluvial events, permanently installed flood protection measures are only practicable to a limited extent. Widely used methods for flood protection (from fluvial floods), such as permanently installed systems for the on-demand construction of flood defence walls, are only partially applicable or not applicable at all during pluvial events. It is therefore crucial that more precise forecasting systems are developed and risk assessment is improved. The latter makes it possible to implement preventive measures and flood warnings in a more targeted and effective manner (Falconer et al., 2009). In order to maximise the integration of risk management, the involvement of citizens and authorities is essential (Ueberham, 2016). Participatory approaches can promote the development of risk awareness and thus increase the population's awareness of e.g. problematic areas in urban runoff events (Rollason et al., 2018). Personal precautions, both in the form of measures at private homes and networking with each other (e.g. by setting up warning chains), but also increasing knowledge about heavy rainfall and its dangers can make people more resilient to pluvial flood events (Gallmetzer et al., 2021). Currently there is often a gap between people recognising the risks and the implementation of measures due to a lack of communication. In order to close this gap, it is necessary to share people's findings with the responsible authorities as easily as possible in order to improve communication and data accessibility (Rosenzweig et al., 2018). Methods from the field of CS are suitable for this purpose.

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2.2 Citizen Science in Environmental Monitoring

Citizen Science refers to the involvement of citizens in research projects and scientific data collection (Bonn et al., 2021). Citizens collect data independently, which is then analysed by researchers. In this way, large quantities of small-scale and diverse data sets can be generated (Abecker et al., 2012a, 2012b; Bonn et al., 2021).

CS in the environmental sciences was first used in ornithological monitoring projects for which it is still very well known today (Bonney, 1996).

The CS approach is a win-win situation for everyone involved (Bonn et al., 2021). In this way, science obtains a large amount of data that is collected by independent persons so that the bias of the scientists themselves can be minimised. At the same time it offers the opportunity to make science accessible and understandable for people and thus gain a greater insight into science and its topics among the population. Science itself benefits, among other things, from the opportunity to release innovation potential at an individual and social level (Bonn et al., 2021).

According to surveys conducted by the Science Barometer (Wissenschaftsbarometer), well over half of citizens are interested in science and research (Ziegler, 2022). An interest that has increased even further in recent years, e.g. due to the coronavirus pandemic (Ziegler, 2022). But also, movements such as 'Fridays for Future' and other climate campaigns clearly show that society is increasingly interested in scientific issues and wants to be involved in them. Environmental issues are often turned into strategic decisions by the existing political and administrative structures, which often do not involve people and leave them as silent observers (Liu et al., 2014). It is precisely these silent observers who are increasingly becoming active participants in political and socially relevant decisions and could be actively involved in research through CS. This form of participation can fulfil citizens' expectations of co-determination and at the same time give them the opportunity to better understand the limits of scientific methods (Bonn et al., 2021; Liu et al., 2014).

In line with the saying 'tell me and I'll forget, show me and I may remember, involve me and I'll understand', this can strengthen society's trust in science and achieve a more positive attitude towards science and the implementation of the resulting measures (Bonn et al., 2021; Liu et al., 2014).

2.3 Technological Solutions for Data Collection and Analysis

In CS projects, data should be collected by participants and sent for example to authorities or researchers. This process can be realised using different apps. These include computer apps that are installed on the device, online apps that can be accessed via a browser or apps that can be used on mobile devices (mD) (Lemmens et al., 2021). The potential of CS has grown immensely since mD has been used across the board. Thanks to the integrated sensors of the Global Navigation Satellite Systems (GNSS), the exact position (within the limits of the inaccuracy of the respective GNSS) can be determined in addition to the data entered manually by the participants, so that the data can be supplemented by an important geo-component. These

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applications are particularly valuable in the field of environmental sciences. The apps are usually installed under the two common operating systems iOS (Apple) or Android (Google) (Lemmens et al., 2021).

Mobile apps offer many functions that are particularly interesting for CS. The most common method of CS is the questionnaire. This can be used on a website or in a local app. Participants answer questions on one or more topics. It is possible to depict different types of questions and thus do better justice to the diverse content (e.g. multiple choice, drop-down menus or free text fields). If the location of data collection is important, questionnaires can be supplemented with this information. Since GNSS sensors are now installed in mD as standard, the apps can automatically determine the position of the device and send it as additional information (Lemmens et al., 2021).

In addition to GNSS sensors, mD also often offer other sensors that can be used to record data. For example, image or sound recordings can be made, compass data can be read out or the brightness and ambient volume can be determined (Odenwald, 2020a). External sensors can also be connected to the mD or used independently of it. Their data can then also be entered via a questionnaire (Lemmens et al., 2021; Odenwald, 2020b). CS games are particularly popular among younger participants. Here, data is generated in a playful way that follows a competitive approach and thus encourages participants to use the app as long and intensively as possible (Lemmens et al., 2021).

The major advantage of using mD in CS also brings challenges. By using mD, more people can generate data more quickly and thus contribute to research. At the same time, this data must be stored and processed accordingly to be able to evaluate and analyse it later. It therefore requires both an app specifically tailored to the needs and data management software that takes over the analysis and visualisation.

In principle, it is possible for CS projects to access existing platforms that already offer some functionalities and can be customised to a limited extent. Another option is to programme new software, which is then generally used by a single project (Lemmens et al., 2021).

In this project, a new software will be programmed as CS project with open-source components so that it is reusable for interested parties and thus, for example, opens the possibility for various municipalities to use the project for their specific locations and thus sustainably organise their risk management in heavy rainfall.

3. Methodology

The methodology describes the development of the CS app on the technical side and addresses design and functionality. It shows the connections between the mobile application and the Geo Data Warehouse (GDW) and explains the methods for analysing data in the latter.

3.1 Development of the CS app

The development of CS apps is strongly influenced by the expectations of future user groups. Lemmens et al. (2021) lists some criteria specifically for CS apps, which are used to guide the development of the FloReST CS app:

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- *Usability: the ease of use for the participants*
- *Look and feel: the visual quality of the app*
- *Performance: the speed with which an app opens and operates*
- *Security: the level of technical security an encryption of sensitive data*
- *Compatibility: the range of operating systems and devices supported*
- *User privacy: compliance with the EU General Data Protection Regulation (GDPR)*

" (Lemmens et al., 2021)

In the following, the various aspects of the design and implementation of a CS app, data collection and subsequent data visualisation are listed and explained.

3.1.1 Technical structure

When developing mobile apps, a distinction is made between web, native and hybrid apps. The FloReST CS app was developed as a hybrid app. This is designed using web technologies but is ultimately output in native format. Hybrid apps combine the advantages of two technologies and are therefore particularly efficient (Schilling, 2016). The actual FloReST CS application is implemented with JavaScript (JS) and displayed as a web view and is therefore nothing more than a standard website. Figure 1 shows that in a hybrid app, this classically programmed website is converted into a native format using AngularJS (single-page application framework from Google) (Weiße, 2016). The Ionic framework is an important building block that makes it possible to implement the CS app on different mobile devices without having to make manual adjustments. If you want to run the CS app on different devices with different screen sizes, for example, Ionic is responsible for automatically adapting the components of the CS app to the respective conditions (Weiße, 2016). As a runtime environment, Capacitor, just like Ionic, enables implementation on different mobile devices. In contrast to Ionic, however, it provides access to the various hardware elements such as the camera or speakers. Both Capacitor and Ionic are part of the AngularJS framework, which in turn depends on the Node.JS runtime environment. As a software development kit, NodeJS is the basis for development, as it makes web technologies such as JavaScript executable outside of a browser and thus enables programming in editors such as Visual Studio Code (Weiße, 2016).

Overall, the FloReST CS app achieves a high level of compatibility with these components and enables implementation on a wide range of devices. It also offers a fluid application for the user.

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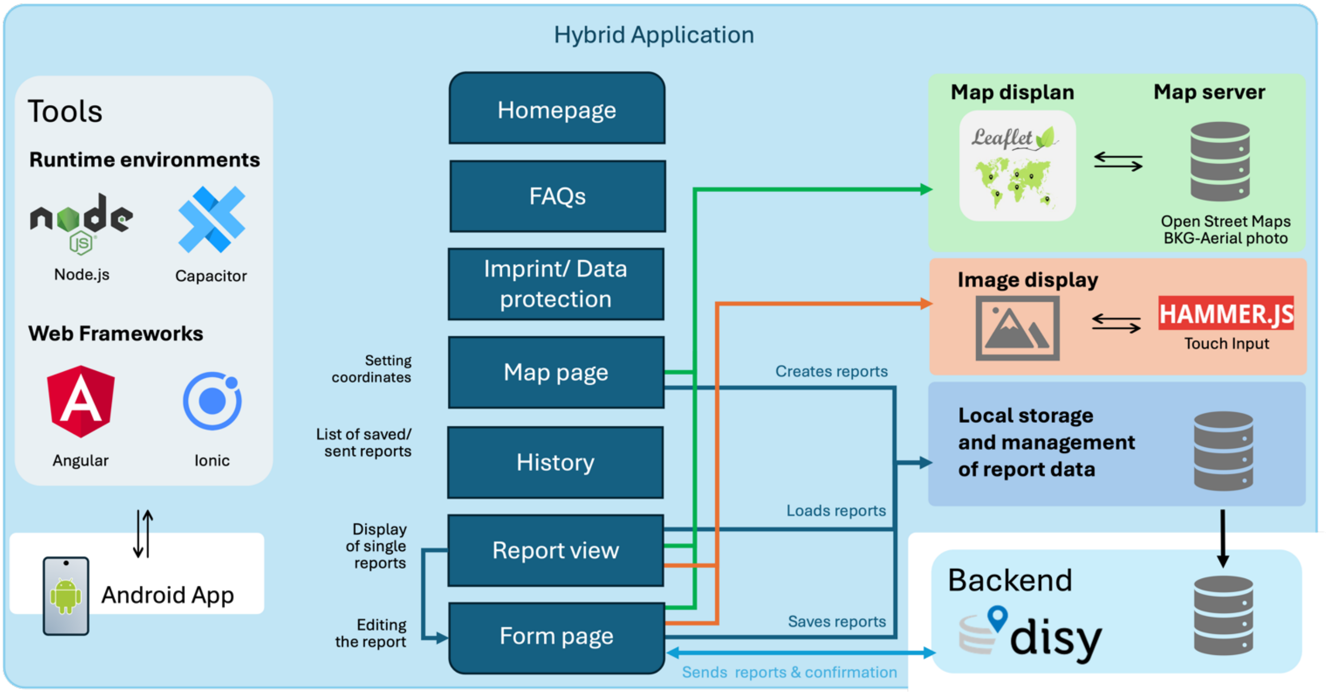

Figure 1: Structure and components of the hybrid FloReST CS app with functional relationships within the application.

3.1.1 Design and functionality

The design and functionality of the CS app play a central role in user-friendliness. The aim is therefore to ensure intuitive operation and, at the same time, to guarantee an appearance that is as barrier-free as possible. Intuitive navigation and operation are achieved through clear structures, easily recognisable interaction elements and a consistent design.

The system functionality was defined as part of a requirements workshop at the start of the research work and is described successively below.

A style guide defines the design and layout of the CS app. Among other things, identical visual elements for the same function were provided in the associated layout specifications. The use of prefabricated components from the Ionic library supports a uniform look. Overall, this creates a coherent overall picture for the user, directing the focus to the essential content.

The colour scheme has been deliberately reduced to create a clear and uncluttered user interface. A broad colour palette has been avoided in favour of high contrasts, which facilitate readability and orientation and thus make the CS app more accessible. Interactive elements, such as blue buttons, are highlighted to clearly signal their functionality.

Typography also makes a decisive contribution to user-friendliness and appearance. The use of the system's internal font, such as Roboto on Android, preserves a native look and ensures a familiar user experience. The focus here is on a low-barrier appearance by adopting the user's global settings. Different font sizes and thicknesses are used to clearly present the structure of the CS app and promote readability.

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Icons are an integral part of the design and user guidance. Common symbols that users are familiar with from other applications are used in a targeted manner. They are designed to be platform-independent to ensure a uniform appearance on different devices. Icons serve as navigation and menu elements as well as contextual support. Their intuitive recognisability ensures quick orientation and improves usability.

The combination of all these elements creates an CS app with a simple design that emphasises functionality and barrier-free use. The evaluation of the user-friendliness of the CS app for different target groups in the risk communication of heavy rain management has already been carried out on one group but still needs to be carried out for the other target groups and analysed as a whole.

3.2 Geo Data Warehouse and data analytics platform

The captured data is transmitted by the FloReST CS app to a backend where the reports are stored and processed. This backend is designed and prototypically implemented as a part of the "FloReST water extremes data platform" (Janßen and Abecker, 2025). For data storage, a GDW (Schrauth et al., 2017) is realized. For data analysis and visualization for specific target groups, the "disy Cadenza platform for business and location intelligence" is employed (Abecker et al., 2024).

During the design of the system a conscious effort was made to ensure the openness of the solution created. The selected components are loosely coupled so they can be used independently of each other. To ensure interoperability, also with other possible software solutions, an Application Programming Interface (API) for communication between the CS app and the datastore has been defined. An OpenAPI specification of the interface was created for implementation and documentation purposes[1].

Another design criterion for the selection of the individual software components was their scalability. This is important to ensure operation in larger-scale load scenarios.

The data analytics application requires an easy access to the datapoints as well as a powerful tool to fit subject-matter experts' needs. A user customizable web application as the analytics platform meets these requirements.

Figure 2 provides a partial overview of those actual components of the water extremes data platform which deal with the CS reports. The API is used to transmit the data recorded by the CS app. A python-based Extract-Transform-Load (ETL) component transforms the received data into the specific target formats. ETL processes realize the basic steps for integrating heterogeneous input data into a homogeneous data warehouse. Structured data of a report, including its metadata, is then stored in a PostgreStructuredQueryLanguage (SQL) database. PostgreSQL is the world's most successful open-source database management system – which can also be extended for efficient management of geospatial data. Transmitted photos are stored in an S3-compatible object storage. The S3 (Simple Storage Service) principle has been introduced by Amazon for a massively

[1] https://www.openapis.org/

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scalable, typically cloud-based, storage system for arbitrary data objects. Additional media files like videos or audio files could also be stored here. Finally, the data can be viewed and analysed using the disy Cadenza as the data analytics software.

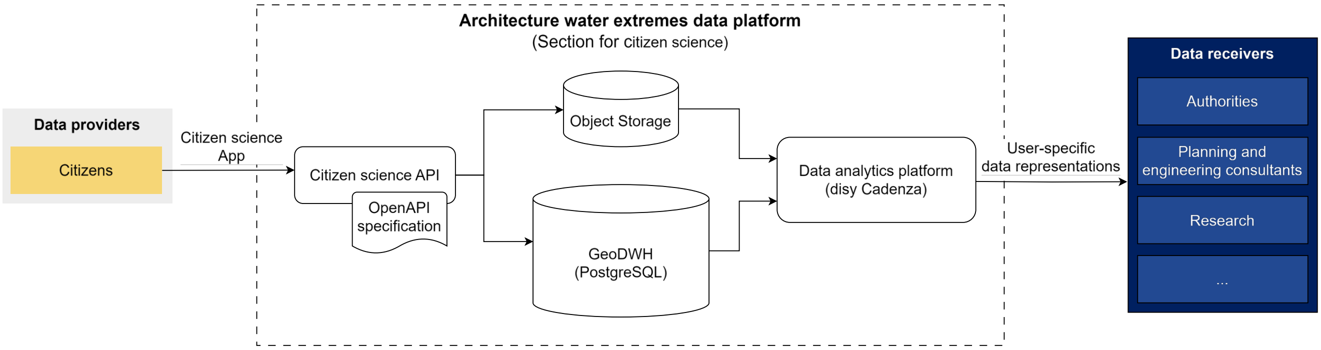

Figure 2: Components used for data processing and analytics of the CS app data

4. Results

The CS app for sustainable risk management in heavy rain prevention has a simple design. The CS app has currently been developed in German. The start page provides a brief introduction to the topic and invites you to start an initial site survey. The main menu provides information on frequently asked questions.

4.1 Data Collection

The data is recorded by the user via a form within the CS app. Only data that is relevant for the assessment of the problem area was selected for recording. The precise data collection process and the exact structure of the captured data are explained below.

4.1.1 Process of data submission by citizens

Data collection should be intuitive and efficient for the user. The first step for the user is to identify a problem area in their immediate surroundings. The CS app can then be opened, and the localisation of the problem area can be started using the map function in the CS app. This is done either by using localisation services, so that the user's currently determined location is used as the location of the problem area, or the user can select any location on the map themselves. A topographical map and an aerial map are provided for better orientation. The user then assigns one of the four possible categories to the problem area. The following categories are available: 'Accumulation of floating debris / driftwood' (Ansammlung von Treibgut / Treibholz), 'Bottleneck' (Engstelle), 'Deflection of water' (Ablenkung des Wassers) and 'Constructed buildings / structures' (Errichtete Gebäude / Bauwerke). The categories are provided with pop-up help so that the user can view a descriptive text and sample images for each category to make the best possible assignment. The user then describes the problem area in detail and has the option of adding images to this description. These images can either be taken directly using the CS app's camera function or added from the mD gallery. If the user can assess the responsibility of the respective location, it can be indicated whether the problem area is located on private property or on public land. Figure 3 provides an overview of the start screen, the location

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selection on an aerial map and a section of the entry page. Once all the information has been entered, the report can be sent via the CS app. The sending process ends with a success or error message informing the user about the status of the submission.

Figure 3: Overview of the CS app with start page (a), location selection (b) and survey page (c).

4.1.2 Types of data collected (e.g., location, description, photos)

The *user ID (userId)* is randomly generated when the CS app is started for the first time so that messages can be clearly assigned to a user without collecting personal data. This guarantees maximum anonymity and minimises data protection risks. The *report ID (reportId)* is an internal identifier (ID) that is primarily used to control the CS app processes. This ID is also transmitted to the server, where it is supplemented by an external ID.

The *recording date and time (timestamp)* document the time at which the report was created (not the time of submission), derived from the system time of the end device. This data is initially stored unformatted (specification of elapsed milliseconds since 1 January 1970, 0:00, *Coordinated Universal Time,* UTC) and converted if necessary.

The *latitude and longitude (latitude, longitude)* define the location of the problem area. They are output in the World Geodetic System 1984 coordinate system (WGS 84, European Petroleum Survey Group, EPSG 4326) in decimal degrees and are therefore compatible with the map service used. The data is then projected in EPSG 3857 for visualisation.

The *problem area is caused by (deficiencyType)* a cause of the problem, such as accumulations of floating debris, bottlenecks or deflections of the water. This categorisation can be carried out by the user themselves and makes it easier for the authorities to assign and prioritise the problem subsequently.

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The *type of spatial utilisation (onPublicProperty)* indicates whether the problem area is located on private or public land. This information can be legally and organisationally relevant.

Under *further information (additionalInformation),* users can enter specific information and notes on the problem area in a text field.

All *images (Report__<No.>.jpg)* are used for visual documentation of the problem area. The images can be added using the camera function or from the gallery.

The collection data listed has been selected to ensure that it covers the relevant information on the problem area while complying with data protection standards. The anonymised user ID ensures that no personal data is collected. The focus is on the technical data required to precisely describe the problem areas during heavy rainfall events and derive recommendations for action. The combination of location data, categorisation, detailed description and photo documentation ensures a comprehensive representation of the problem area. At the same time, the requirement to minimise data storage is met so that recording remains quick and uncomplicated for the user. After the message has been sent, the user receives confirmation of the result of the sending process.

4.2 Data analytics and data visualization for public authorities

The web-based application disy Cadenza is used for data discovery and analytics of the CS report data. Disy Cadenza is in daily use in many federal and state authorities in Germany and has already proven its value to the public sector, especially when dealing with geo and environmental data. Disy Cadenza allows the user to link the data with one another and it provides a user-friendly Graphical User Interface (GUI) to combine data visualizations with data-analytics capabilities to create data dashboards. A variety of possible data representations, including tables, bar charts, pie charts, maps, heat maps, etc. can be utilized for this purpose.

For recurring tasks, the user has the option to access predefined curated workbooks to fulfil the analytics requirements. A user-defined customisation of the data view allows the completion of individual inquiries. On all dashboards, the data can be restricted by filtering the considered data points geographically, temporally, or by other attributes of the data. Using these capabilities, the CS reports can be selected by the attributes recorded with the CS app, such as the categorization of problem area, but also spatially, restricting the area of consideration on the map. A fully integrated Web Geographic Information System (GIS) completes the spatial analytics capabilities. This enables the user, for example, to measure distances in the map (e.g., between an observation and a watercourse) or to add geodata layers such as Points-of-Interest (where are vulnerable buildings, facilities, or infrastructures) or task-specific maps (e.g. about critical infrastructures, land survey register, other cadastre data etc.) and additional cartographic information (like aerial pictures or even flood simulations) to the result view. In addition to that, activating the Cadenza live mode will result in a periodic update of the data shown.

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In Figure 4 one of the predefined curated workbooks is displayed. As an entry point for the users, an overview dashboard was created. It shows the CS report data on different aggregation levels. A map shows the spatial distribution of the reports. The color-coded dots each represent a single report, coloured according to the categorization of problem area. By selecting a point, further details of the report can be observed.

On the right-hand side, the report data is presented in tabular form, sorted by the submission date. A pie chart provides an overview of the distribution of the reported problem area types. The total number of reports displayed is shown by an indicator. By default, the submitted reports of the last three month are selected. The data can be further expanded or restricted using the filters on the left-hand side. The type of the problem area as well as the period in which reports were received, can be adjusted, in absolute and relative terms.

Weblinks at the bottom right offer an option to jump to a detailed view of the reports or a heat-map representation of the data. By using these links, the state of the applied filters is transmitted to the corresponding page.

The detailed report view utilized a table component to show all available details of a report. Attached images can be selected and viewed here. A spatial summarisation of the reports can be created by a heat-map representation of the data. It can be used to determine focus points of reported problem areas. By zooming in and out, the heat map is recalculated and adjusted accordingly to the zoom level.

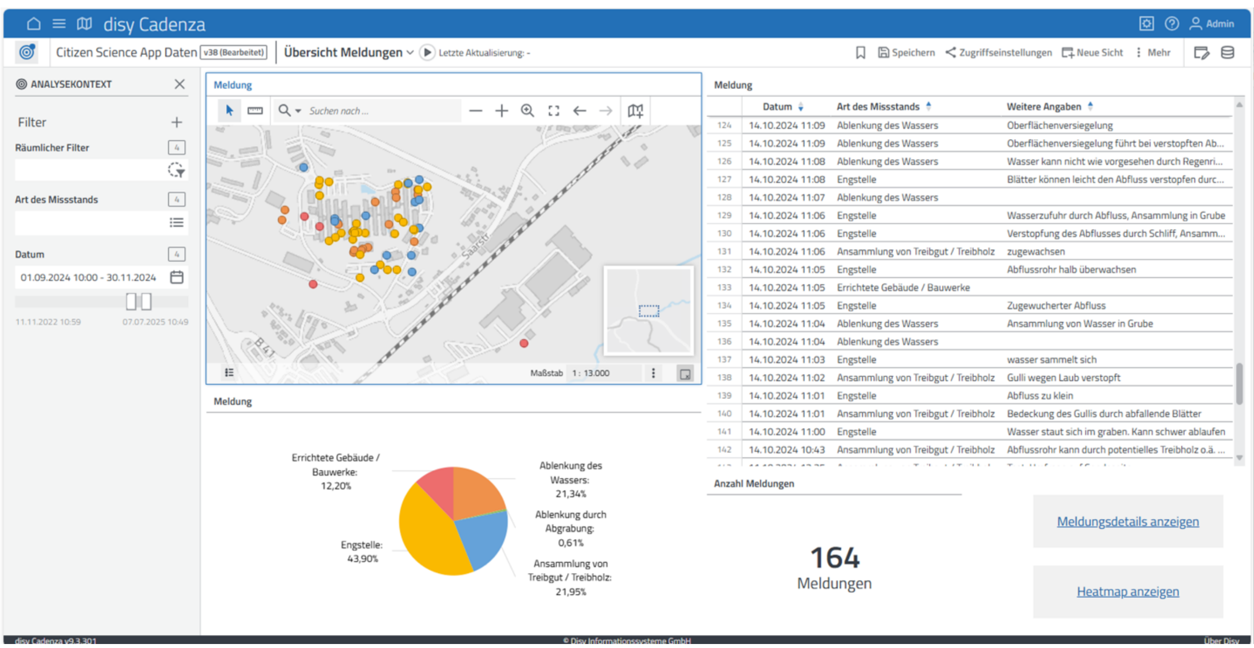

Figure 4: Selected dashboard of the analytics application.

4.3 Data protection and security

Using disy Cadenza it is possible to implement a fine-grained rights-and-roles concept. This allows to restrict the access to the data, the created dashboards and the analytics views to authorized personal only. A state-of-the-art identity provider can be used for authentication of the users. For example, the widely adopted OpenID Connect protocol is supported.

Only the data related to a report is recorded. No user-related data is stored in the database. Just a randomly generated user id is attached to a report which enables a grouping of the individual messages related to a specific CS report. It is therefore not possible to draw conclusions about a specific person.

The transmission of data from the CS app is secured by a transport encryption via Transport Layer Security (TLS, an internet communication protocol for safe data transport). Authentication of the CS app at the API-Gateway is implemented using token authentication.

4.4 Performance analysis

The app was evaluated by conducting a performance analysis. This involved using and evaluating the application in test groups of different ages. Bugs identified during these tests were documented and fixed in several releases of the app. Remaining technical issues are described in section 5.2.1.

A comprehensive practical evaluation of the app's impact on flood risk management requires further investigation with a broad user base. Conducting such evaluations was challenging because the topic is highly politicised. Several participation appointments were cancelled at short notice, making it impossible to conduct a large-scale survey. In addition, some local authorities were cautious because reporting problem areas could potentially highlight additional action that might be required, which could entail administrative and financial obligations.

However, the non-representative results of an evaluation of participants from different test groups show that people are particularly willing to engage with flood protection when they themselves have emotional ties to the topic and feel personally affected by it or have been affected by it in the past. In the evaluation, participants completed a questionnaire before and after testing the app.

5. Discussion

Targeted risk communication always includes the perspective of the affected citizens. Therefore, a survey was conducted in five different pilot municipalities in Rhineland-Palatinate, Germany, as part of the preparatory work for this project. One of the aims of this survey was to identify target groups for certain risk communication tools based on socio-economic data. The survey revealed that accessibility through the chosen media has a significant influence on the under-35s and on the under-20s. For this reason, the CS app was chosen as the preferred citizen science method. In the following the different components

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(sustainable risk management, heavy rainfall, citizen science) of the initial question are analysed and evaluated in relation to the chosen method of the CS app.

5.1 Advantages of the Citizen Science approach in emergency flood path management

Sustainable risk management requires that the affected persons can apply realistic benchmarks when differentiating between global and personal risk perception (Netzel et al., 2021). If the risk is assessed as a personal risk, the personal involvement of the affected individuals increases. This usually leads to people associating stronger emotions with the situation and consequently increases the likelihood of a reaction, in this case the implementation of protective measures (Netzel et al., 2021). By using the CS app, the affected persons learn directly that there are potential sources of danger in their personal environment. This increases the likelihood of protective measures being implemented after using the CS app. It is also important to consider the different scale levels for successful risk management. As heavy rainfall events are often very localised events and even small-scale changes can lead to major differences in runoff behaviour, it is particularly important to record the small-scale conditions and get as detailed information as possible (Rosenzweig et al., 2018). This is made possible by using the CS app, as it is primarily designed for small-scale problem areas in private and public spaces.

Furthermore, the individual level of knowledge and education of the people involved should be considered. These two factors are essential for the likelihood of measures being implemented. Accordingly, the CS app should not only be intuitively designed and usable but also fulfil an educational function by providing information on the topic of heavy rainfall and flooding, as well as providing information on further education both within the CS app and beyond. This is provided in the CS app as info buttons (Figure 5) and as additional links. The CS app provides additional information on, for example, different categories of problem areas and makes people aware of possible drainage blockages in their neighbourhood. The CS app also links to the Rhineland-Palatinate flood management website, which provides comprehensive information on the topic. The CS app thus fulfils its important educational mission regarding sustainable risk management for heavy rainfall.

The development of more precise forecasting methods is crucial in the prevention of heavy rainfall events. Today, these forecasting methods are often implemented using trained machine learning / deep learning models, which require a large amount of training data. The requirement for this training data is the highest possible spatial, temporal and thematic coverage. The amount of data needed for this cannot be collected by the scientists themselves, which is why models are often only reliable for certain regions with temporal and/or thematic restrictions. For improving these models, it is essential to have a more comprehensive database. The CS app offers the opportunity to collect such data with the help of local stakeholders and then make it available to the scientific community. In this way, a unique data set with high variability in the observed parameters can be created. It is also very important for citizens to be able to carry out a realistic risk assessment in the event of heavy rainfall. This is the only way they and their neighbours can react in time and protect themselves. The CS app's participatory approach and the information provided enable users to make such an estimation. At the same time, these skills

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increase users' awareness (Gallmetzer et al., 2021; Rollason et al., 2018), allowing them to react earlier in the event of heavy rainfall.

Another gap exists between people recognising risks and the implementation of measures by the authorities. The CS app provides the opportunity to precisely close this gap by giving people a direct link to the relevant authorities and allowing them to report their findings directly. The evaluation of the data and, if necessary, the implementation of a measure is then at the decision of the public authorities, depending on their responsibilities.

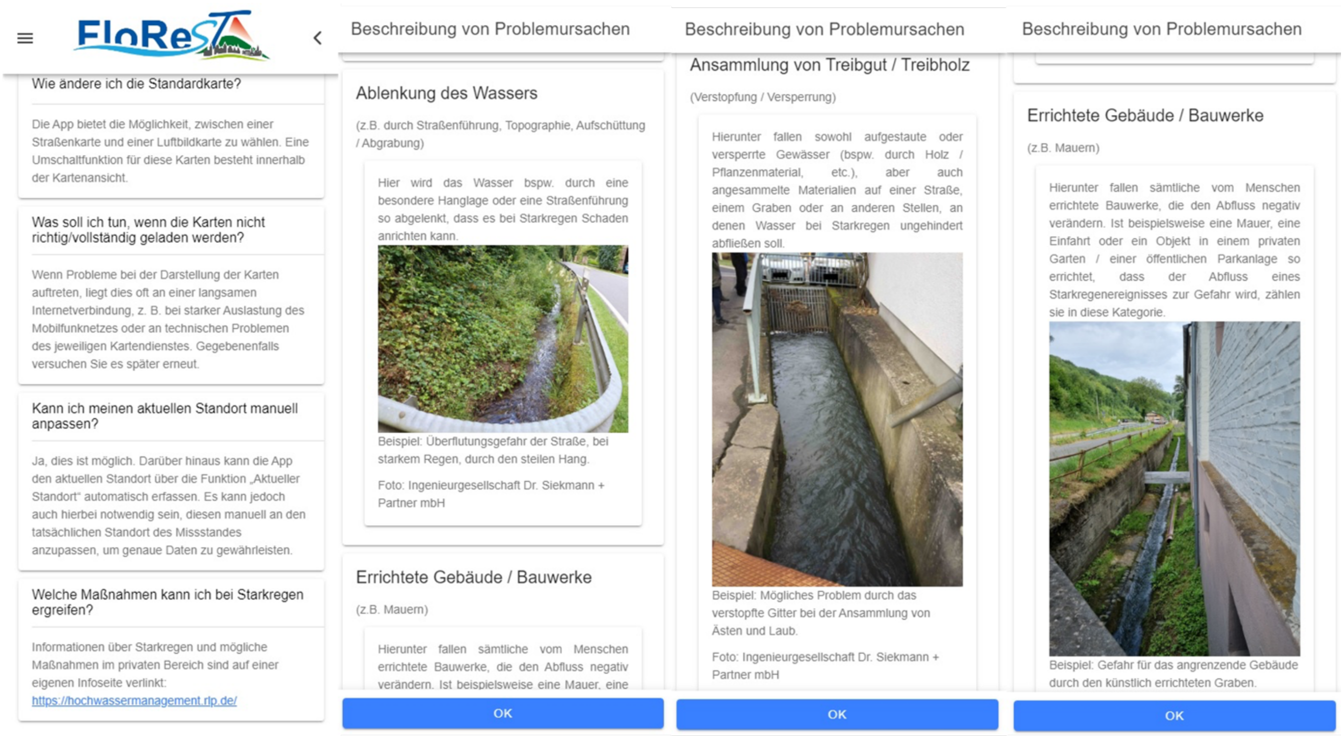

Figure 5: Information on heavy rainfall (a, b, c and d) and links to information pages of the state of Rhineland-Palatinate (a, bottom) in the CS app.

Individual problem areas are usually not responsible for large amounts of damage in the case of a heavy rainfall event. It often involves several problem areas that add up to considerable damage (Wang et al., 2019). As the authorities do not have the staff to identify and record the large number of problem areas, the CS method offers a major advantage over conventional mapping options. The CS app can be used to record large amounts of data in equally large spatial distributions without having to increase staffing levels. Only the evaluation of the data requires the attention of the authorities.

When measures are implemented, they can achieve a higher level of acceptance than without the use of the CS app. Due to the greater knowledge base of the affected persons and residents, they can relate to the measures and are more willing to contribute to them because their risk assessment is improved.

An CS app offers the possibility of quick and large-scale distribution without requiring too many resources. It can collect thematic data (like a questionnaire) and at the same time offers data such as the exact location and image material, which

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would have meant a great deal of effort for the surveyors using the conservative method. The report can be submitted in less than two minutes and can be used by many people thanks to its high level of compatibility with all standard Android devices on the market. The CS app is basically aimed at citizens of all ages, but also specifically addresses the younger generation. The CS app thus provides an answer to the low level of knowledge of the younger generation about heavy rain and flooding. Users do not need any prior knowledge of citizen science or flooding and are guided intuitively through the CS app. The categorisations can be made as accurately as possible using example images and descriptions.

In the application test, it became clear that the topic of flooding and heavy rainfall evokes strong emotions in many of the affected people. Those affected often feel anxious and worried because they feel unable to act in a flood situation. The CS app offers the opportunity to regain the ability to act and to name and report the problems specifically for their own property or the neighbouring public space. This returns autonomy to users that many have lost to the water. While the accompanying emotions before using the CS app were predominantly fear and concern, this changed to trust and security after using the CS app. Many of the respondents were also motivated and felt a sense of commitment. The results of the application test confirm the assumptions that the CS app is a suitable tool for sustainable risk management in the context of heavy rainfall.

5.2 Challenges and Limitations

When using the CS app and the GDW, there may be challenges and restrictions during development and use. Both technical as well as thematic and data-related aspects can influence functionality, user-friendliness and data quality. The main problems are identified, and potential solutions are presented to increase the effectiveness of the application afterwards.

5.2.1 Technical challenges

Technical difficulties can occur both on the CS app side and on the GDW side. The problems were recognised but could not be fully resolved within the scope of the project. Solution approaches are provided that could point the way for further development of the application.

The problem with many mobile applications is that they are dependent on the use of mobile data connections. In principle, messages can also be sent later with the CS app when mobile data is available again. However, it is not possible to send a message without an active mobile data connection. In addition, the map services are not available if there is a lack of connection, which makes manual localisation on the map impossible. This is particularly problematic in rural areas. Inaccuracies can also occur if there are not enough satellites available for positioning by the mD used. As the number of available satellites decreases, the accuracy of the positioning also decreases and may lead to incorrect markings of the problem area. To minimise this problem as far as possible, images of the problem area can be supplied from different perspectives. This makes it possible to correct or reposition the problem area during data analysis.

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It is also possible that the spatial resolution of the maps provided (digital orthophoto, spatial resolution 20 cm and Open Street Map) may make it difficult for users to correctly locate the problem areas, making it harder to allocate and find them again later.

The validity of uploaded data has also not yet been checked. The date and time are automatically recorded from the mD internal data. All other data can be customised by the user and is not compared with data such as the coordinates of a captured image (should corresponding data be collected by the mD). Such a comparison would further increase the accuracy of the data and could eliminate possible sources of error. However, the inaccuracies of the data automatically collected by the mD must also be considered here.

The current implementation of the data processing after receiving a report via the API gateway, includes only a minimal form data validation. On the server-side the data fields are just validated on the data type level. A domain specific plausibility check, if still possible at the backend level, has not been implemented yet. For example, a cross-check of the media metadata and the location could prevent the misuse of the CS app backend. Thinking further, using Artificial Intelligence for the analysis of the picture content and the submitted additional textual information, could enhance the validation and therefore the data quality. For privacy protection, mechanisms to automatically review the picture content or to remove personal identification information, could be implemented as well, e. g., for removing faces of people on photos, or for removing license plates of cars.

5.2.2 Thematical and data quality limitations

Users can have a significant influence on data quality. Although appealing to emotions is important to encourage participation and the implementation of measures by those involved, this appeal can also lead to emotional behaviour that can impair data quality. For example, users may submit false reports or deliberately make false statements in the report. It is therefore particularly important that the data is subsequently evaluated by experts to generate objective drain problems from subjectively viewed problem areas.

One of the biggest problems of citizen science projects and the data collected is the motivation of citizens to use the CS app. If the CS app is not used or not used regularly and extensively, it is not possible to generate sufficient data with corresponding spatial, temporal and thematic coverage. This is where incentive systems such as gamification (for younger users) or feedback systems (for older users) can be useful. Feedback can consist of a direct message within the CS app stating what happens to the data or regular messages in the CS app when measures have been implemented because of messages.

A fundamental problem is that some people do not consider it necessary to use the CS app. Even if they are aware of the existence of the CS app, basic knowledge about the problems of heavy rainfall is helpful to increase motivation to use it. Pluvial events often occur in areas where people would otherwise not experience floodings and are therefore unlikely to be sensitised to the issue. In addition, the use of mD can exclude people from participating who do not have an mD. This often

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affects elderly people, who either do not have an mD or are technically unable to download or use the CS app. The user group is restricted here, which is a clear disadvantage compared to other options for data collection such as physical questionnaires.

5.3 Potential for scaling and replication in other regions

The CS app was developed under open-source standards so that it can be set up and installed in any location. The instructions are made publicly available at the end of the project. This means that the CS app can be used throughout Germany and internationally. For international use, both the language and the integrated maps would have to be adapted, as these services are currently only available for Germany. For location-specific categories that describe problem areas, these can also be adapted accordingly.

For some regions that cannot guarantee a mobile data connection, the relevant map sections should be integrated into the CS app (offline map function) and not accessed as a web map service. This means that although the CS app uses more memory on the mD, it can be used independently of mobile data connections. A corresponding geodatabase with Geoserver is required for data transfer, storage, evaluation and visualisation of the data. This can either be set up and hosted in-house or purchased externally. This decision depends on the available resources.

6. Conclusion

The focus of the FloReST project is on the identification and prediction of emergency flow paths caused by heavy rainfall events and the resulting risk management and communication. As climate change is expected to lead to an increase in such extreme events in the coming decades and conventional flood protection measures largely cover fluvial hazards, rather than pluvial ones, the aim of this work was to develop and test a citizen science app that can be used by the public to identify and report problem areas during heavy rainfall events. One focus was the app's contribution to sustainable risk minimisation and early warning in the event of heavy rainfall events in an urban context.

With its intuitive and user-friendly design, the app offers the public a low-threshold opportunity to participate in risk management processes. This is the basic requirement for effectively utilising local knowledge and recognising problem areas before they can lead to damage. The app has both a documenting and an educational function. Numerous help and information buttons are offered to provide users with further information on the topic of heavy rainfall, recognising problem areas and taking personal precautions. The GDW gives those responsible access to all relevant data and their analysis options. Depending on the analysis, different dashboards can be created that summarise and present information for different target groups.

The various, non-representative test runs showed a high level of acceptance and improved self-efficacy among the target group. By using the app, the emotional expression of the discussed topic developed positively from a feeling of fear to a feeling of trust. This participatory approach together with the technical implementation of the CS app, the GDW and the associated analysis and presentation tools can be summarised as successful. The CS method is particularly suitable for local and hard to predict pluvial events, as the amount and level of detail of the data obtained could not be managed by staff in the public sector.

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In everyday use, there are some technical limitations that cannot yet be solved. Depending on the user's mobile phone network connection, the map services offered may not load and users may not be able to locate themselves on the map. Although there is a function to save a message and send it when reception is restored, the maps are unfortunately not visible in offline mode. In addition, inaccuracies in GNSS positioning can lead to incorrectly positioned problem areas. This is one of the reasons why the validation of submitted user data is useful. This has not yet been implemented either and must be taken into account afterwards when analysing the data.

The potential for further development of the app and the GDW is therefore in the areas of offline functionality and accessibility, among others. Furthermore, user frequency could be increased through possible gamification elements and feedback systems. Thanks to the open source approach used, the app also offers the possibility of scaling to other regions or countries. In addition, an expansion of the functionalities could be considered that would make the app usable for rescue teams in an actual heavy rainfall event and point out particularly acute danger spots. Another use case would be for engineering companies and other experts to take stock of endangered areas.

The CS app together with the GDW is an innovative and effective tool for urban heavy rain risk management that can be scaled to other regions and use cases. Due to the involvement of citizens, data gaps can be closed and citizens can participate in risk management. In this way, the CS app and the GDW contribute to a resilience-orientated, sustainable approach to climate impacts in urban areas.

Code availability

The CS app code can be accessed via the following link: https://gitlab.rlp.net/ISS/florest/florest-smart-app

Author contributions

PFS and AA planned the project; SN, SA and VT programmed the app; JJ and AA set up the Geo Data Warehouse; JH, SN and JJ analysed the data; JH and JJ wrote the draft manuscript; JH, JJ, AA and PFS reviewed and edited the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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