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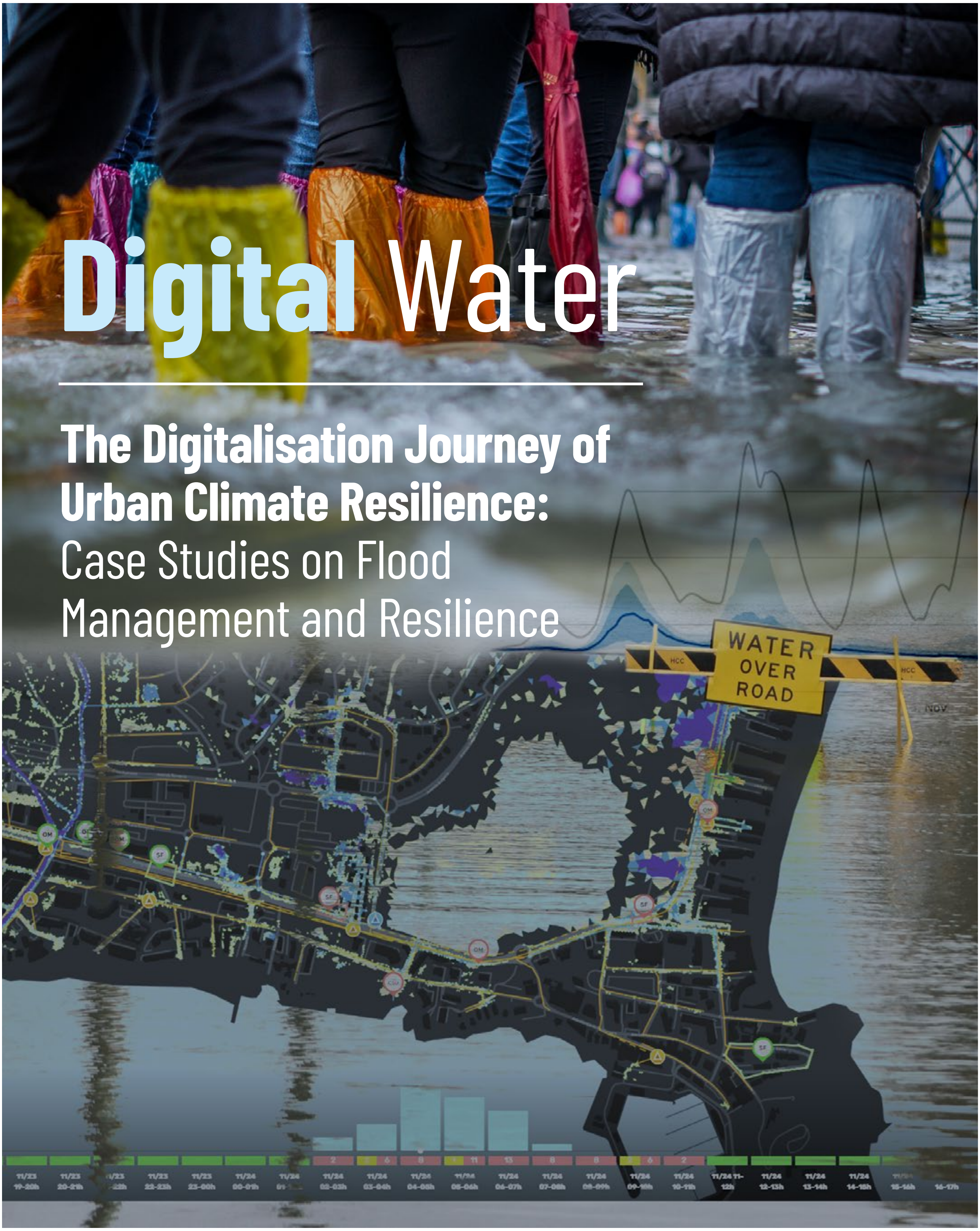
Digital Water

The Digitalisation Journey of Urban Climate Resilience: Case Studies on Flood Management and Resilience



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The Digitalisation Journey of Urban Climate Resilience:

Case Studies on Flood Management and Resilience

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We would like to acknowledge Oliver Grievson for providing motivation and support while we were writing this paper. Also, we would like to acknowledge Mr Sham Chaudhari, Sales Director, India/South-Asia at Xylem for sharing the case studies with us for the resilience.

Summary

This white paper focuses on presenting digitalisation as an important tool to help improve flood resilience in cities, to cope with the climate crisis. The aim is to connect the concept of resilience to the wide number of digital tools that can be used in different parts of the resilience cycle, when dealing with floods. Examples are presented to show the applicability of the digital tools in real-life case studies.

Foreword

In an era when the pace of urbanisation is accelerated and the impacts of climate change are intensified, our cities face unprecedented challenges in ensuring the resilience of their water systems. Uncertainty in weather patterns, especially with increased frequency of flash flooding, poses a threat to human life and presents governments with the costly burden of rehabilitation. Meanwhile, we are working against time and a pressing need for resources to achieve the UN Sustainable Development Goals by 2030. Despite progress in some areas, the exacerbation of existing challenges, such as population growth, and the advance of new ones, such as cybersecurity breaches, add to the demands of meeting this deadline. Against this backdrop, cities need to advance urban climate resilience to give them the ability to withstand, adapt to, and recover from the adverse impacts of climate change while maintaining essential functions and services.

Digitalisation of the water sector offers a myriad of opportunities to enhance the resilience of urban water systems. From real-time monitoring and predictive analytics to advanced modelling and decision support tools, digital technologies empower cities to anticipate, adapt, and respond to the impacts of climate change on their water infrastructure. Technological options are available and evolving fast. At the same time, realisation of these opportunities requires concerted efforts from stakeholders across sectors and scales. It demands a paradigm shift in our approach to urban water management — one that embraces interdisciplinary collaboration, embraces data-driven decision-making, and prioritises the resilience of communities, particularly those most vulnerable to the effects of climate change.

Over the past five years, IWA has advanced its action on digitalisation, placing it at the forefront of our efforts to bridge the gap between research and practice. This action is helping shape the digital transformation journey of the water sector. The IWA Digital Water Programme stands at the forefront of this transformative journey, catalysing innovation and fostering collaboration to address the pressing water challenges of the 21st century.

In this time, IWA has produced numerous knowledge-sharing products to help practitioners, solutions providers and utilities address the challenges and growing pains of digitalisation. In particular, we have published ten white papers showcasing developments in the digital transformation journey of the water sector.

We are pleased to add to the list this latest white paper on innovations in the vital area of urban climate resilience. This paper highlights the synergy between urban climate resilience and digital water solutions as an essential means for safeguarding the well-being of our communities and the sustainability of our cities.

An important feature of IWA's ability to work with and through its network is that, through our knowledge-sharing products, we continue to highlight different perspectives, often casting light on the need to scale solutions in the move to digital maturity. This latest paper adds a similar contribution, providing a broader context by showcasing perspectives from South America, Asia, Europe and Africa.

IWA firmly believes that the generation and sharing of knowledge, along with the exchange of best practices, is critical to driving progress in the water sector. By fostering collaboration and promoting innovation, we can collectively address the pressing water challenges of today and create a sustainable future for all. Through this commitment, IWA continues to empower professionals and communities to ensure access to clean, safe water worldwide and to improve water management more broadly.

Kalanithy Vairavamoorthy

Executive Director of the International Water Association

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Assembly point

1. Introduction

The need for resilience has become a strategic decision-making priority globally to tackle the emerging and more frequent natural and man-made challenges, such as rapid urbanisation, increasing population, climate change and other socio-political challenges. In the case of extreme weather events, the impacts on people and communities are growing increasingly severe due to the rising frequency and intensity of events like floods and droughts, which are a consequence of climate change (Vermij, 2023).

According to a report published by the United Nations (CRED & UNISDR, 2015), the majority (90%) of natural disasters recorded in the last 2 decades were climate-related. As per the international database (EM-DAT), which is the Emergency Events database, 6457 weather-related disasters have occurred between 1995 and 2015. Floods contribute to the maximum percentage of 43% among the natural disasters. More recently, we have seen other examples of these disasters such as the floods that occurred in Pakistan in 2022 and affected a third of its territory; the floods in northeast Brazil which lasted more than two months between the end of 2021 and the beginning of 2022; the floods in Eastern Europe in 2021, which reached Germany, Belgium, and the Netherlands, among others. Floods in Libya in 2023 led to devastating loss of life with some 11,000 confirmed dead and at least 10,000 missing. The latter part of 2023 had seen unprecedented rainfall and major flood events with severe consequences to people and communities, infrastructure, and economies as well as natural environments.

The new IPCC report AR6 projects a 1.5-fold increase in heavy storms (return period = 10 years) across the globe, even under scenarios of a more conservative rise in temperatures of 1.5°C (IPCC, 2021). Given that 55% of the world's population lives in urban environments (UN DESA, 2019), there is an urgent need to strengthen the urban resilience of water, sanitation, and stormwater drainage infrastructure.

There is a wide range of definitions and approaches to **resilience**, and it is important to have a clear understanding of the needs, perceptions, and priorities when choosing a method or definition. Internationally, the most adopted definition for public policies is the one presented by the United Nations Office for Disaster Risk Reduction (UNDRR) and used in the Sendai Framework (UNDDR, 2015):

More specific to the context of cities, Zhang and Li (2018) have surveyed the terms 'Urban Resilience and Urban Sustainability', used in different applications in international studies, and suggested the definitions:

> “Resilience means the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of the hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions.”

> “Urban resilience is the passive process of monitoring, facilitating, maintaining and recovering a virtual cycle between ecosystem services and human wellbeing through concerted effort under external influencing factors,” and “Urban sustainability is the active process of synergetic integration and co-evolution between the subsystems making up a city without compromising the possibilities for development of surrounding areas and contributing by this means towards reducing the harmful effects of development on the biosphere.”

Using these definitions, we can understand urban resilience to climate change as a city's ability to withstand the negative impacts of external climate changes and restore its previous state within a suitable timeframe, ensuring the recovery of ecosystem services and human well-being. This ‘suitable timeframe’ is different for each negative effect generated. For example, in the case of floods, the suitable period is the duration of the precipitation event and peak flow recession.

Many approaches, techniques, and policies have been presented to increase cities’ resilience and reduce risk exposure. However, as stated by Martens and Carvalho (2023), “many organisations simply do not know where to start their climate resilience journey due to the complexity and multiplicity of the topic”. Digital tools have been presented as a growing and promising approach to help actions to be taken at different stages of the resilience cycle and can be enablers to organisations to prepare themselves against the impacts of climate change (Martens & Carvalho, 2023).

This white paper aims to present inspiring experiences of how digital tools have helped the process of urban resilience to floods in different contexts. The authors hope that these experiences can promote and inspire new success stories. The document presents the background to the problems of extreme flooding in the urban context and climate change, in order to aid understanding of the main associated risks. Subsequently, the different steps of the resilience cycle in which digital tools can help optimise the process are presented. This is followed by case studies related to the use of these tools to build resilience to floods. Finally, the main lessons learned from these experiences and recommendations for future applications are presented.

2. Digital tools on urban resilience cycle

The actions involved in improving resilience to disasters are usually classified as short-, medium-, and long-term actions, which can also be divided into actions that take place before the disruptive event, that is, risk reduction measures, and after the event, that is, recovery measures. These actions can be perceived as a cycle in disaster management (Figure 1), involving the stages of individual disaster response, response/relief, rehabilitation, reconstruction, mitigation, and preparedness (Davis & Alexander, 2015). In the context of urban disasters related to floods and droughts, different types of digital technologies and tools have been used at each stage of the resilience cycle, and these are presented in this section.

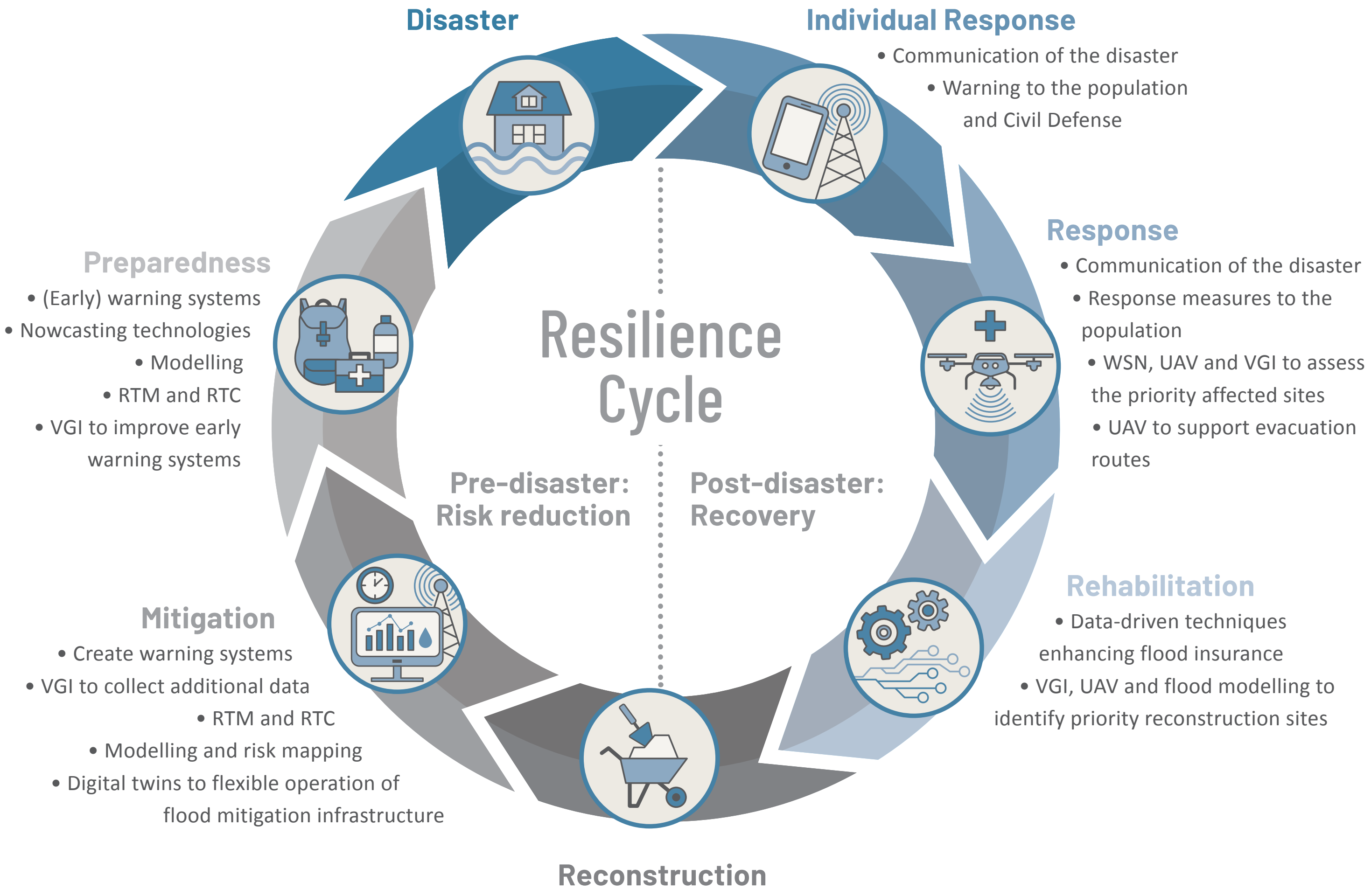


Figure 1: Insertion of digital tools into different parts of the resilience cycle to mitigate the effects of the disaster.

Abbreviations. RTM: Real-time Monitoring; RTC: Real-time control; VGI: Volunteered Geographic Information; WSN: Wireless Sensor Networks; UAV: Unmanned Aerial Vehicles.

2.1. Individual disaster response

At the **individual disaster response** stage, the actions and measures focus on an immediate response, aiming at an individual's security and safety, providing first aid, and securing essential supplies. In this sense, it is necessary that people have access to information about the disaster, its location, scale, and with sufficient time to take actions. Therefore, digital tools are being used in this part of the resilience cycle to forecast, visualise, communicate, and alert the population and key stakeholders about the disaster. Examples of use of digital tools are:

- Communicating flood alerts to the population through mobile networks, social media, and traditional media (Feldman et al., 2016; Shrestha et al., 2021).
- Cell-broadcast (CB) technology (Parsons & Hamilton, 2023): unlike SMS, which is a one-to-one channel, CB is a one-to-many technology. This means that one message can be sent to millions of devices within a few seconds. CB works by distributing content via specific cell sites based on a subscriber's location. Unlike SMS, CB does not require a phone number to send a message. It therefore enables location-specific emergency alerts to be sent without the need to register or track devices. As well as being more private than SMS, visitors to the target area, including from abroad, will also receive alerts, and even in their own language if the system is multi-language enabled.

A big challenge remains on how to disseminate the information to the most vulnerable groups (including economic), that may not have access to digital technologies (Downer & Hamilton, 2024).

2.2. Response/relief

At the **response/relief** stage, the interventions are of short-term duration and are provided by more structured and institutional agencies, such as civil defence groups. These actions aim at search and rescue; provision of food, water, sanitation, and safe shelter; and delivery of medical, social, and economic support. During this stage, it is also necessary to have a good communication system between the institutional agencies and the population, so they can be advised/warned about the disaster, how to proceed after the disaster happens, and where to look for help.

- Wireless Sensor Networks (WSN) and Unmanned Aerial Vehicles (UAV) systems have been used to improve the response and relief to flood disasters (Erdelj et al., 2017). Aiming at improving victims–civil defence communication, WSN coupled with UAV can be used to extend internet connectivity, allowing the victims to use their own mobile devices. Another example is the use of UAV to provide an overhead view and help surface vehicles to find an optimal path to rescue and provide support to the victims.
- WSN can be integrated with crowdsourcing/crowd-sending and Volunteered Geographic Information (VGI) platforms, allowing smartphone users to provide real-time information about the conditions of the affected area to civil defence, helping them to conduct rescue and support missions (Poser & Dransch, 2010). As examples, Waze and Twitter/X have been used as platforms to collect VGI information (Lowrie et al., 2022, Yuan et al., 2022).

2.3. Recovery (rehabilitation and reconstruction)

Recovery involves **rehabilitation** and **reconstruction**. The rehabilitation and reconstruction stages aim, respectively, at restoring the basic services/functions of the system, in the short- and mid-term, and the full capacity of the system, also including preventive measures for future disasters, in the mid- and long-term. Here is where the idea of 'build back better' should be strongly embedded, driving not only the full recovery/reconstruction of the system, but in a way better and more resilient than it was in the first place. Digital tools that support this process include the following:

- Data-driven techniques to enhance insurance risk analysis, by mapping the flood risk and communicating to the population (Rumson & Hallet, 2019). For this, data collection techniques and analytics, such as satellite-derived data, internet of things (IoT) sensors, cloud computing, and Big Data solutions are used. This allows extending coverage of flood insurances, helping rehabilitation and reconstructing individual assets.
- Flood damage estimation, including critical and recurrent sites, through VGI, UAV, and flood modelling, to identify where reconstruction is needed and where to take in preventive measures for future disasters, designing and sizing of the measures, and efficient assessment (Poser & Dransch, 2010, Erdelj et al., 2017).

Figure 2: The Delta Works contribute to climate resilience by offering both short-term protection against extreme weather and long-term solutions for rising sea levels, ensuring that the Netherlands can thrive in a changing climate.

2.4. Mitigation

The resilience cycle also encompasses measures that should be enacted before potential disasters and focus on risk reduction. **Mitigation** measures must focus on risk assessment and prevention. At this stage, it is important to understand the risks, in terms of their processes and their different levels spatially and temporarily. After assessing and understanding the risk, structural and non-structural measures must be developed to help prevent the risk or reduce its impacts. Examples of digital tools that are being used in this stage include the following:

- VGI collected from social media, e.g. pictures and videos from flood events, and processed to obtain flood depths, to help calibrate and validate 2D flood models (Drews et al., 2023).
- Real-time Monitoring and Control (RTM&C) systems (consisting of sensors, actuators, communication devices, and web server) aimed at flexibilisation and adjustment of flood mitigation infrastructure to manage real rainfall-runoff events and conditions, e.g. artificial wetlands (Pang et al., 2023) and bioretention (Persuad et al., 2024).
- Use of Digital Twins is a new approach that is emerging in flood resilience (Brasil et al., 2022) and aims at more integrated systems of flood modelling, RTM&C, and life-time performance evaluation of urban flood infrastructure.

2.5. Preparedness

An important part of the resilience cycle is the **preparedness**, where action plans are developed to take place right before the disaster event, in order to reduce its impacts by ensuring the population is better prepared and knows how to conduct the response measures needed. Ideally, preparedness should be the first stage of resilience building. Humanitarians strongly emphasise that preparedness is often overlooked even though it is the most cost-effective measure and saves many more lives than do actions taken after a disaster.

At this stage, it is important to develop contingency plans, warning systems, and evacuation systems, as well as other measures to consolidate preparations for further disasters. Examples of digital tools that are being used in this stage include the following:

- Water-depth sensors in the river channels as part of Real time Monitoring (RTM) systems and early-warning systems. Low-cost sensors have been developed to increase the applicability of this solution in various contexts (Catsamas et al., 2023, Baratella et al., 2023).
- Crowdsourcing platforms to collect VGI on channel water depths to update flood models in real-time, helping improve flood prediction and early flood warning (Degrossi et al., 2014).
- Transformed geo-social media activity (obtained by Twitter/X platform) as a proxy for rainfall-runoff estimation and flood forecasting, in ungauged or poorly gauged catchments to improve early flood warning (Restrepo-Estrada et al., 2018).
- Improving real-time rainfall estimation (nowcasting), through the existing closed-circuit television (CCTV) network coupled with convolutional neural network (CNN) models (Sukumaran et al., 2024) and radar X-band data (Keem et al., 2021).

3. Case studies on floods

3.1. Resilience building in a data-transition context; from data poor to data dense: experience of a GARID project in Ghana

Bernard Makafui Agbelengor *(GARID, Ghana)*

Company presenting the case study

The case study is presented by the Greater Accra Resilient and Integrated Development (GARID) Project, which is an initiative of the government of Ghana, jointly with the Ministry of Works and Housing; Ministry of Sanitation and Water Resources; and Ministry of Local Government, Decentralization and Rural Development. Funding comes from the World Bank.

Introduction

Responding to the need for flood management in Accra, the government of Ghana, with the help of World Bank, has initiated a flood mitigation and adaptation measure project called the Greater Accra Resilient and Integrated Development (GARID) Project. The GARID Project is supporting the Greater Accra region to adapt its drainage and flood risk management and has also in collaboration with the MMDAs developed an ongoing programme to gather, organise, and analyse flood data and make the necessary engineering and non-engineering interventions.

This case study focuses on building resilience in a data-transition context: from data poor to data dense. The aim was to show how different data technological tools are used in the GARID Project to ensure resilience in the long run. Key areas of this case study included an overview of what GARID is and how it was developed.

The GARID project uses different data-centric approaches, such as Google Earth, Kobo collect aerial imaging (UAV), LiDAR, Hydrologic Engineering Center River Analysis System (HEC-RAS) for flood modelling, and Geographic Information Systems (GIS). They have been used for risk, damage assessments, monitoring, mitigation, adaptation, and prediction in hydraulic and hydrologic flood simulations.

Many studies lack specific references to data-driven built-asset resilience decisions and unambiguous consequences on flood and built-asset resilience enhancement. This implies that there are more chances to contextualise data for flood resistance in the built environment. The study concluded that the conceptual map of the flood context, approaches, data types, and the data technology have improved resilience.

Objectives

The objective of the GARID Project is to improve flood risk management and solid waste management in the Odaw river basin of the Greater Accra Region and to improve access to basic infrastructure and services in the targeted communities within the basin. The overall goal of the project is to achieve clean, resilient, inclusive, and integrated development in the region. The project has been scheduled into five different components:

1. Climate Resilient Drainage and Flood Mitigation Measures;
2. Solid Waste Management Capacity Improvements;
3. Participatory Upgrading of Targeted Flood Prone Low-Income Communities and Local Government Support;
4. Project Management;
5. Contingent Emergency Response.

The project was a result of the flood event that happened in Accra on Wednesday, 3rd of June 2015, now known as the 'June 3rd disaster', and other recurring floods. This event was considered a “black day” in Ghanaian history because heavy rainfall transformed into a terrible fire and flood disaster that claimed the lives of an estimated 154 people and left scores more with varied degrees of burns and injuries that left them permanently disabled.

Intervention through digital tools

The project began with several feasibility studies, with some data acquired to guide the implementation of the project. Collecting and analysing more data in relation to the baseline data that were acquired during the feasibility works relied on a number of digital tools. These tools were open source, but with the transition of the project to the implementation phase, the project has acquired servers, and set up a data centre, that meet international standards, which will be leveraged upon by the citizenry.

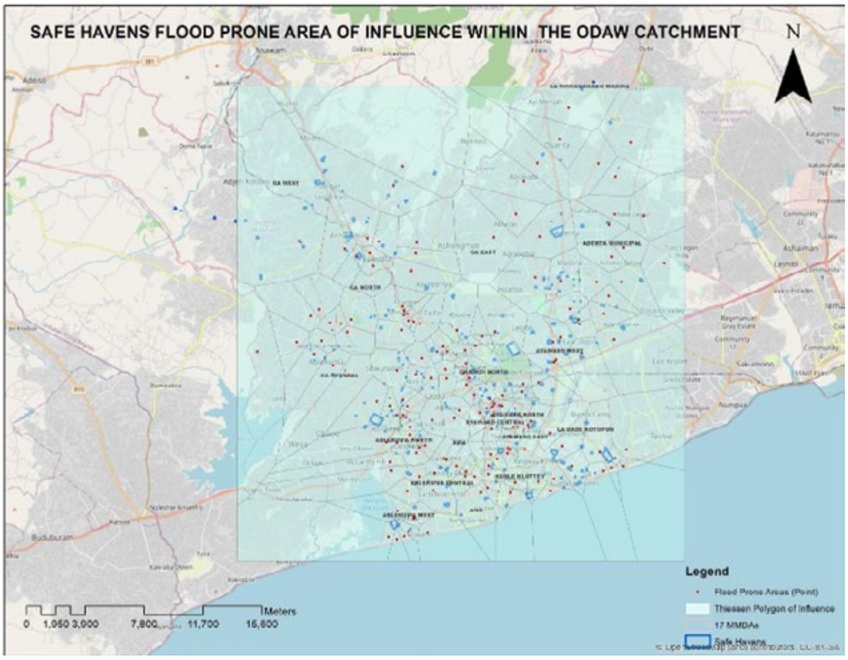


Figure 3: Safe havens and flood prone areas of influence within the Odaw catchment.

Google Earth was used to locate and map project sites and to measure distance. Being able to locate the project sites helped to show the general public places that are flood hotspots and the interventions to be undertaken. Storage was also required for all the data that was being acquired, and since the project was at its inception, Google Earth served as storage for all the spatial data being gathered; thus, the project spatial database was on this program. Although eventually the tool became very slow to open due to the load of data stored there, it was our only sustainable hope at that time.

Aerial imaging (by UAVs) was used to capture videos and images of the affected project sites as well as to capture images of safe havens in the region. This gave the project coordinating unit and implementing units a bird's eye view of the Odaw river (Figure 3). The accumulation of silt and solid waste in the river was clearly shown. These videos and images gave a head start to deciding how to go about solving the problem of flooding in the Odaw Basin.

LiDAR was used to help in the engineering designs of the intended project interventions and to capture all the building footprints in the Greater Accra Region. The measurements of all the buildings were also captured. This was very useful in determining compensation of project-affected persons. The building footprint data made it possible to generate a map showing all the buildings in each Assembly in the region. Further, maps were generated showing how many buildings had encroached on the 50-metre buffer zone of the Odaw channel (Figure 4).

Figure 4: Maps constructed from LiDAR images containing buildings that had encroached the 50-metre buffer zone of the Odaw channel.

KoboToolbox was very useful in the data collection process of the project. This was pinned to project sites on the Google Earth locations. Any data collected using Kobo could be displayed on Google Earth. This tool was used in collecting data on all existing drainage in the basin catchment.

HEC-RAS for Flood Modelling used the RAS Mapper to create a 1D model of all the river systems in the region. Finding the key locations of flood hotspots assisted the project coordinating and implementing units in taking steps to lessen the impact of floods or to put adaptation plans in place to prevent future flooding events of the same type.

QGIS served as the GIS tool for digitising and conducting spatial manipulations on the data gathered. Due to sustainability concerns, this tool was the optimal choice for all government agencies. Occasionally, other tools like Arc GIS and Global Mapper were used when the need arose. Global Mapper is used for manipulating raster data and it accepts a wide range of data set formats. The ArcGis Online platform was used in mapping out all gender based violence relief centres and used for periodic updates of the data. This was relied on mainly because of its dashboard functionality.

Qfield was another data collection tool deployed in data collection and field verification exercises. Its mother tool is QGIS. This tool helped in digitalising on field data and made any spatial edits that were required on field data.

Thus, Kobo was mainly used to collect attribute data and some spatial data. Once the data was transmitted to the GIS operating tool and the digitisation was completed, the data was migrated to the Qfield environment for field verification.

Conclusion

The case study illustrates the use of digital tools for gaining a comprehensive understanding of the current context of data utilisation for flood resilience of built assets for societal sustainability from data poor to data dense. The data digital tool has helped the project to: prepare a safe haven register, prepare principles and guidelines for safe havens, conduct safe havens distribution analysis, make the project team aware of when each safe haven needs renovation or enhancement, and be able to monitor all the safe havens and project construction sites without being present on site.

Technology's impact on resilience

Digitalisation technology has improved the resilience of flood modelling scenarios making it easy to predict river flows and rainfall levels combined with topographic data to generate flood risk information effectively. These tools have provided data for the setting up of a flood warning system, a spatial asset management platform, and flood models for the Odaw basin area. These are just but a few of the contributions of such digital tools for resilience building.

3.2. Flood monitoring and warning system in urban areas based on a Long Range Wide Area Network: case study for the city of Itajubá, Brazil

Benedito Cláudio da Silva *(Federal University of Itajubá and ASTHON, Brazil)*, **Danilo Spadoti** *(Federal University of Itajubá and ASTHON, Brazil)*, **Caio Tácito Borges da Costa** *(ASTHON, Brazil)*, **Vitória Jacomelli Baratella** *(ASTHON, Brazil)*

Company providing the case study

The case study began with research developed at the Federal University of Itajubá (UNIFEI), which resulted in the creation of the start-up company ASTHON Tecnologia Ltda., responsible for this case study. The solution presented is a partnership between UNIFEI, ASTHON, and the civil defence of the municipality of Itajubá.

Introduction

The growth of Brazilian cities without proper planning of the drainage system, combined with increasingly intense and frequent extreme meteorological events, has led to increasing and high economic and human life losses, annually reaching billions of dollars and hundreds of deaths.

Among the measures to mitigate the effects of extreme events, hydrological monitoring and the issuing of alerts to affected communities stand out. Although the national telemetric monitoring network has been expanded in recent years, mainly after the creation of the National Center for Monitoring and Alerting of Natural Disasters (Centro de Monitoramento e Alerta de Desastres Naturais - CEMADEN) in 2011, the number of rain and river level measurement stations is still very small, falling short of meeting the needs of urban areas. In addition to the insufficient number of stations, traditional monitoring solutions with transmission, via satellite and cellular networks, are expensive for municipalities and unsuitable for installation in urban areas, due to the infrastructure and space they require. Furthermore, simply installing the equipment and transmitting the data also does not serve municipal civil defence organisations, as they do not have specialised teams to interpret the data and maintain the system. There are recurring cases of cities with systems that no longer operate due to a lack of specialised professionals to operate the system.

Therefore, the challenge addressed in this case study was to develop a monitoring and alert system for urban areas based on compact measuring stations, with low construction cost, minimum energy consumption, simple maintenance and that communicates measured data to the user in an objective manner and in accessible language.

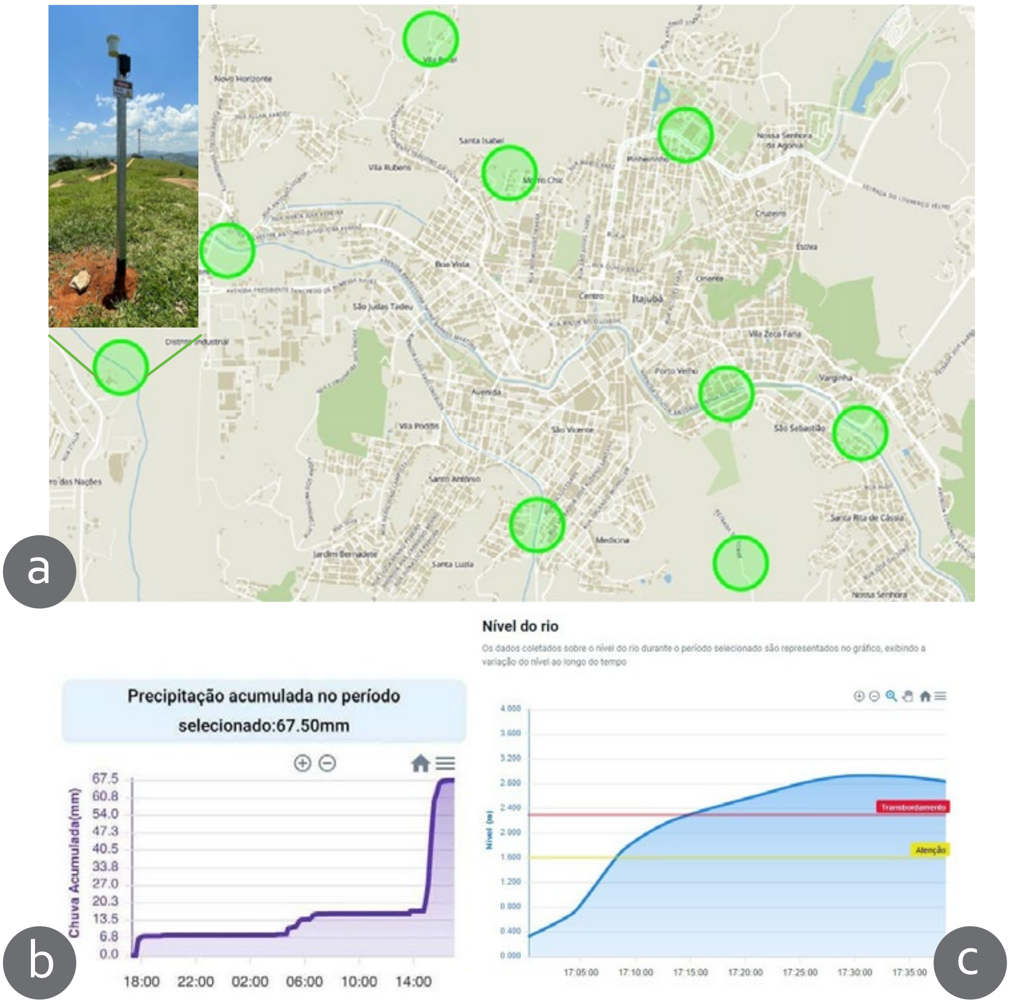


Figure 5: (a) Map with part of the monitoring points in Itajubá, highlighting the monitoring station; (b) and (c) Monitored level and rainfall events, respectively.

The city of Itajubá is located in the south of the State of Minas Gerais, Southeast region of Brazil. The Sapucaí River is the main watercourse that crosses the urban area of the city and has a long history of major floods. In recent years, flash floods of tributary streams of the Sapucaí River within the urban area have become more frequent. Intense, short-term rains cause riverbanks to overflow and streets to flood in several neighbourhoods. The mountainous and complex terrain requires a high density of monitoring stations, so that the full spatial variability of rainfall is captured. Furthermore, the response time of the basins is short, requiring telemetry measurements at very short intervals.

Objectives

The main objective was to develop a telemetric hydrological monitoring system using a Long Range Wide Area Network (LoRaWAN) (Joiner et al., 2023) to monitor, predict, and alert extreme hydrological events in the urban area of Itajubá.

The proposed system will:

- Monitor basins of different spatial scales, from areas smaller than 1 km^2 to around 1000km^2;
- Monitor events with different temporal scales, with temporal discretisation starting at 1 minute;
- Create a communication network with LoRaWAN protocol to cover all monitoring points;
- Develop an electronic module for collecting and transmitting data via the LoRaWAN network;
- Dimension monitoring stations at the lowest cost and most compactly possible;
- Develop a web platform to make data available and issue real-time alerts for municipal civil defence, with clear and objective information.

Intervention through the digital tools

The main digital tool used in this case study was the LoRaWAN communication system. The current low cost of its implementation motivated and enabled the development of all other components of the system. A network of LoRaWAN receivers (gateways) was designed for the study area to receive measurements from all installed rain and water level sensors. The receivers are connected to the Internet and the data is stored on a cloud server and sent for users to view.

The main digital component developed by ASTHON was the data reception and transmission module via LoRaWAN. Entirely developed by the company and called MARLIN, this module consists of a digital circuit board where sensors are connected, and data is received and sent to LoRaWAN receivers. Extremely compact and with low energy consumption, it requires a small battery whose charge can last for months, without needing a solar panel for recharging. The sensors used are preferably nationally manufactured and low cost.

To complete the system with digital tools, a web platform was developed to visualise data and issue alerts. Data visualisation is graphical and uses colour scales, with indication of alert thresholds (Normal, Attention, Emergency). It is possible to set the viewing period and access numerical data as well. The interface's appearance is simple and highlights the most important information, in order to facilitate decision-making in critical situations. Figure 5 shows some images of the system.

Conclusion

The system is currently in the final phase of implementation, but the preliminary results obtained indicate that it meets the proposed objectives. The biggest difficulties in the implementation phase are linked to identifying the locations for installing the stations, both in terms of the most suitable hydrological conditions and the safety of the equipment. Throughout the current rainy period, October 2023 to March 2024, the system will be tested in different situations that will contribute to its improvement. From this first period of measured data, forecast models can be developed.

The entire development of the system has been based on several years of cooperation between team members and municipal civil defence teams. This experience made it possible to identify the municipality's deficiencies and needs in relation to the occurrence of extreme hydrological events. This way, it was possible to build a system tailored to these needs. However, it is a tool that requires continuous improvements, the success of which depends heavily on the collaboration and trust of civil defence teams and other agents involved. Listening to, and incorporating the experience of people who work on the front lines of preventing and combating extreme events, is equally as important as using the best technology available.

Technology's impact on resilience

The monitoring and alert system proposed in this case study will improve the city's resilience because it allows it to deal with extreme events more assertively. Anticipating the occurrence of a flash flood within minutes can save lives and reduce much material and economic damage. Furthermore, monitoring expands knowledge about the hydrological behaviour of basins, making it possible to plan short-, medium-, and long-term measures more effectively, increasing the water security of populations.

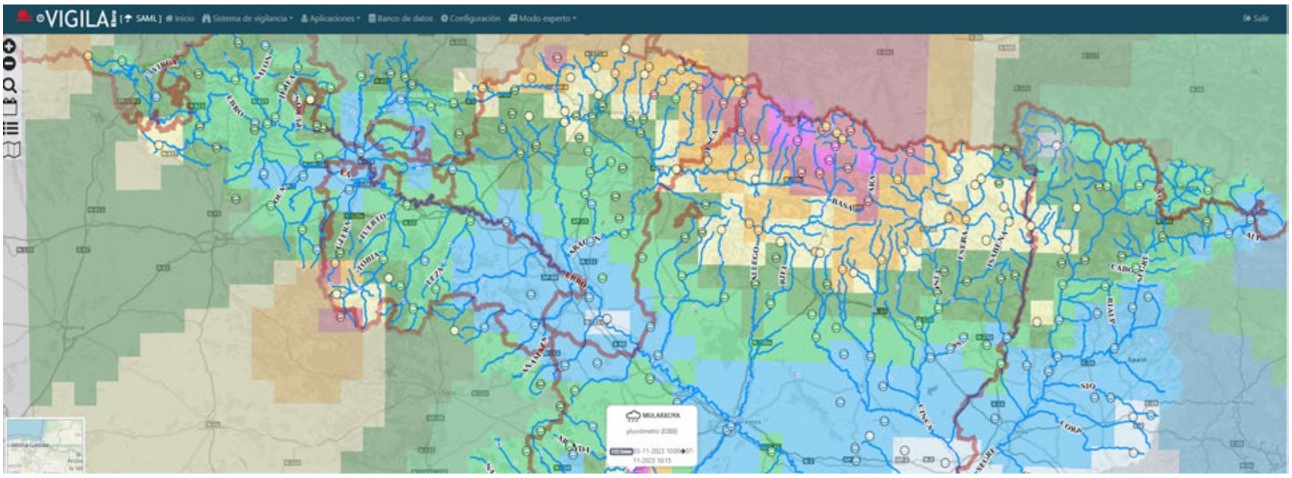


Figure 6: VIGILAEbro rainfall maps. Use of geo-statistical and machine learning correction algorithms.

3.3. An Early Warning System to Prevent and Manage River Basin Flooding. Application to the Ebro River Basin (Spain)

Antonio Moya *(IDRICA, Spain)*, **Mario Carreras** *(CHE, Spain)*, **Esther Ruíz** *(CHE, Spain)*, **Ramón Lúquez** *(CHE, Spain)*

Company presenting the case study

This case study is presented by Idrica in collaboration with Confederación Hidrográfica del Ebro (CHE). Idrica is a company specialising in the digital transformation of the water industry; in partnership with Xylem, Idrica leads the development of Xylem Vue powered by GoAigua. Confederación Hidrógrafica del Ebro is the river basin authority that manages, regulates, and maintains the water and irrigation of the Ebro River basin (northeastern Spain).

Introduction

The Ebro River is 9,309 km and flows through the north-east of the Iberian Peninsula. The Ebro basin covers a surface area of around 85,000 km^2 and 347 main rivers. It gathers most of its waters from the north of Spain (mainly from the Pyrenees and pre-Pyrenees), and it is probably the most important river basin in Spain in terms of the water resources it provides. The river flows through territories characterised by the three different types of climates: Atlantic, Mediterranean, and a transition area with a great range of evapotranspiration and precipitation rates. In every season, the combination of these geomorphological and climatological factors and climate change cause heavy flood events of different types: river, pluvial and flash floods.

The Ebro basin water authority is in charge of implementing the European Floods Directive (2007/60/EC). In this framework, it is necessary to develop a Flood Risk Management Plan covering measures, such as urban development, territorial planning, the natural environment, forest management, insurance, hydrology, and hydraulics. The Early Warning System (EWS), referred to as 'VIGILAEbro' in the water authority's software infrastructure, is a holistic software system to help in most of them by applying high innovative technologies.

Objectives

The case study presents two main aims:

- Reduce flood damage;
- Provide early warning to civil protection and other stakeholders for disaster management.

To fulfil these two main objectives, some specific tasks were needed, such as providing hydrologic and hydraulic probabilistic modelling, building a tool to provide recommendations on dams' manoeuvres minimising risks and damages, and finally providing a tool to disseminate warnings to each stakeholder, such as other authorities and the general public.

Intervention through the digital tools

This case study is supported by the EWS tool , which is part of the solutions provided by Xylem Vue powered by GoAigua.

The tool computes, analyses, and provides warnings and recommendations based on a big amount of data. So, a wide variety of technologies have been developed and combined:

- Cloud computing and Big Data analytics supporting probabilistic modelling in real time, both hydraulic and hydrologic.
- Geo-statistics and machine learning techniques, to improve input data quality as rainfall estimates or weather forecasts (see figure 6).
- AI inference engine and heuristics, to provide basin-wide management recommendations.

EWS runs in 10-minutes cycles in order to provide early warnings as soon as possible. To achieve the goals, each cycle is composed of: (1) acquisition of information provided by hydrological and meteorological sensors, rainfall radar, and weather forecasting models; (2) weather data correction

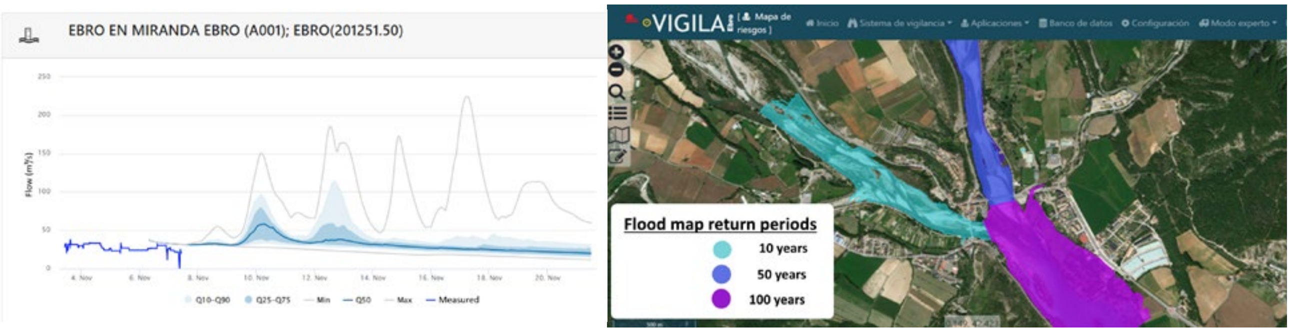


Figure 7: Probabilistic flow forecast (left) and flood maps by return period (right).

algorithms; (3) hydrological and hydrodynamic simulation (see figure 7, left); (4) computation of current and forecasted flows for different return periods to obtain flood maps (a return period is the estimated average time between events and represents the estimated likelihood of a flood event to occur; the longer return periods are the least likely and, generally, the most dangerous; see figure 7, right); (5) run the inference engine and feedback with modelling to compute recommendations on dams management to minimise risks and damage; and (6) warnings and alerts dissemination to mobile phones and websites filtered by user needs, such as location and role in the disaster management.

Conclusion

The deployment of the EWS in a system as large as the Ebro River basin, and its adaptation to current Spanish and European legislation on water and floods, has taken three years. Currently, the system is operating at full capacity, some of its capabilities are in the testing phase with the aim of collecting feedback from stakeholders and the general public, which represents a valuable input to improve and ensure the accuracy and reliability of the system's operation.

In terms of technology, the EWS software system combines different technological approaches to provide early warnings during floods in a variety of flood scenarios, involving different information and the application of a specific methodology for each case.

Benefits are quite significant because it has been shown that:

- EWS has enough flexibility to adapt to different types of floods events (from localised heavy rainfall to rivers floods and with or without snowmelt);
- It provides high accurate flows and levels forecasts by using probabilistic approaches;
- It adapts to the information required by each stakeholder in terms of location and technical knowledge needed (from technicians to the general public);
- It provides very early warning, usually days or hours before the event happens.

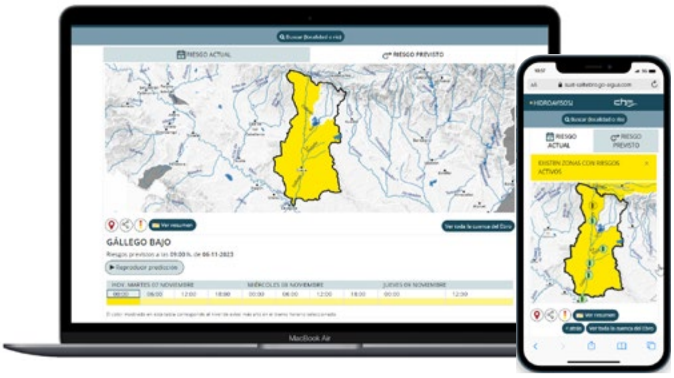


Figure 8: Alerts and warning dissemination for public.

The next steps of EWS are focused on providing more machine learning algorithms and geo-statistical computation capabilities in order to make the system useful for drought events. Focused on this, the platform must ingest climate change scenarios models, be able to compute future water resources volumes in different what-if scenarios, and, finally, build new dashboards to help decision-making.

Technology's impact on resilience

In terms of resilience, EWS use in the Ebro River basin water authority provides several improvements for all the people involved in a flood event. For the Ebro River water authority, the most significant benefit is the better understanding of the current and forecasted hydrological status of the basin. It allows the improvement of dams' management which provides important damage reduction in terms of economic costs and affected population. Also, after each flood event managed by EWS, strengths and weaknesses of the protocols, organisations, and communications and software systems involved are highlighted. These conclusions are highly relevant for planning of future efforts and investments.

All the actors involved in a disaster management such as civil protection, police, or municipalities, can know in advance the affected infrastructures, such as schools, bridges, commercial buildings, which allows the earlier activation of the disaster management protocols focusing on affected elements filtered by population and infrastructures costs. In terms of people, the software system provides a comprehensive and easy-to-use user interface updated in real time. The aim is to warn of the real risks and improve risk perception (refer figure 8). This is achieved by focusing only on the user location using semaphoric widgets.

3.4. Urban Flooding Early Warning System: Application to the Municipality of Calpe (Spain)

Vicente Balanzá *(IDRICA, Spain)*, **José Alberto Mut** *(Aguas de Calpe, Spain)*, **Dola Gupta** *(DST Women Scientist, India)*

Company presenting the case study

This case study is presented by Idrica in collaboration with Aguas de Calpe. Idrica is a company specialising in the digital transformation of the water industry, in partnership with Xylem, Idrica leads the development of Xylem Vue, powered by GoAigua. Aguas de Calpe is the company that manages the entire water cycle in the municipality of Calpe.

Introduction

The municipality of Calpe, located on the coast of Alicante, Spain, has a total of 24,000 inhabitants. It is a touristic area, so it experiences a significant seasonal fluctuation of population, reaching a 600% increase in the number of inhabitants in summer.

The urban development of Calpe occurred very quickly in the 1960s. Therefore, several watercourses' floodplains were occupied, and runoff evacuation was not adequately planned. Consequently, the municipality suffers from flooding problems in urban areas and water pollution issues in sensitive areas, such as Las Salinas (wetland of great environmental value) or the touristic beaches.

In this region, flash floods are frequent due to an extreme rainfall regime and orography, where mountains are close to the coast. In addition, this extreme regime has been accentuated in recent years because of climate change. For example, in September 2022, it rained more than 140 mm in 1 hour with tragic consequences as a policeman died while participating in rescue work.

The sewer network of Calpe is a combined system formed by 75 km of pipelines, 17 pumping stations, and two wastewater treatment plants. Several watercourses, usually dry except during heavy rainfalls, cross urban areas.

Objectives

The municipality of Calpe aims to have a system that improves the future management of urban flooding events and flood alleviation by a digital tool, in order to:

- Reduce/mitigate the impact of flooding:
    i) Predicting urban flooding events, determining in advance affected areas, and water levels and their temporal evolution. Alarms are triggered to anticipate mitigation measures. This prediction is based on the integration of rainfall prediction models feeding hydrological–hydraulic models.
    ii) Simulating rainfall scenarios (what if) with real-time network information in order to adapt emergency actions.
- Minimise the impact of overflows from the combined sewer system to water body receptors such as wetlands or beaches during storm events. Overflows occur when the capacity of the network is exceeded, so it alleviates the environment causing pollution issues. Overflow predictions allow the municipality to take mitigation measures in advance.

Intervention through the digital tools

This case study is supported by the tool Real Time - What If Scenarios for Wastewater, which is part of Xylem Vue Value powered by GoAigua.

The solution combines the precipitation forecast with hydrological and 1D-2D hydraulic models in order to predict the areas that could be affected by flooding in the next 24–48 hours. The solution has two main functionalities, depending on the data availability:

- Early Warning Prediction System;
- Real-Time Early Warning System.

The first of these functionalities is being implemented in the municipality of Calpe and provides predictions of urban flooding and flood alleviation for the next 24–48 hours, based on the rainfall prediction (provided by AEMET-weather Spanish Agency) and the results of simulations of the hydraulic model. It is, therefore, required to have a calibrated mathematical model of the sewerage network and urban surface runoff in rainfall events.

The tool provides alarms based on estimated water levels or flow rates at several hotspots defined and configured by the user. Estimations and alarms are shown in a map (Figure 9) as well as in specific graphs for representing the evolution of a variable over the time. In addition, all alarms are shown in a table format (Figure 10).

Real-time sensors are not strictly necessary for this functionality, although its consideration will improve the quality of the predictions. In this sense, it is recommended to have level sensors at least at road underpasses and other vulnerable areas where a large volume of water can accumulate.

On the other hand, the Real-Time Early Warning System functionality, not implemented in this case study yet, is based primarily on real-time sensor data for both sewer levels and rainfall. In this way, the uncertainty associated with weather forecasting is eliminated. However, the predictions made are shorter term (less than 1 hour). The system provides alerts of expected time to flood events, such as manhole overflows or spillways. This estimate is obtained from the mathematical model based on the current water level inside the sewer pipe and the current rainfall intensity, assuming that this intensity is maintained over time. The data is updated with the frequency of the sensor data.

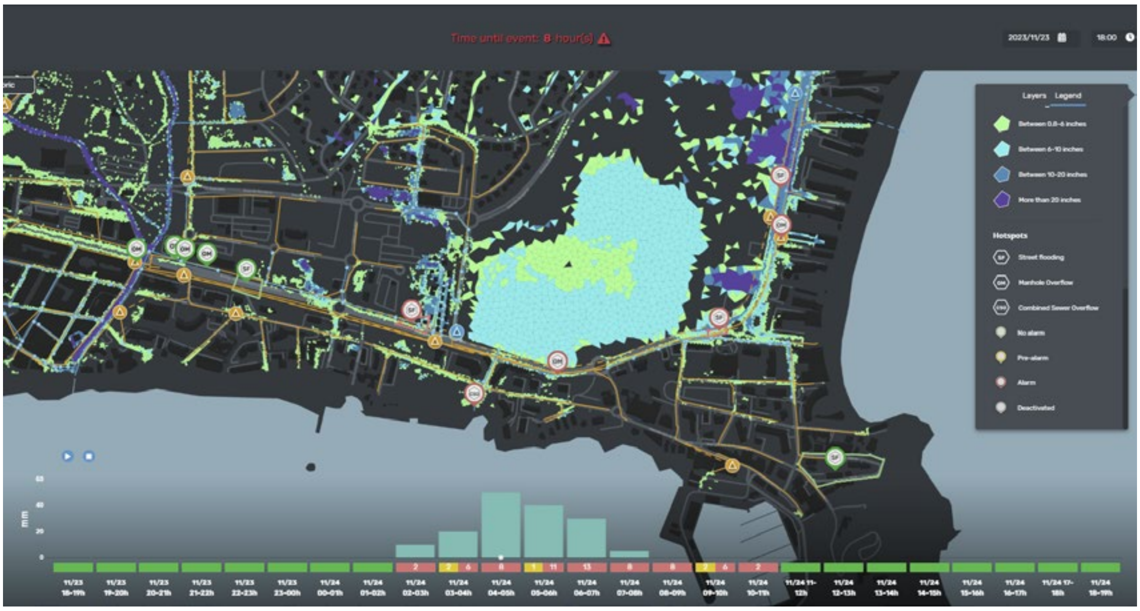
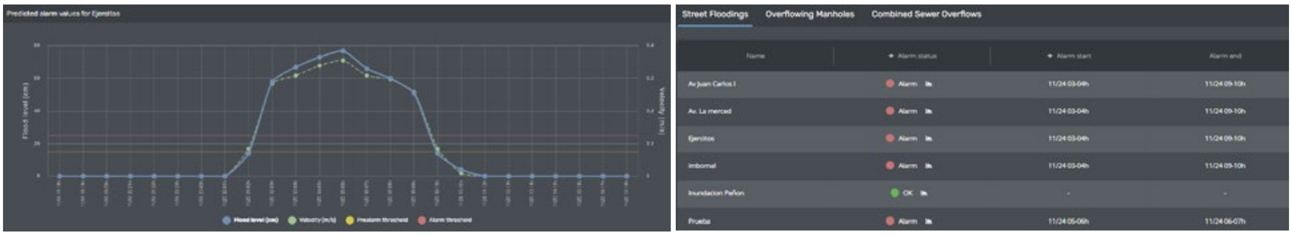


Figure 9: Expected rainfall, water levels and alarms map.



Name	Alarm status	Alarm start	Alarm end
Av Juan Carlos I	Alarm	11/24 03-04h	11/24 09-10h
Av. La merced	Alarm	11/24 03-04h	11/24 09-10h
Ejercitos	Alarm	11/24 03-04h	11/24 09-10h
imbornal	Alarm	11/24 03-04h	11/24 09-10h
Inundacion Peñon	OK	-	-
Prueba	Alarm	11/24 05-06h	11/24 06-07h

Figure 10: Estimated water levels above ground level and alarms table

Conclusion

The main limitations of the capabilities of the tool in the case study of Calpe are:

- Accuracy of the rainfall prediction and hydrological-hydraulic models;
- Limited possibilities of operation in the current sewer network.

In order to improve the rainfall prediction, future developments could use different sources and probabilistic models to consider several flooding scenarios. In addition, historical and real-time data captured by the sensors could be used to automatically modify the parameters of the hydrological-hydraulic models to improve its accuracy.

Based on the capabilities of the present tool, the municipality of Calpe will be able in the future to optimise the performance of the sewer network installing electromechanics equipment controlled in real-time.

Technology's impact on resilience

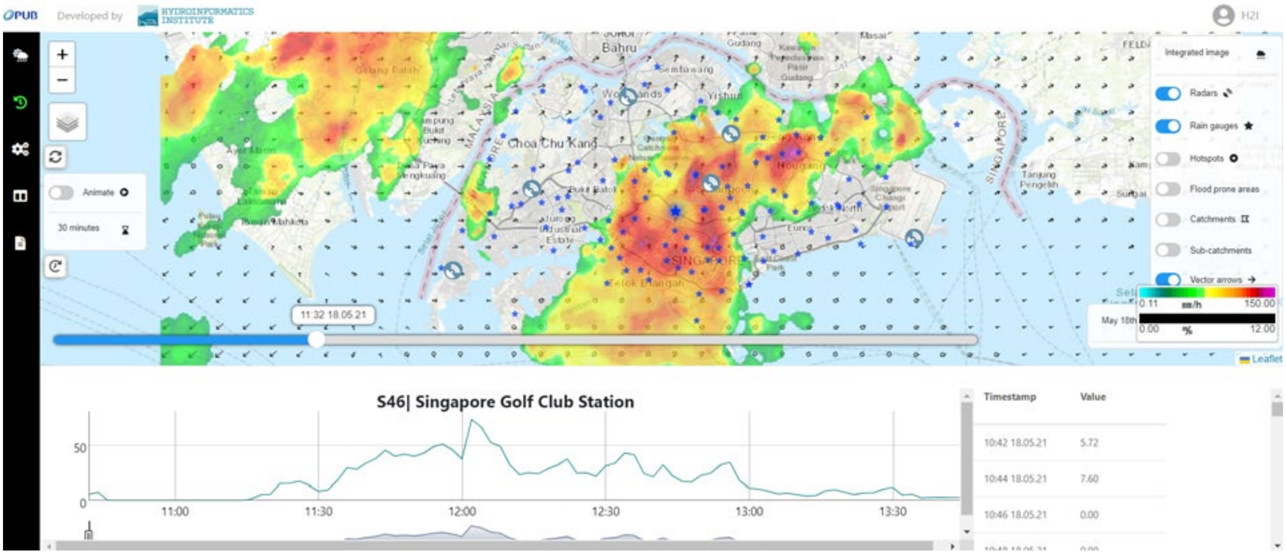
The use of this digital solution will bring in the future a lot of benefits for urban flooding management in the municipality of Calpe, because:

- It will be able to provide prediction of the sewer system performance during rainfall events, determining the potential areas affected, water levels and overflows.

- It will anticipate decision-making and early activation of action protocols.

- The algorithm and information management carried out by the application will be able to improve the decision-making process in the definition of coordinated plans or during their development.

- The system will be more resilient as it can reduce or mitigate negative impacts of urban flooding. In addition, the information captured during every event will be used to improve future predictions and protocols.



Integrated image
● Radars
● Rain gauges
○ Hotspots
○ Flood prone areas
○ Catchments
○ Sub-catchments
● Vector arrows

May 18th
0.11 mm/h 150.00
0.00 % 12.00

Timestamp	Value
10:42 18.05.21	5.72
10:44 18.05.21	7.60
10:46 18.05.21	0.00

Figure 11: Example of the web interface.

3.5. A Multi-Sensor Approach to Precipitation Measurement and Nowcasting for Flood Resilience in Singapore

Munsung Keem *(H2i, Singapore)*, **Gineesh Sukumaran** *(H2i, Singapore)*, **Wei Kit Lee** *(H2i, Singapore)*, **Ni Qing Puay** *(PUB, Singapore)*, **Wing Ken Yau** *(PUB, Singapore)*, **Sara Teh** *(PUB, Singapore)*, **Tien Ser Tan** *(PUB, Singapore)*

Company presenting the case study

This case study is presented by Hydroinformatics Institute (H2i) in collaboration with PUB, Singapore's national water agency. H2i is an organisation at the forefront of applying data science and artificial intelligence to water management and environmental challenges. With a mission to develop impactful solutions, the institute leverages over 9 years of expertise in water management in partnership with PUB and other stakeholders. PUB is a statutory board under the Ministry of Sustainability and the Environment in Singapore, and manages Singapore's water supply, water catchment, and used water in an integrated way. PUB leads and coordinates whole-of-government efforts to protect Singapore from the threat of rising seas and the holistic management of inland and coastal flood risks.

Introduction

In recent years, the world has witnessed a surge in extreme weather events, with floods posing a significant threat to communities and infrastructure. Monitoring and predicting rainfall at high spatiotemporal resolutions in real time is critical to minimising damage during times of flooding, enabling an accurate inundation prediction to allow flooding-defence resources and evacuation efforts to be deployed efficiently. This reduces the risk to the public and infrastructure by providing early warnings of flash floods and/or flood-related information to stakeholders to take more effective flood mitigation and prevention measures.

It is, however, challenging to accurately measure and predict extreme precipitation at the desired resolutions due to their highly variable characteristics in space and time that typical ground rainfall stations (e.g., rain gauges) cannot capture due to their sparsity. In this case study, we (the Hydroinformatics Institute (H2i) and PUB) demonstrated our efforts in tackling this challenge through digital innovations to bolster flood resilience, especially in urban areas: weather radar-based rainfall estimation and nowcasting systems, and closed-circuit television (CCTV)-based rainfall monitoring system. By integrating radar and CCTV technology, the institute aims to enhance work done in precipitation measurement and forecasting.

Objectives

The primary objectives of this case study include:

- Enhancing the accuracy and efficiency of precipitation measurement;
- Improving short-term rainfall forecasting through advanced nowcasting techniques;
- Improve the data quality and quantity for rainfall forecasting and evaluation.

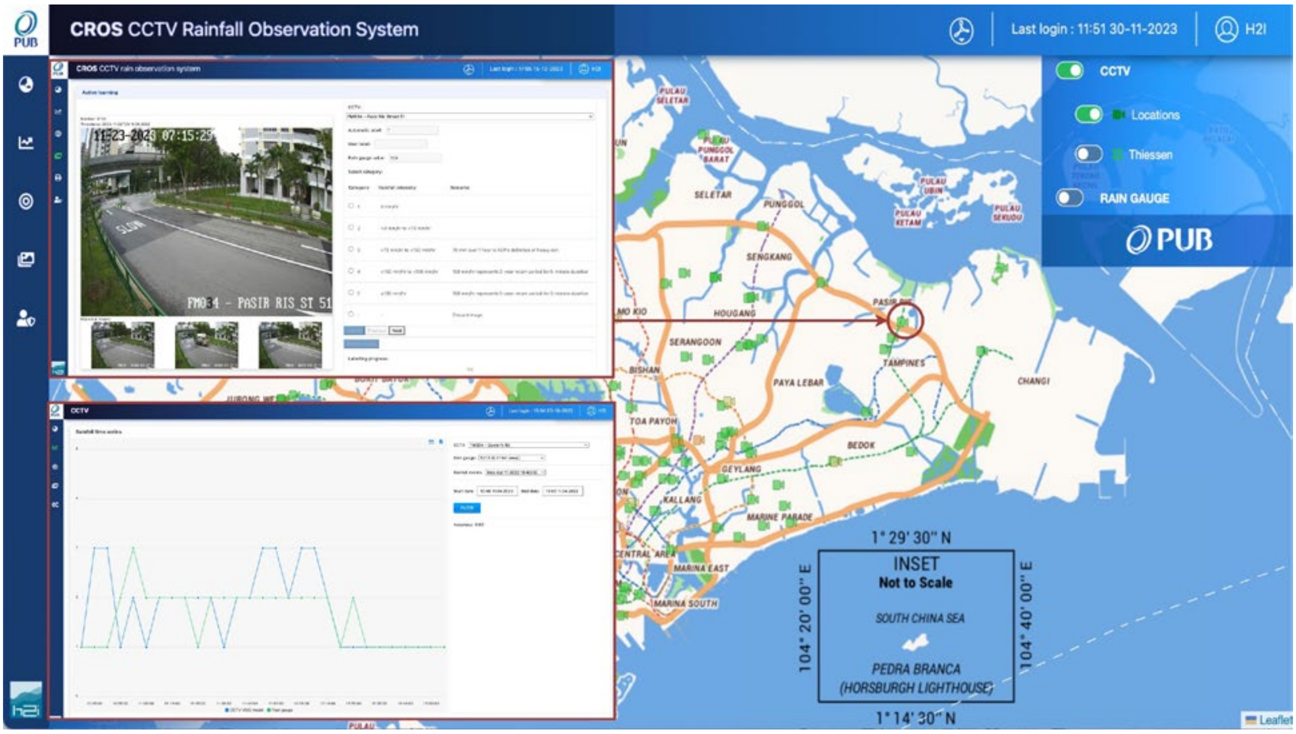


Figure 12: Demonstration of the CCTV-based rainfall monitoring system.

Intervention through digital tools

(i) Radar-based rainfall estimation and nowcasting systems

H2i, in collaboration with PUB, has been developing comprehensive and advanced methods to monitor and predict rainfall using cost-effective and compact X-band weather radars (six in total), which are suitable for complicated urban settings.

Since radar does not directly measure rainfall, but returns signals from targets in the atmosphere, the accuracy of radar rainfall estimation is highly affected by various sources of uncertainty, such as non-precipitation targets, beam blockage, and signal attenuation. Our system consists of multiple algorithms, each of which mitigates each uncertainty source taking advantage of physical relationships among dual-polarimetric radar variables and machine/deep learning technologies. The system developed shows outstanding performance: for example, it shows 91.1% accuracy on average at the ground level in removing non-precipitation radar signals; and the attenuation correction algorithm decreases rainfall estimation errors by 35% on average compared to those derived from the typical rainfall-reflectivity relationship. The monitoring system seamlessly merges multi-radar rainfall estimates into a single comprehensive rainfall map every 2 minutes at 100-metre spatial resolution.

Due to the short flood response time in urban areas (~30 min), the radar-based nowcast model is required to produce nationwide rainfall forecasts for up to the next 90 minutes every 2 minutes. Based on the rainfall maps generated by the monitoring system, the nowcasting model estimates spatially distributed advection vectors of a storm and captures the temporal evolution of rain intensities at a pixel level while tracking the storm movement. The model considers the spatial-scale dependency of rainfall predictability. In addition, its adaptive parameter estimation scheme allows us to consider the precipitation characteristics at the moment of the forecast. The real-time nowcast model achieved approximately 70% probability of detection at the 30-minute lead time at a 2-minute resolution for the past year. The nowcast model also has machine learning functionality. The forecast accuracy is expected to improve over time as more data is collected and the machine learning model is retrained.

All information produced by the system is accessible and visualised in real-time via a web interface, providing early warnings of heavy rainfall, if any, for flood-prone areas and hotspots defined by users. With this system, which gives a more localised forecast, PUB can pinpoint with higher accuracy the specific areas that are likely to experience heavy rainfall. This gives sufficient time for PUB to travel to locations with high flood risks in anticipation of any potential floods, keeping the public out of harm's way.

(ii) Closed-circuit television-based rainfall monitoring system

Many cities operate their own closed-circuit television (CCTV) cameras, mainly for surveillance purposes. In Singapore, such CCTVs are also used by PUB to remotely monitor the road conditions at flood-prone areas and hotspots. This fact motivated us to explore solutions that re-purpose the existing optical sensors network at the ground (i.e. CCTVs) into new sources of rain rate measurements since (1) they can capture rain images at ground level; (2) the records are streamed and accessible in real time without additional cost; (3) the density of the cameras is usually much higher than rain gauges and more so in urban areas.

Due to the low resolution of most CCTV cameras (640 × 480 pixels), we proved the feasibility of the technology in 2020 by classifying rainfall status into five categories: no-rain, light rain, medium rain, heavy rain, and extreme rain based on deep learning technologies, achieving the probability of rainfall detection greater than 82%. Following the results from the feasibility study, the project has been scaled up, providing an operational CCTV-based rainfall estimation system using 150 cameras covering the whole of Singapore. The system has incorporated an active learning framework to automate the data labelling and classification of rainfall from all these CCTV cameras by using computer vision and deep learning. This allows us to reduce reliance on manual annotation as well as to increase the quality and quantity of data. Through the system, the data annotation pipeline, model drift detection, and automated and continuous model retraining are streamlined, contributing to the overall efficiency of the machine learning process.

Conclusion

Real-time rainfall data at high spatio-temporal resolutions are fundamental to the flood-related decision-making processes (i.e. prediction, operation, and evacuation). In this paper, we provided details of two technologies using weather radars and CCTV networks. All systems are built on the cloud and modularised for conveniently scaling up and algorithm parameter adjustments with the functionality of continuous accuracy monitoring and model retraining. For any area of interest, the systems can be efficiently deployed and optimized under given weather and device characteristics. As climate challenges persist, innovative approaches like these are crucial for developing adaptive solutions and building a more resilient future.

Technology's impact on resilience

The technologies described in this case study have contributed to improvements in flood resilience. Weather radars coupled with a nowcasting model and CCTV data can offer an improved understanding of precipitation patterns, enabling better forecasting and real-time monitoring. The active learning system reduces manual effort, streamlining the data processing pipeline and improving overall efficiency. Moreover, radar-based deep learning nowcasting can enhance short-term rainfall forecasting accuracy, enabling better preparedness and response to impending flood events.

This case study contributes to a comprehensive climate resilience strategy, leveraging multi-sensor integration and advanced digital tools. As climate challenges persist, innovative approaches like these are crucial for developing adaptive solutions and building a more resilient future.

Acknowledgments

The CCTV-based rainfall monitoring operational system was developed under the project “Demonstration Project on Improving Rainfall Observation Using Street Level CCTV Cameras in Singapore”, supported by the National Research Foundation (NRF), Singapore, and PUB under its Living Lab (Water) scheme.

4. Key lessons learnt

The critical point we aimed to bring across is that digitalisation and digital tools have a key role to play in building more robust, resilient, and sustainable systems and cities. This is evidenced by the many ongoing applications in this field and case studies, of which only a few were highlighted here, where digital tools help to improve data management; enhance our knowledge and awareness of cities and related systems; introduce smarter and more efficient ways to pre-empt and predict possible scenarios; create more visibility and transparency on how to address these and how to prioritise efforts, resources and so on. The key lessons from this are summarised below:

1. Digitalisation and digital tools in the context of climate resilience are innovative, yet the novelty comes in their application in real practical problems and in utilities. Additionally, more research and development needs to be done to refine and advance these innovations. Therefore, the question should not be "should we" but rather "how should we?" adopt digital tools in this space.
2. Digital innovations are for all, irrespective of geographies, granted that there are differences in readiness hence there should be tailored approaches to adoption. A holistic approach is key to reaping the benefits and ensuring adoption at scale, but one can start with the basics: data and information management.
3. The importance of data and a data-driven approach should be further underscored and certainly provides a key foundational pillar to the adoption of digital tools.
4. There are many examples to draw from across the entire resilience cycle and the ongoing work and innovations are nothing short of astounding. The focus should therefore be on sharing these insights and best practices as well as cross-collaboration to foster adoption (with less risk) at a more rapid pace and larger scale.
5. The case studies have their own strengths/limitations, and an International Advisory Group for Resilience should be immediately formed to share the key lessons learnt and arrive at the best decision results.

5. Conclusions and recommendations

This white paper set out to highlight the role digitalisation and digital tools and innovations can play towards improving flood resilience in cities and ultimately help mitigate the impact of climate change. The broad outlook on resilience in the context of climate change provided here is by no means all-encompassing but rather laid out some key foundational concepts and highlighted some significant gaps in understanding this complex topic and the ramifications for people and places. It also suggested how to connect new and established digital tools that are being used in dealing with resulting extreme weather events such as floods, across the resilience cycle. The case studies presented here are a snapshot of a growing field of innovation, development, and adoption of digital tools in the space of climate resilience. This served as a starting point and a segue to a series of white papers aiming to explore in much more detail and multiplicity this diverse field of climate resilience and digitalisation. The paper sets a stage for a brainstorming session amongst the experts committee to discuss the latest strategies and practices and the future course of action thereof.

References

Baratella, V. J., Costa, C. T. B., Almeida, A. G., da Silva, B. C., & Spadoti, D. H. (2023). Ultra low power water level transmission system using LoRaWAN technology. In: *XLI Brazilian Symposium on Telecommunications and Signal Processing - SBrT 2023*.

Brasil, J. A. T., de Macedo, M. B., de Oliveira, T. R. P., Ghiglieno, F. G., de Souza, V. C. B., Marinho e Silva, G., ... & Mendiondo, E. M. (2022). Can we scale digital twins of nature-based solutions for stormwater and transboundary water security projects? *Journal of Hydroinformatics*, 24(4), 749–764. https://doi.org/10.2166/hydro.2022.142

Catsamas, S., Shi, B., Wang, M., Xiao, J., Kolotelo, P., & McCarthy, D. (2023). A low-cost radar-based IoT sensor for noncontact measurements of water surface velocity and depth. *Sensors*, 23(14), 6314. https://doi.org/10.3390/s23146314

CRED – Centre for Research on the Epidemiology of Disasters & UNISDR – United Nations Office for Disaster Risk Reduction. (2015). *The Human Cost of Weather Related Disasters*. https://www.unisdr.org/2015/docs/climatechange/COP21_WeatherDisastersReport_2015_FINAL.pdf

Davis, I., & Alexander, D. (2015). *Recovery from Disaster*. Taylor and Francis. https://doi.org/10.4324/9781315679808

Degrossi, L. C., de Albuquerque, J. P., Fava, M. C., & Mendiondo, E. M. (2014, July). Flood Citizen Observatory: a crowdsourcing-based approach for flood risk management in Brazil. Proceedings:26th International Conference on Software Engineering and Knowledge Engineering (SEKE 2014) (pp. 570–575).

Downer, M., & Hamilton, Z. (2024). Connectivity in Crisis: The humanitarian implications of connectivity for crisis-affected communities. GSMA. https://www.gsma.com/mobilefordevelopment/blog/connectivity-in-crisis-the-humanitarian-implications-of-connectivity-for-crisis-affected-communities

Drews, M., Steinhausen, M., Larsen, M. A. D., Dømgaard, M. L., Huszti, L., Rácz, T., ... & Schröter, K. (2023). The utility of using Volunteered Geographic Information (VGI) for evaluating pluvial flood models. *Science of the Total Environment*, 894, 164962. https://doi.org/10.1016/j.scitotenv.2023.164962

Erdelj, M., Król, M., & Natalizio, E. (2017). Wireless sensor networks and multi-UAV systems for natural disaster management. *Computer Networks*, 124, 72–86. https://doi.org/10.1016/j.comnet.2017.05.021

Feldman, D., Contreras, S., Karlin, B., Basolo, V., Matthew, R., Sanders, B., ... & Luke, A. (2016). Communicating flood risk: Looking back and forward at traditional and social media outlets. *International Journal of Disaster Risk Reduction*, 15, 43–51. https://doi.org/10.1016/j.ijdrr.2015.12.004

IPCC. (2021). Summary for Policymakers. In: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3−32, doi:10.1017/9781009157896.001.

Joiner, J., Patsioura, C., Borole, S., & White, Z. (2023). IoT for Development: Use cases delivering impact. GSMA. https://www.gsma.com/mobilefordevelopment/resources/iot-for-development-use-cases-delivering-impact/

Keem, M., Goedbloed, A., & Vierstra, M. M. (2021). Leveraging dual polarimetic x-band radar rainfall and nowcast for urban flood management in Singapore. Singapore International Water Week 2021, Singapore. https://www.siww.com.sg/qql/slot/u143/2021/SIWW2021/Attend/SIWW2021%20Online/WC2021%20Poster%20Sessions/WCP.5%20Poster%20Q&A%20Session.pdf

Lowrie, C., Kruczkiewicz, A., McClain, S. N., Nielsen, M., & Mason, S. J. (2022). Evaluating the usefulness of VGI from Waze for the reporting of flash floods. *Scientific Reports*, 12(1), 5268. https://doi.org/10.1038/s41598-022-08751-7

Martens, D., & Carvalho, S. (2023). Digital enablers for enhanced climate resilience. *Smart Water Magazine*. Available at: https://smartwatermagazine.com/news/smart-water-magazine/digital-enablers-enhanced-climate-resilience

Pang, C., Shi, B., Catsamas, S., Shi, X., Wang, M., Fletcher, T. D., ... & Mccarthy, D. (2023, July). Activating lazy stormwater wetlands through real-time monitoring and control. In Novatech 2023. https://hal.science/hal-04184768/

Parsons, O., & Hamilton, Z. (2023). Cell Broadcast for Early Warning Systems: A review of the technology and how to implement it. GSMA. https://www.gsma.com/mobilefordevelopment/resources/cell-broadcast-for-early-warning-systems-a-review-of-the-technology-and-how-to-implement-it/

Persaud, P. P., Hathaway, J. M., Kerkez, B., & McCarthy, D. T. (2024). Real-time control and bioretention: implications for hydrology. *Journal of Sustainable Water in the Built Environment*, 10(1), 04023011. https://doi.org/10.1061/JSWBAY.SWENG-527

Poser, K., & Dransch, D. (2010). Volunteered geographic information for disaster management with application to rapid flood damage estimation. *Geomatica*, 64(1), 89–98. https://doi.org/10.5623/geomat-2010-0008

Restrepo-Estrada, C., de Andrade, S. C., Abe, N., Fava, M. C., Mendiondo, E. M., & de Albuquerque, J. P. (2018). Geo-social media as a proxy for hydrometeorological data for streamflow estimation and to improve flood monitoring. *Computers & Geosciences*, 111, 148–158. https://doi.org/10.1016/j.cageo.2017.10.010

Rumson, A. G., & Hallett, S. H. (2019). Innovations in the use of data facilitating insurance as a resilience mechanism for coastal flood risk. *Science of the Total Environment*, 661, 598–612. https://doi.org/10.1016/j.scitotenv.2019.01.114

Shrestha, M. S., Gurung, M. B., Khadgi, V. R., Wagle, N., Banarjee, S., Sherchan, U., ... & Mishra, A. (2021). The last mile: Flood risk communication for better preparedness in Nepal. *International Journal of Disaster Risk Reduction*, 56, 102118. https://doi.org/10.1016/j.ijdrr.2021.102118

Sukumaran, G., Lee, W. K., Jiang, Y., Keem, M., Parameswaran, S., Fong, S. L., Moskalov, V., Keijzer, M., & Yau, W. K, T.S.Tan (2024). Improving rainfall observation in urban areas: A large-scale study on repurposing CCTV cameras for precipitation measurement Singapore International Water Week 2024, Singapore.

UNDDR - United Nations Office for Disaster Risk Reduction. (2015). United Nations General Assembly Report of the open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction. https://www.undrr.org/publication/report-open-ended-intergovernmental-expert-working-group-indicators-and-terminology

UN DESA - United Nations, Department of Economic and Social Affairs, Population Division. (2019). World Urbanization Prospects: The 2018 Revision (ST/ESA/SER.A/420). New York: United Nations.

Vermij, H. (2023). Is climate change altering trade routes around the world? Businesses should plan for potential trade route changes. Royal Haskoning DHV. Available from: https://www.royalhaskoningdhv.com/en/newsroom/blogs/2023/is-climate-change-altering-trade-routes-around-the-world

Yuan, F., Fan, C., Farahmand, H., Coleman, N., Esmalian, A., Lee, C. C., ... & Mostafavi, A. (2022). Smart flood resilience: harnessing community-scale big data for predictive flood risk monitoring, rapid impact assessment, and situational awareness. *Environmental Research: Infrastructure and Sustainability*, 2(2), 025006. doi: 10.1088/2634-4505/ac7251

Zhang, X., & Li, H. (2018). Urban resilience and urban sustainability: What we know and what do not know? Cities, 72, 141–148. https://doi.org/10.1016/j.cities.2017.08.009

ABOUT THE INTERNATIONAL WATER ASSOCIATION

The International Water Association (IWA) is the leading network and global knowledge hub for water professionals, and anyone committed to the future of water. IWA, which is a non-profit organisation, has a legacy of over 70 years.

IWA connects water professionals in over 130 countries to find solutions to global water challenges as part of a broader sustainability agenda. IWA connects scientists with professionals and communities so that pioneering research provides sustainable solutions.

In addition, the association promotes and supports technological innovation and best practices through international frameworks and standards. Through projects, events, and publications, IWA engages with its members to stimulate innovative ideas and content in support of IWA's vision of a water-wise world.

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