Stockholm Junior Water Prize 2025

WarnMe -

Early flood warning for everybody!

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1. Abstract

In view of the increasing number of heavy rainfall events, we have developed WarnMe - a flood warning system. It records water levels in real time using infrared and ultrasound sensors and measures flow velocity via radar. The data is sent to our server via LoRaWAN, where it is analyzed using intelligent algorithms. A user- friendly app ensures that users are immediately informed of potential hazards. Simple installation instructions enable independent setup without professional assistance, creating a decentralized, cost-effective, and scalable system. In summer 2024, WarnMe successfully detected an imminent flood event and contributed to public safety by issuing timely warnings to the affected population.

2. Motivation and problem definition

The Intergovernmental Panel on Climate Change (IPCC) predicts an increase in both the frequency and intensity of floods and inundations as climate change progresses [1]. This assessment was further reinforced in the most recent IPCC report on climate change:

"Human-induced climate change is already affecting many weather and climate extremes in all regions of the world. Since the Fifth Assessment Report (AR5), there is stronger evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts and tropical cyclones, and in particular of their attribution to human influence." [2]

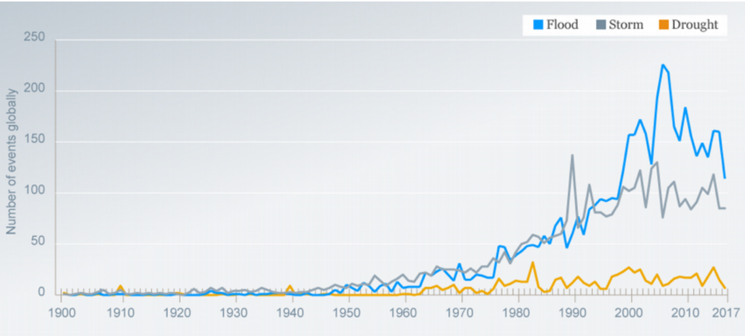

Figure 1. Weather extremes 1900 - 2017

The frequency of extreme weather events has increased significantly over the past century as a result of climate change (Fig. 1). The consequences are felt worldwide and affect many regions around the world. For example, in 2024, prolonged heavy rainfall in Spain led to extensive flooding in the Valencia area, causing significant damage to infrastructure and property. Such events illustrate the fact that disasters of this kind can not only occur locally but affect communities globally [3]. In recent years, our own home region has also repeatedly experienced floods of varying degrees of intensity. In 2016, our school suffered considerable damage due to flooding, resulting in substantial property losses and the cancellation of a significant portion of teaching, as numerous classrooms were rendered unusable (Fig. 2) [4]. In 2024, our hometown was once again affected by flooding, resulting in significant financial damage but, fortunately, no loss of human life.

The small town is situated along the Rottum, a small river that can quickly overflow its banks during heavy rainfall. In Ochsenhausen it is mainly fluvial floods that occur, i.e. floods caused by the Rottum rising after prolonged or heavy rainfall. Because such events develop with a time delay, they are generally easy to predict and a good use case for early detection and warning systems.

Figure 2. School corridor affected by the 2016 flood

However, local hydrological monitoring is patchy - and not just in Ochsenhausen: There are too few public water level measurement stations, and those that exist are insufficient to reliably assess the situation in local communities. As of today, approximately 250 public water level measurement stations are available to cover the entire state of Baden-Württemberg, which spans around 35,750 square kilometers and is home to about 11.1 million inhabitants [5]. Local and decentralised systems specifically designed to monitor small rivers in local communities and automatically send alerts to the local population and first responders when critical water levels are reached have been lacking not only in Ochsenhausen but in most municipalities.

Flood prevention and risk management are addressed at all levels of public administration. Following the implementation of the EU Flood Risk Management Directive, all federal states in Germany, including our home state Baden-Württemberg, developed detailed strategies for flood management. This process included the nationwide creation of detailed flood hazard and risk maps [6]. However, this overarching framework lacks practical applications at the local level - to date, the application of flood management strategies and the use of maps remain limited, and the overall framework has not yet been translated into actionable warning systems at the local level.

One key issue is that the public water level measurement network, which serves as the basis for warnings, is primarily designed for medium and large river basins. The network of stations on smaller bodies of water is incomplete and inadequately equipped to reliably measure and provide warnings during local heavy rainfall events. Our hometown Ochsenhausen serves as a prime example of this shortcoming: there is only a single public water level measurement station, and it is positioned downstream, rendering it inadequate for reliably predicting imminent flooding within the town itself [7]. While useful for assessing the overall flood situation, the station provides no information about when or where specific areas in the town are at risk, making early warning and response difficult.

The warnings based on the publicly accessible water level stations are therefore often delayed, imprecise or misleading. This crucial limitation is even reflected in the flood strategy of the state of Baden-Württemberg, which states:

"The water level and precipitation measurement network of the state of Baden-Württemberg is essentially designed for medium and larger catchment areas. For this reason, there is often a lack of information on the course of flooding in smaller bodies of water during heavy rainfall events. In particular, the German Weather Service (DWD) is usually only able to issue small-scale (district or municipality-specific) warnings of severe thunderstorms with heavy rainfall

with a very short warning time of just a few minutes. Further development of the available information in small catchment areas must be stepped up in the future." [8]

Although climate protection initiatives and technical measures like dykes and retention basins have been implemented in and around Ochsenhausen and other municipalities, a comprehensive early warning system remains essential, as it is key to reducing future risks and ensuring timely protection of the local population [9].

Our aim is to develop a decentralized flood warning system that closes this gap. The system must be simple, cost-effective and suitable for deployment across a great number of small rivers. This requires monitoring multiple water gauges near bodies of water and in flood-prone areas, while relating these measurements to local hydrological conditions. In some locations, it may also be necessary to measure flow velocities and estimate the resulting water volumes.

We see a great need for a cost-effective, scalable system that is capable of quickly and easily measuring a large number of water levels, analyzing the data on site and issuing targeted warnings as required.

3. Project idea

To ensure the most comprehensive warning of potential flood events, the system must fulfill certain requirements:

- It must be **cost-effective** to allow large-scale production and rapid deployment across vulnerable regions. Given the increasing frequency and severity of floods, an affordable solution is essential for expanding coverage. Currently, high costs limit the use of commercial localized flood monitoring systems, resulting in insufficient area coverage and leaving many communities unprotected.
- It must be **easy to install**, as measuring stations often need to be placed in hard-to-reach locations. Therefore, straightforward installation is essential, enabling end users and local citizens to assemble and set up the devices independently.
- It must work **autonomously** and must not be dependent on an internet connection, as many locations do not have sufficient network coverage for WLAN or mobile communications.
- It must be **low-maintenance**, as regular maintenance involves considerable time and material expenditure.

- It must be **durable**, as the measuring stations are permanently exposed to weather condictions.
- It must be **simple, accessible, and scalable** so that many individuals with minimal technical expertise can replicate the measuring stations within their local communities.

To develop a system that fulfills all these requirements, we designed a solution from scratch, utilizing infrared and ultrasonic sensors to measure the distance to the water surface. Radar sensors are employed to assess flow velocity and water volume. The collected data is transmitted to our server via the LoRaWAN wireless protocol, where it is analyzed. In the event of imminent flood risk, a warning is issued through our own developed warning app.

We have been continuously developing and enhancing this project for more than four years. Following several revisions, we found mounting the measuring stations under bridges in flood-prone areas to be the most effective solution (Fig. 3 and 4). We have developed and programmed our own warning app, which is now available in the Google Play Store (inclusion in the Apple App Store is pending). Additionally, our own homepage is now accessible online, providing comprehensive information including instructions for building and commissioning the various measuring stations [10]. User instructions are available as text and as video. Thanks to the warning system and instructions provided, citizens can now easily build their own measuring stations, which are seamlessly integrated into our data processing and warning system, enabling widespread application in local communities and at small rivers.

Figure 3: One of our water level measurement stations installed beneath a bridge in a flood-prone area.

4. Technical implementation

4.1 Water level measurement

Our system can use two technologies to measure water levels – infrared sensors and ultrasound sensors. Both measurement methods are based on the same fundamental principle: The measuring station is installed under a bridge using cable ties or brackets (Fig. 3 and 6). The sensors measure the distance to the water surface, allowing the water level in the body of water to be determined (Fig. 4). One advantage of this approach is that the width of the river at the measuring point does not have to be considered.

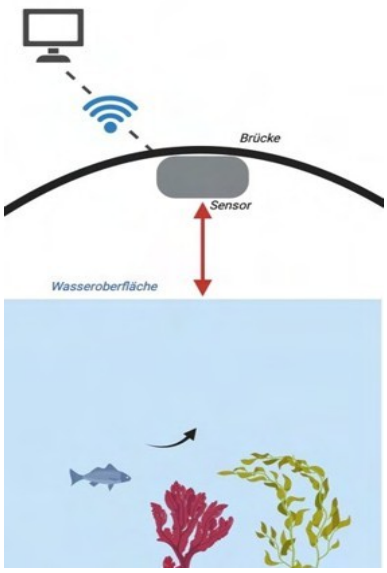

Figure 4: Schematic illustration of a measurement sensor

One limitation of infrared sensors is that they require users to 3D print their own sensor housings. Therefore, developed our measurement system to include ultrasonic sensors, which come with ready-made, weatherproof housings available for purchase. This simplifies installation and makes the system more accessible to users with limited technical skills..

Inspired by a YouTube video [11], we use an ELV ultrasonic distance sensor [12] connected to an ELV LoRaWAN interface [13], housed in a weatherproof junction box [14]. The sensor is installed in a 29.5 mm hole drilled in the junction box (Fig. 5). All components are commercially available. Using the junction box offers the added advantage that installation under bridges with brackets or cable ties is quick and easy (Fig. 6). With a total price of approximately 85 €, our measurement system is highly affordable compared to commercial systems, enabling widespread application. We have published step-by-step instructions for the easy reproduction and construction of sensor networks on our website, WarnMe.info.

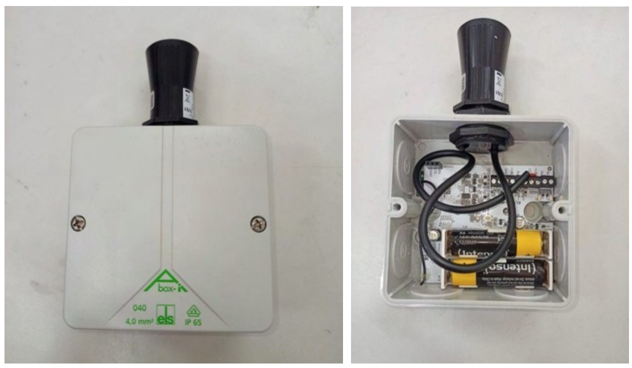

Figure 5: Housing of the ultrasonic sensor, left: closed,

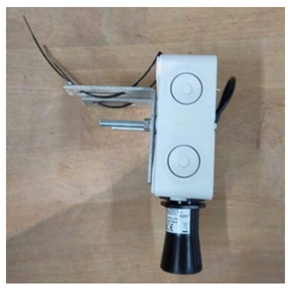

Figure 6: Mounting using brackets and cable ties

4.2 Flow velocity and flow rate measurement

Over the past four years, we continuously tested our concepts with external stakeholders. Feedback from mayors and fire departments indicated that assessing flow velocity or flow rate should be integrated into our measurement system. Based on this feedback, we met with experts from Karlsruhe Institute of Technology (KIT) and Baden-Württemberg Flood Forecasting Center (HVZ) to learn about possible ways of measuring flow velocity and flow. In Baden-Württemberg, flow rate is determined at state water level measurement stations by manually measuring surface velocity at various water levels. This data is combined with laser scans of the riverbed to estimate the overall flow rate. If enough data is available, regression analysis allows calculation of current flow rate as a function of the current water level. This approach requires repeated manual measurements and thus significant manpower, making it unfeasible for use in our measurement stations.

We were later invited to the Technical University of Ulm (THU). A recent bachelor's thesis submitted to the Institute for Radar Technology demonstrated a radar system capable of measuring the flow velocity of a stream. Building on these findings and the underlying sensor concept, we integrated this approach into our own measurement system. It consists of an Frequency-Modulated Continuous-Wave (FMCW) radar (BGT60TR13C, Infineon Technologies, Fig. 7), a Raspberry Pi 3B+, a Dragino LoRaWAN board and a 99 Wh power bank coupled with a solar panel. With this, we expand our sensor system to include measuting of flow velocity and flow rate.

Figure 7: Development kit for radar based measurement of flow velocity and flow rate.

Using a radar sensor has a number of technical advantages. FMCW radar allows for simultaneous measurement of water velocity via the Doppler effect and the distance to the water surface. A range of up to twelve metres is achieved, which can be further extended with an additional lens if necessary. Data are recorded across a 90° field of view, thereby providing information on river width.

Despite its advantages, we recommend integrating the radar-based flow rate sensor only for specific use cases rather than as a standard component. Its application is limited by the additional cost of approximately 300 € and the considerable effort needed to assess river topography for accurate data interpretation. Moreover, flow rate is generally considered a secondary factor in most flood scenarios.

Important applications for the radar-based system are inflow structures and retention areas attached to rivers, as precise flow rate measurements are particularly relevant in these settings. The development of the radar-based sensor was initially prompted by a mayor who reported that retention areas in his municipality lacked precise information on their filling and discharge.

In the event of flooding, such information could be critical—a knowledge gap that can now be addressed effectively through the use of our system.

4.3 Communication via LoRaWAN

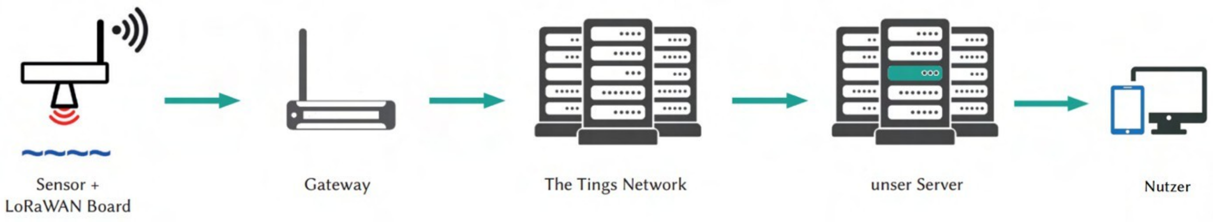

Figure 8: Schematic and simplified illustration of the individual components and their interconnection within the WarnMe system.

To transfer the data from the sensor to our server, we use Long Range Wide Area Network (LoRaWAN), a new type of data transfer protocol. First, the data is transmitted via radio at 868 MHz. These radio signals are received by a gateway, converted to internet data, and forwarded through multiple stages to our server. Anyone interested can install a gateway to ensure LoRaWAN coverage within their local area. Due to it's low price of approximately 150 €, the LoRaWAN network is already widely used [15]. To enable shared use of gateways, so-called brokers are required to link multiple gateways and users. For this purpose, we utilize The Things Network (TTN). Since TTN does not store or analyze data permanently, the collected data is forwarded to our own server for processing and storage.

LoRaWAN provides significant advantages. Firstly, it's energy consumption is very low; an ultrasonic measuring station can operate for more than 1.5 years on only two AA batteries. Secondly, the technology supports long-range communication of up to 12 kilometers in rural areas. Additionally, overall costs remain relatively low due to the affordability of transmitter modules and the absence of recurring contract or subscription fees. Importantly, this technology enables our system to operate independently of WLAN or mobile network coverage, allowing reliable functionality in rural areas and ensuring continued operation even if other networks fail during extreme weather events.

4.4 Data processing and computer science

A Python program operates on our server, utilizing the Paho library to establish an MQTT connection with The Things Network. The received data is subsequently stored in an SQLite database. An algorithm then evaluates the data to determine whether a warning is required and identifies the appropriate recipients. For details refer to section 4.5.

Over the past four years, we continuously refined our warning system to ensure timely and reliable alerts. Events like the flood in the German Ahr Valley have demonstrated that affected populations frequently receive warnings either too late or not at all. After testing various options, including e-mail notifications and interfaces to existing flood warning apps "Meine Pegel" and "NINA", we concluded that developing our own warning app was the most suitable approach. We coded the warning app using the programming languages Flutter and Dart. Alerts are delivered directly to mobile devices via Firebase Cloud Messaging.

Further technical details on the underlying computer science exceed the scope of this manuscript but can be found on our homepage [16]. The Android version of our warning app is also available for download there, with an iOS version currently under development.

4.5 Warning logic and features of the app

We use two different approaches in the warning logic of WarnMe.

On the one hand, users can use their own, predefined water level theshold values. Comparison of threshold versus observed values allows to generate early warnings. This setup helps detect rising water levels before the flood reaches the town. It can also be used for private purposes, such as monitoring sewers, inflow structures, or flood areas. Importantly, the stations must not be placed too far outside the town, as that could make the warnings less accurate.

Figure 9: Screenshot of WarnMe Android App.

On the other hand, the stations can also be installed within the municipality. In the state of Baden-Württemberg, such stations can be linked to the flood hazard maps provided by the local government [17]. This allows to determine which water level at a measurement station corresponds to which extent of overserved flooding or specific flood event (HQ). Users who have installed the app can select the flood event (HQ) — that is, the extent of flooding — at which they wish to receive a warning. This ability to relate measurements at exemplary locations to existing geodata and generate warnings for affected people is a major advantage of our system.

To allow early detection, additional parameters beyond mere water level measurements are taken into account, e.g. relative increase, speed of water level increase, and others. To prevent false alarms, a warning is only issued if values are confirmed by several measurement, several stations, and has been compared to current weather data. A designated group of experts - such as members of the fire department and municipal specialists – can choose to receive alerts at an early stage of a potential flood event, allowing for timely investigation and intervention in case of emergency.

5. Distribution and application

5.1 Suitable locations for installation of WarnMe systems

There are currently six measuring stations installed in and around Ochsenhausen (Fig. 9). We have deliberately chosen the locations of each station based on important hydrological considerations. Two stations (1 and 2) are located near flood compensation areas and a swamp so that changes in the water level can be detected early and the retention capacity of the area can be assessed. We placed the other four stations along the small river Rottum, which has been the cause of frequent floodings in recent years. This allows continuous monitoring of water levels and early warnings in case of emergencies.

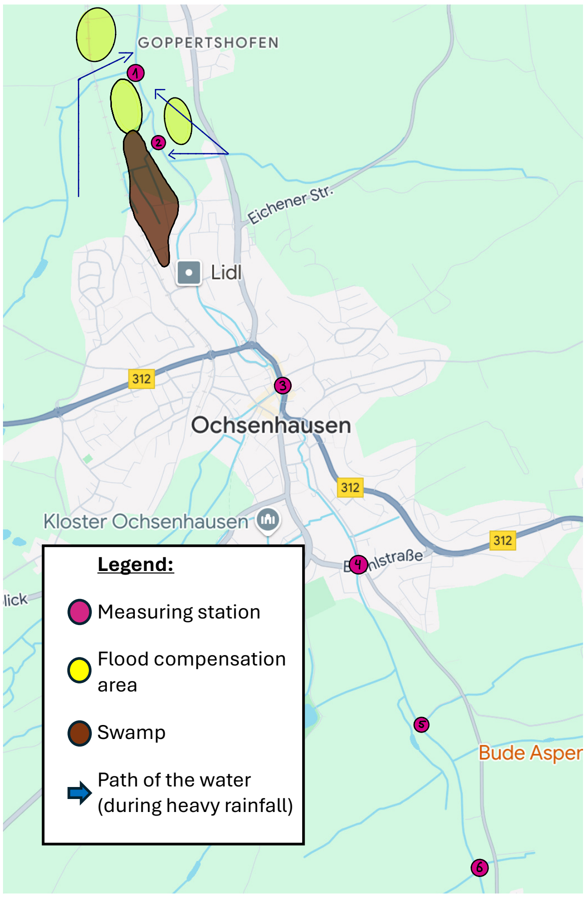

Figure 10: Overview of Ochsenhausen including measuring stations

5.2 Current use and planned expansion

Our system is already in use in two German cities, Ochsenhausen and Tuttlingen. Further locations are in planning, e.g. in the Alb-Donau district and Vienna (Fig. 10). At further locations (marked in red) we are in contact with private individuals, industry associations, mayors and district administrations, interested in installing WarnMe. We are also working with the Neu-Ulm district office to implement our system in their district. The aim is to set up and test the first pilot locations in the district and then gradually expand the system.

Figure 11: Overview of the (planned) locations, blue: installed, red: in planning

5.3 Target groups

WarnMe is primarily designed for use by cities, municipalities, and private households. Both cities and communities benefit from a low-cost, customizable solution. This allows them to better monitor areas at risk. They can also react more quickly to impending floods.

WarnMe also offers private households a decentralized opportunity to protect themselves on time without having to rely on central warning systems. This is particularly important in areas where no good local flood warning system is available. Another advantage for any user group is the system's easy installation and autonomous operation.

6. Outlook

Our infrared and ultrasound systems are fully operational, and we are actively working to expand their range of applications. Looking ahead, we envision significantly reducing the cost of our radar measuring station. Currently, costs of non-radar stations are just 20 € - while reliance on commercially available Infineon radar technology significantly drives up the cost of radar stations. If long-term testing with the radar kit proves successful, we plan to design our own custom circuit board for the radar sensor. This would allow us to bypass Infineon's software and instead use an Arduino to connect directly to the LoRaWAN network. While this setup would consume more power than previous versions, it would bring the total cost down to around €110 - making this setup much more affordable than it is now.

As part of our expansion strategy, we aim not only to drive forward the installation of additional measuring stations, but also to deliver a major update to the WarnMe app. This updated app will include a user-friendly drop-down menu that allows users to select their municipality. Each measuring station in this municipality is linked to its precise GPS coordinates, and we are developing an interactive map—available both on warnme.info and within the app—where all station locations will be clearly displayed. Users will be able to select specific stations, view real-time data, and incorporate this information into their personalized algorithms.

7. Acknowledgements

Tobias Beck

Tobias Beck was the main reason why we started working at SFZ Ochsenhausen more than four years ago. His good humor and his way of motivating are always contagious, even after several hours of Python troubleshooting, for example. He was also the person who got this project rolling.

Benno Hölz

We would especially like to thank our supervisor Benno Hölz for his great support over this long period of time. He supported us with his immense knowledge during the first LoRaWAN workshop, the provision of the server, the DIY ultrasonic measuring station, the data evaluation and everything in between. His help with questions, even during the vacations or at weekends, has brought us to the point where we are now.

Matthias Ruf

Special thanks also go to Matthias Ruf for his active support during the entire project implementation. He stood by us with his knowledge and craftsmanship, especially during the construction of the model and with difficult technical problems.

8. List of sources

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8.2 Image sources

Cover photo: Jugend forscht, 09.06.2025

Figure 1: https://www.dw.com/de/tödliches-klima-weltweit-durch-hitze-sturm-und-flut-klima-risiko-index/a-51506072, 08.06.2025

Figure 2: Private archive

Figure 3: Private archive

Figure 4: Created with BioRender.com, https://app.biorender.com/, 08.04.2025

Figure 5: Private archive

Figure 6: Private archive

Figure 7: Private archive

Figure 8: AATiS e.V. (2025). Graphic from: Practice booklet 35, page: 45

Figure 9: Private archive

Figure 10: Own illustration based on https://www.google.com/maps, 13.04.2025

Figure 11: Own illustration based on https://www.google.com/maps, 13.04.2025