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Near real-time flood risk modelling in response to increasing uncertainties in flood predictions: Insights from the Kakhovka Dam breach in Ukraine

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Abstract

In the face of increasing uncertainties and the expected rise in flood events worldwide, this technical note presents an innovative approach for enhancing rapid response capabilities, exemplified during the Kakhovka Dam breach in Ukraine 2023. Utilizing the Tygron Platform, our methodology combines open-source data with high performance computing for swift hydrodynamic simulations — a departure from traditional flood risk assessment techniques. Central to this approach is the strategic use of social media to gather crowd-sourced feedback during the emergency, enhancing the precision and relevance of flood risk information. During the Kakhovka Dam breach event, our model processed geographic datasets, enabling effective predictions of flood characteristics, including extents, velocities, depths, and arrival times. The near real-time modeling capability allowed for dynamic updates using social media inputs, which were of value for emergency responders to optimize response strategies for relief coordination. While the underlying technology is used for flood simulations, its application in emergency response is novel and promising for more adequate disaster response coordination. However, further research and applications are necessary to refine the approach in order to ensure real-time flood risk information during emergency situations.

Keywords

Hydrodynamic modelling, High-Performance-Computing, Kakhovka dam breach, Crowd-sourced feedback, Climate change adaptation, Emergency response

1 Introduction

Amid increasing uncertainties due to climate change, with heightened risks of floods and unpredictable timings and magnitudes, there is a growing need for a new type of modeling approach. An example of this were the 2021 Summer Floods in Europe (Jonkman et al, 2023). Traditional methods, characterized by long setup times for models, extended durations per simulation, and delays in integrating new insights, are becoming increasingly inadequate. The advent of GPU-accelerated High-Performjance Computing (HPC) and the availability of open data are facilitating the development of models that can rapidly predict outcomes, swiftly incorporate new data, and instantly share results with emergency services and authorities using GIS data (Lavers, 2023; Buwalda, 2023).

In June 2023, such an innovative approach was put to the test during the catastrophic breach of the Kakhovka Dam in Ukraine, a crisis of unprecedented scale that demanded an immediate response to its potentially devastating flood impacts. A specialized team employed these new technologies to assess and model the flood's impact in near real-time (i.e. on the same day of the disaster). This technical note outlines the processes and techniques used, showcasing a significant departure from traditional flood risk management methods and underscoring how this approach significantly aided emergency responders by providing timely and accurate flood impact information.

Through a case study, the authors aim to initiate a discussion on this approach to emergency response, using the recent event as a pivotal learning opportunity and a starting point for a new way to manage disaster responses.

2 Methodology: leveraging high performance computing for real-time modeling

2.1 Rapid hydrodynamic modeling and team coordination

During the Kakhovka dam crisis, the authors utilized the Tygron Platform Water Module, a GPU-based hydrodynamic model (Tygron, 2024). This tool is widely adopted by consultants and water authorities in the Netherlands and internationally. Notably, it facilitates rapid assimilation of big data and generation of accurate, real-time hydrodynamic simulations. The model collects open-source geographic data such as digital elevation, road networks, and waterways to establish a comprehensive environmental model. The inclusion of GPU technology, akin to those used in AI models like ChatGPT, increases the speed of simulations and model building, which in the event of an emergency is very important to get real-time feedback.

Key features of the model:

- **GIS-based modeling:** The Tygron Platform can quickly build a hydrodynamic model from scratch anywhere in the world, significantly reducing the traditional weeks or months of construction to mere minutes. A user simply selects the relevant area, and the Tygron Platform automatically begins retrieving data from various geo-sources.
- **GPU-powered simulation:** Enables the simulation of floods in seconds to minutes, a stark contrast to the hours or days required by traditional methods.
- **2D grid-based shallow water model:** Based on the 2D Saint Venant equations, this model provides predictions about flow velocities, flood depths, and which roads and houses are affected.

Automatic Input Types for the Tygron Platform:

- **DEM:** For Ukraine, NASA SRTM data was automatically selected via ESRI World maps due to the best available resolution for this area.
- **Satellite:** Images also via ESRI World Maps.
- **Land use:** Interpreted from OpenStreetMap (OSM).
- **Topology:** Includes houses, roads also from OSM.

After this automated process (approximately 1 hour) several additional settings were inserted into the model:

- **Initial water levels:** Determined by expert judgment
- **Breach:** location and initial reservoir levels: From web sources and satellite imagery.
- **Initial bathymetry:** for details see chapter 2.3

Coordination and communication in a rapid flood response

Effective flood response requires a blend of technical expertise and real-time communication. Key roles in the workflow included dam breach specialists, hydrodynamic modelers, and emergency sector liaisons. While experts focused on simulating breach dynamics and water flow, the team also played an active role in communicating with emergency responders.

Team members were responsible for explaining key model decisions and updates through social media posts, ensuring that stakeholders could follow the evolving flood situation. A dedicated video on YouTube was created to guide users through the interactive flood viewer, demonstrating its practical application for real-time decision-making (Agerbeek, 2023). This integration of technical modeling with proactive communication enabled emergency responders to make informed choices swiftly and accurately during the Kakhovka Dam crisis.

This streamlined coordination and engagement with the emergency sector highlights the importance of continuous interaction between technical teams and field operators during disasters.

2.2 The Kakhovka Dam breach case

In June 2023, the catastrophic breach of the Kakhovka Dam on the Dnipro River led to extensive flooding in downstream communities, notably Kherson (see Figure 1). This event, initiated by an explosion, necessitated immediate and thorough flood risk assessments to direct emergency responses effectively. (UNEP, 2023; Harpham, 2024).

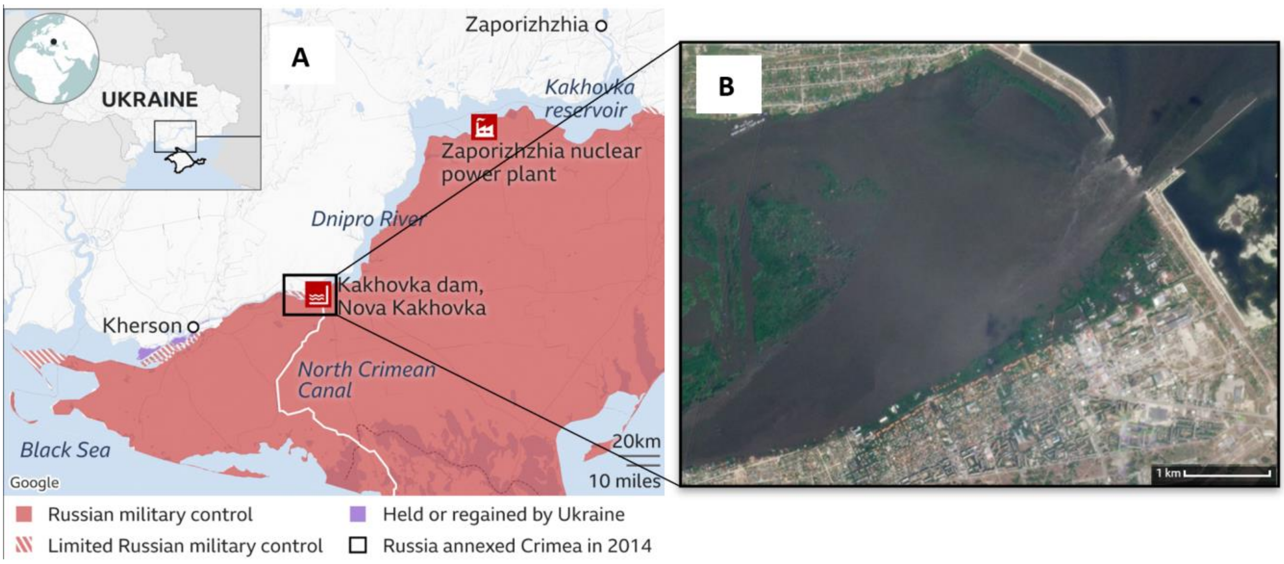


Figure 1: Map showing location of the Kakhovka reservoir, Kakhovka dam and Kherson (A, source: BBC News, 2023); a satellite image on June 6th. (B)

2.3 Model schematization

The flood modeling employed the Verheij-van der Knaap incremental timestep formula for breach simulation (Verheij, 2003; Figure 2). This formula bases the breach growth on observed water levels at the upstream input area and a specified downstream point. Initially, the breach width was set at 200 meters following the initial explosion, expanding to 550 meters within one day as more of the dam collapsed, as seen in news images. Although this formula was originally designed for clay/sand levees, it can be adapted to replicate this expansion by modifying the parameters.

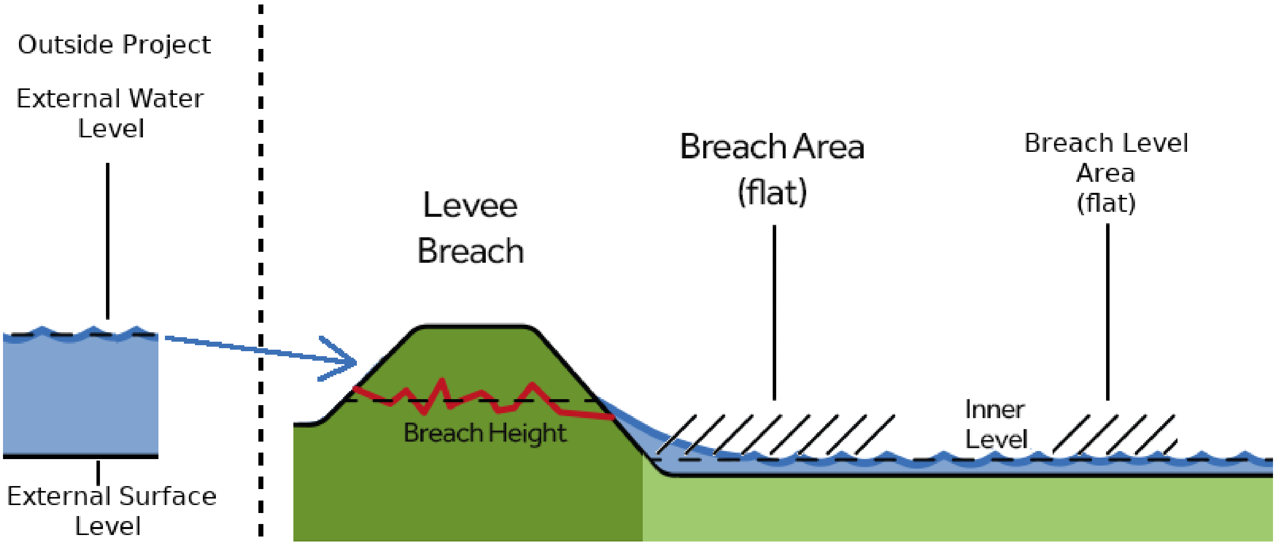


Figure 2: Schematic representation of the Verheij-van der Knaap breach formula in the breach module.

The exact formation of the breach in the hours following the (multiple) explosions is largely unknown and could not be modeled in detail; however, it could be inferred from updated news images taken during the initial hours. It is important to note that the city of Kherson is located 60 km downstream, and peak flood levels were reached after two days, providing sufficient time to create an initial prediction for this city.

- **Topography**: Utilized the NASA SRTM 1 ArcSecond digital elevation model with a grid resolution of 30.92 meters. The model calculated flood results based on an interpolation, downscaling the resolution to 2 by 2 meters using mid-points of grid cells.
- **Bathymetry**: The river bathymetry was created using the known water levels and average river discharge prior to the flood. By conducting multiple simulations with normal discharge, the bathymetry started at the elevation model and was adjusted downward until it aligned with the observed water levels near the dam and downstream around Kherson.
- **Upstream Boundary Conditions**: Modeled as an external reservoir with the capacity matching the reservoir's surface area of 2,155 km². The external reservoir was modeled in a trapezoidal shape to correspond with the length cross-section of the Kakhovka reservoir, which has a width of up to 23 km and a depth ranging from 3 to 26 meters, with an average depth of 8.4 meters. This shape also accounts for the significant initial discharge and the reduced throughput after a few days.
- **Dam Specifications**: The dam's height was modeled at 30 meters with a total length of 3,273 meters, affecting the flood propagation and breach dynamics.
- **Model Settings**: The model settings included a one-hour timestep to capture the rapid changes in flood propagation accurately.
- **Initial Breach Size**: The initial breach size was adjusted based on aerial photo analysis.
- **Manning Value**: The Manning value was increased to account for debris and its significant impact on flow speed and surface resistance. The Manning value varied in the model based on land-use data (ESRI Land Cover, Sentinel 2, 10 m resolution).
- **Infiltration**: The model could also allow water to infiltrate into the soil based on land use, with a maximum infiltration of 50 cm over the entire simulation period.

The flood simulation was conducted at various resolutions, ranging from 20 m to 2 m cell sizes. This approach enabled a rapid feedback loop, starting with a coarse simulation that provided feedback within minutes, followed by more detailed simulations throughout the 20-day flood event. For more information on model schematization: *support.tygron.com/wiki/*

2.4 Calibration and validation

The model results were validated through three methods. These validations were subsequently utilized to further refine and calibrate the model for the next update (refer to Chapter 3 for the process):

1. **Direct feedback**: The model results were posted on social media, leading to feedback from a local environmental engineer in Kherson, who contributed geolocated images from various platforms (shown in Figure 3). These images were shared and geo-tagged using a Google Maps layer (Mykola, 2023).
   By analyzing these pictures, the extent of the flooding can be confirmed, and they also offer insights into the water depth at specific locations. For instance, a photo showing a person standing knee-deep in water indicated an approximate flood depth of 40 cm.

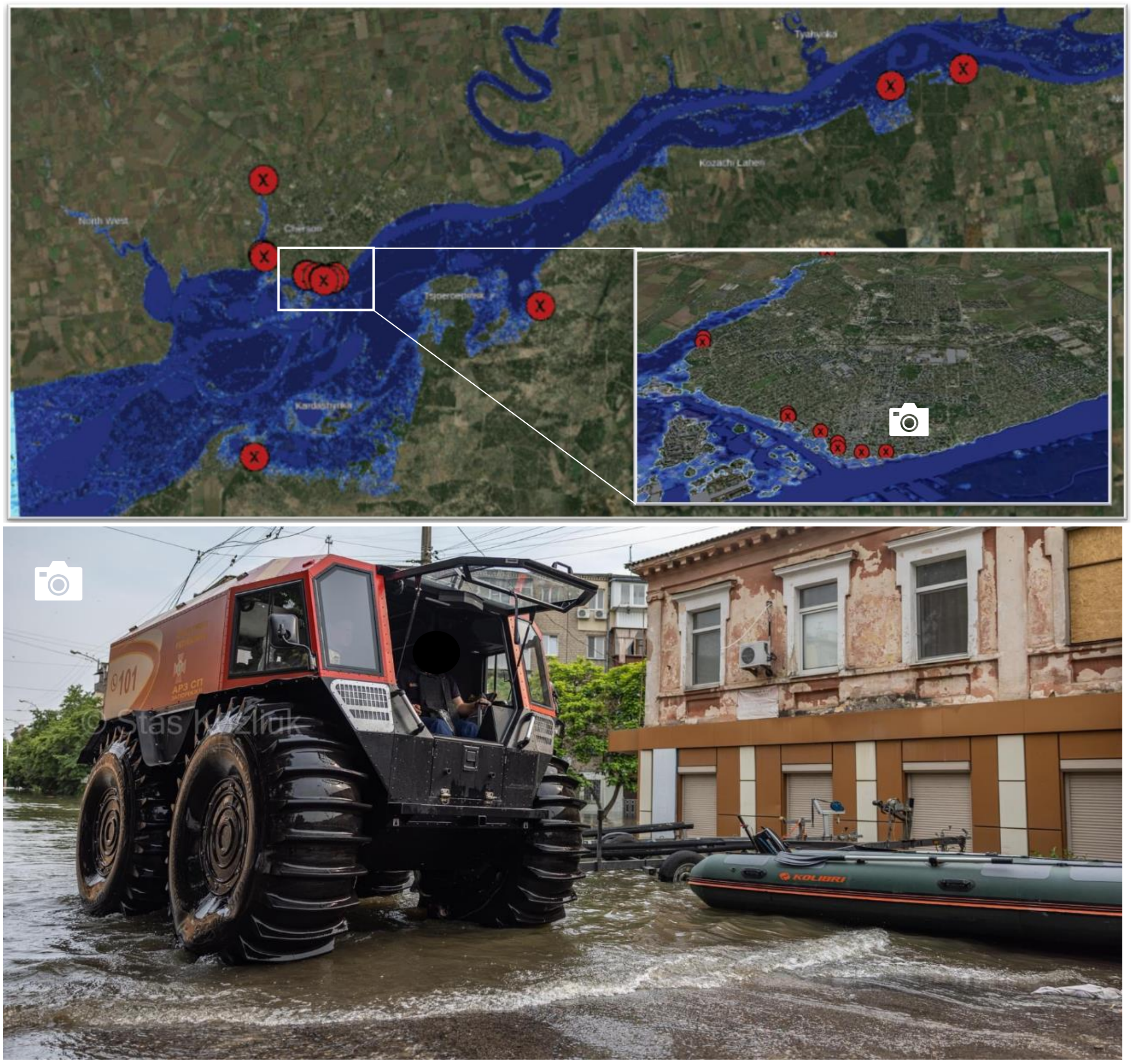
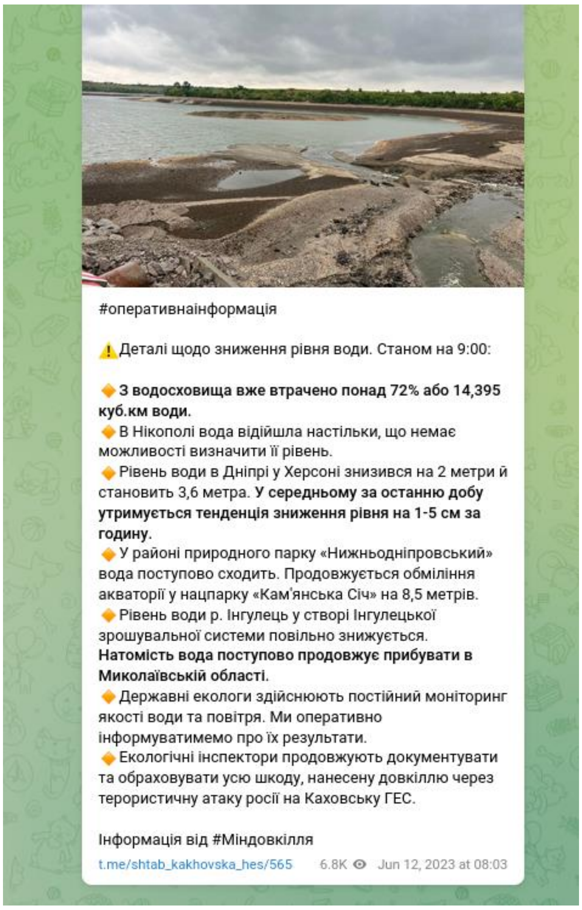


Figure 3: Overview of picture geolocations provided by a local environmental engineer from Kherson, showing the accuracy of the flood model in relation to observed flooding extents and an example of one of the pictures with geolocations.

2. **Daily feedback**: Local authorities in the city of Cherson shared exact water level measurements on social media Telegram (Figure 4) in the city and reservoir. Assumptions were also based on Hydroweb, which published reservoir levels.



#оперативнаінформація

⚠️Деталі щодо зниження рівня води. Станом на 9:00:

🔶**З водосховища вже втрачено понад 72% або 14,395 куб.км води.**
🔶В Нікополі вода відійшла настільки, що немає можливості визначити її рівень.
🔶Рівень води в Дніпрі у Херсоні знизився на 2 метри й становить 3,6 метра. **У середньому за останню добу утримується тенденція зниження рівня на 1-5 см за годину.**
🔶У районі природного парку «Нижньодніпровський» вода поступово сходить. Продовжується обміління акваторії у нацпарку «Кам'янська Січ» на 8,5 метрів.
🔶Рівень води р. Інгулець у створі Інгулецької зрошувальної системи повільно знижується. **Натомість вода поступово продовжує прибувати в Миколаївській області.**
🔶Державні екологи здійснюють постійний моніторинг якості води та повітря. Ми оперативно інформуватимемо про їх результати.
🔶Екологічні інспектори продовжують документувати та обраховувати усю шкоду, нанесену довкіллю через терористичну атаку росії на Каховську ГЕС.

Інформація від #Міндовкілля

t.me/shtab_kakhovska_hes/565 6.8K Jun 12, 2023 at 08:03

Translation:

#OperationalInformation

⚠️ **Details on water level reduction. As of 9:00 AM:**

- **From reservoirs, more than 72% or 14,395 cubic kilometers of water has already been lost.**
- **In Nikopol, the water has receded so much that it is impossible to determine its level.**
- **The water level in the Dnipro in Kherson has dropped by 2 meters and now stands at 3.6 meters. On average, over the past day, the tendency of the water level to decrease by 1-5 cm per hour persists.**
- **In the area of the "Nyzhnodniprovskiy" nature park, water continues to recede. The exchange of the water area near "Kamianska Sich" at 8.5 meters is ongoing.**
- **The water level in the Inhulets River near the Inhulets irrigation system is slowly decreasing. Instead, the water continues to arrive in the Mykolaiv region.**
- **State ecologists are monitoring the condition of water and air. We will promptly inform about the results.**
- **Environmental inspectors continue to document and assess the scale of damage caused by the Russian attack on the Kakhovka Hydroelectric Station.**

Figure 4: Telegram post from local authorities with flood levels, (translated on the right).

3. **After three days**: The model's outputs were validated against ICEYE satellite results, providing a comparison of simulated and observed flood extents in a web viewer (Link to the webviewer showing the results of Tygron and the imagery of the ICEYE satelite: https://tygron.maps.arcgis.com/apps/webappviewer/index.html?id=4d454f03a32243b8bd3e6c9093c6fc99). Blue is the modelled results and red the ICEYE results (Figure 5).

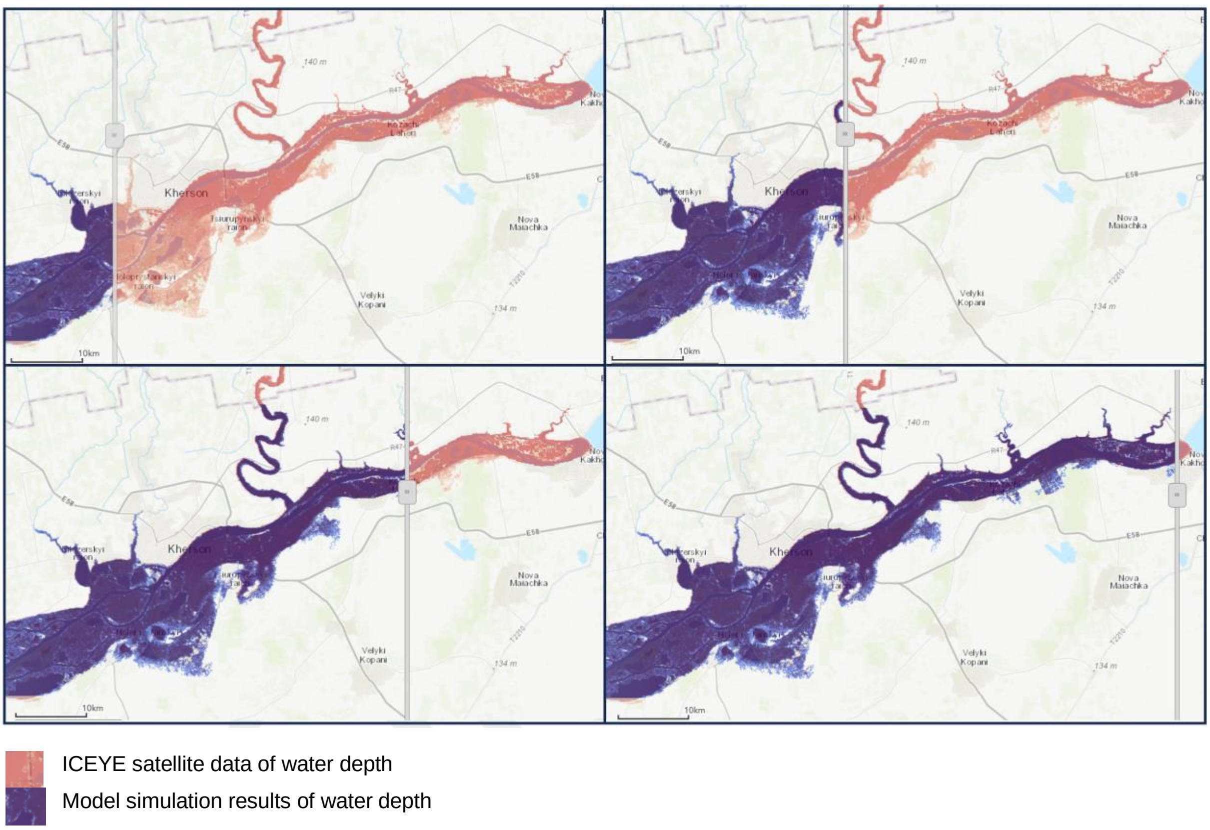


Figure 5: Comparison of modeled flood depths with ICEYE satellite results.

By utilizing these three feedback loops, the model could be further calibrated by adjusting the trapezoidal shape of the reservoirs, the Manning roughness of the riverbed, and the size of the dam breach. The initial iteration indicated a lower water level (~40cm) than anticipated based on the social media images, which was attributed to additional dam collapses.

After several iterations, the model closely matched the measured values: for Cherson, a measurement of 5.6m was recorded compared to 5.5m in the model, and near the dam, the model showed 11.9 m against a measured level of 12.1 m. Experts from Deltares were also able to estimate the water speed (based on debris observed in video images) at approximately 6 m/s, while the model indicated a speed of 5.7 m/s. Additionally, the ICEYE satellite results indicated a flooding extent that closely matched, which can be seen in the web viewer. The extent of the flooding was also validated using social media images of side rivers, which illustrated how far the flood was noticeable.

After three days, the model was deemed stable and capable of predicting an additional 17 days into the future (for a total simulation time of 20 days). This was particularly useful for emergency workers who needed to know when and where road access to flooded villages would be restored and where water puddles could form, potentially becoming a source of diseases.

2.5 Model results

The model provided hourly simulated results, projecting flood characteristics such as arrival times, discharge rates, water depths, and velocities for up to 20 days into the future. It also identified roads that would become impassable when water depths exceeded 40 cm or when velocities increased significantly. These hourly updates were crucial for real-time decision-making and were accessible through an interactive web viewer. A lite-version of the model results can be viewed via this link: https://geo.tygron.com/share/tygronrd/ua/cherson5/?token=2fQOQUcVF7AxfwicSZ4JBQlS0TubYS00

For a visual representation of the arrival time predictions and non-accessible roads, refer to Figure 6, which illustrates how this specific result was displayed on the web viewer interface.

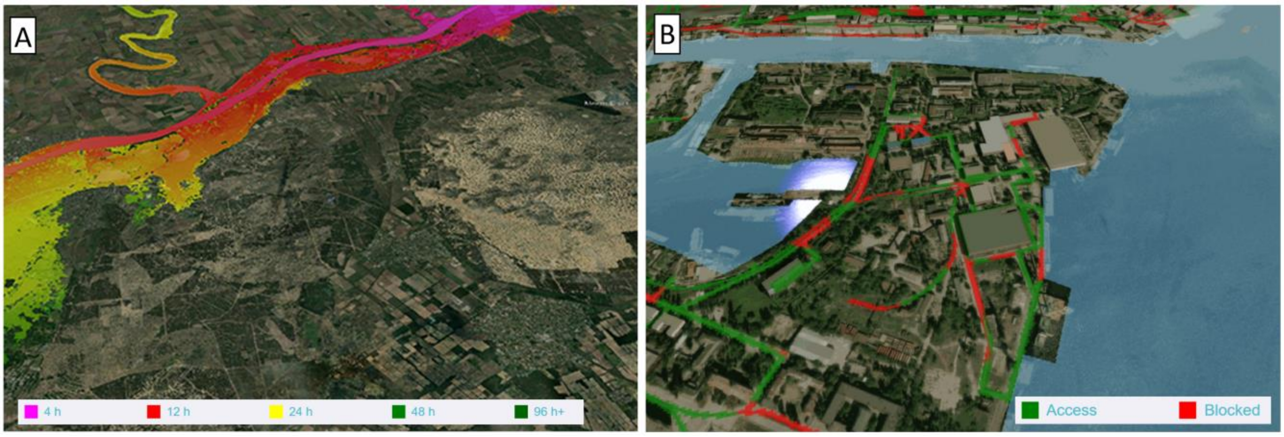


Figure 6: Simulation showing the arrival time of the flood event (A); Simulation results showing non accessible roads during a timestep (B).

3 Crowd-sourced flood validation and insights for emergency response

3.1 Integration of crowd-sourced feedback in modeling effort

The integration of crowd-sourced feedback played a key role in validating the flood simulation model. One notable feature was the real-time dissemination of model results through a web viewer on social media platforms, which extended the model's reach and provided valuable insights for emergency responders. Local Ukrainian experts, including environmental engineers, contributed feedback that significantly improved the model’s accuracy. Based on this feedback, the team iteratively refined the model, enhancing its effectiveness for emergency response. Figure 7 presents a flowchart of this process:

- Data was initially collected from a variety of sources including literature, open-source data, news articles, Wikipedia, and social media posts.
- This data underpinned the assumptions used in setting up the model.
- Model results were shared on social media and a geographic information web viewer, along with public GIS data, such as geolocations provided by a local environmental engineer.
- Feedback from various stakeholders on social media informed subsequent adjustments to the model and assumptions.
- Valuable feedback led to further model refinement and additional analyses, such as identifying inaccessible roads and estimating flooding durations in specific areas.
- This ongoing feedback loop continually enhanced the model and supported a robust validation process, requiring a transparent approach to sharing progress with the public.

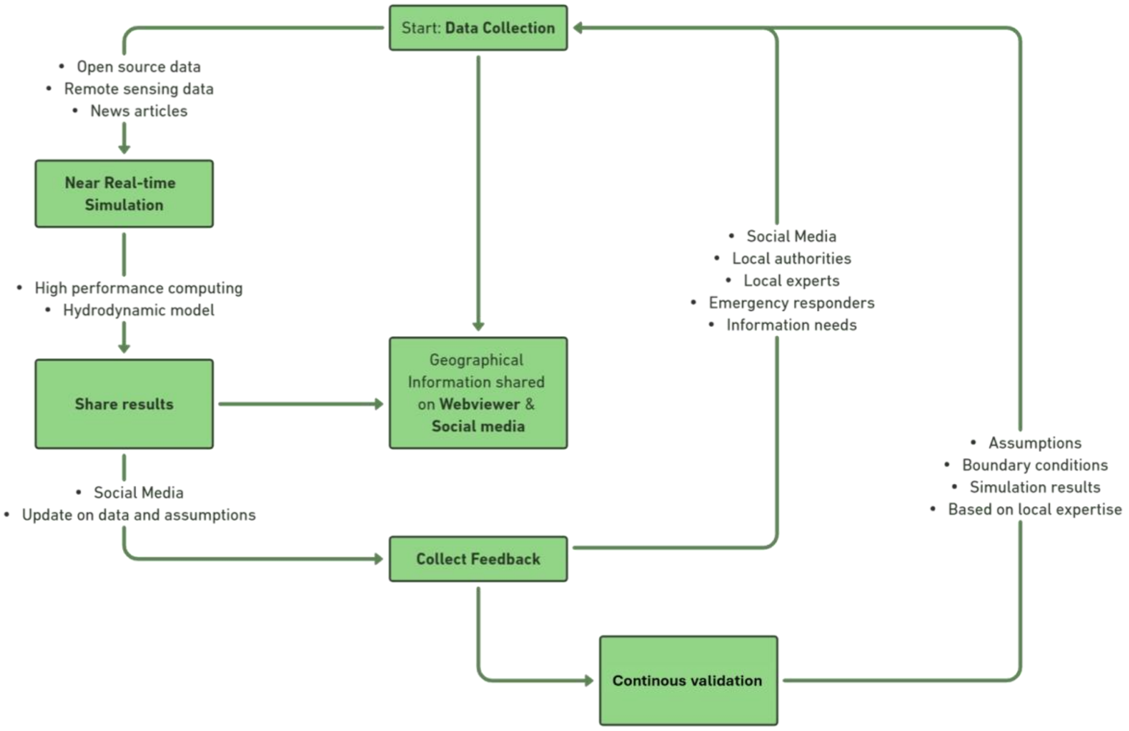


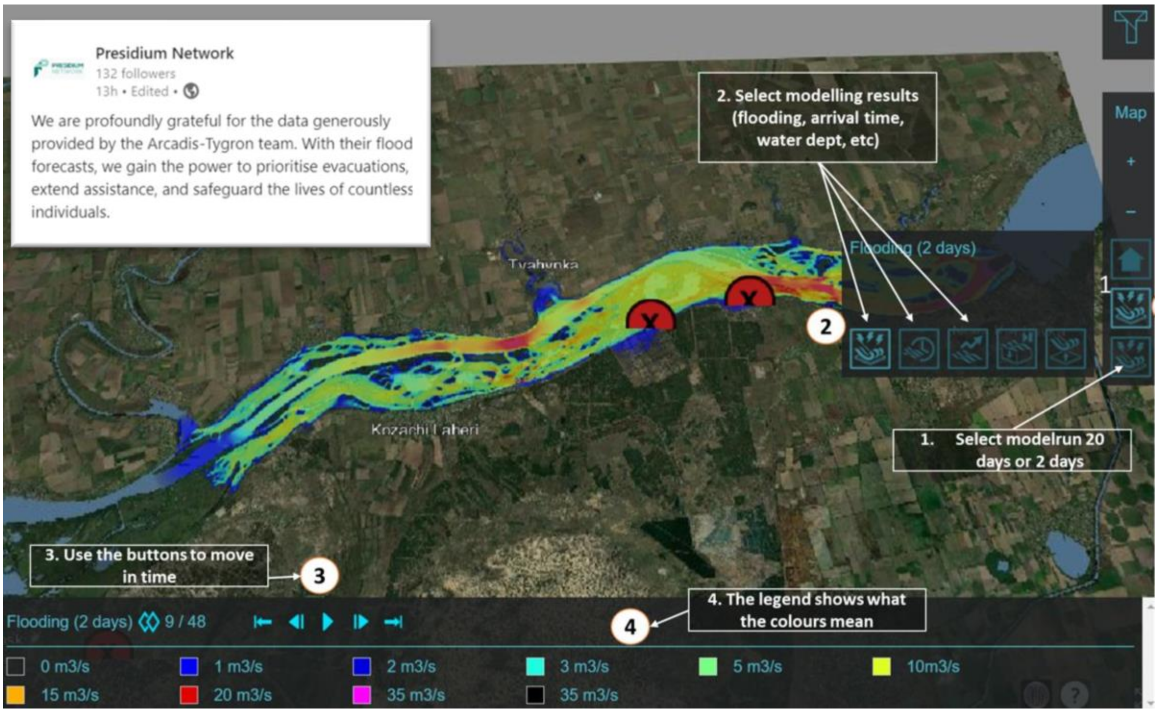
Figure 7: Flowchart describing the process of integrating crowd-sourced feedback in providing accurate and relevant flood risk information.

3.2 Support to emergency response: real-time access to flooding information

The modeling process, designed for rapid response, automatically collected relevant data such as digital elevation models (DEM), satellite images, and land-use data. This allowed the team to complete the initial setup within approximately one hour. By the evening of the same day as the dam breach, the first model run was executed.

Daily iterations followed, incorporating new information and feedback from various sources, including satellite updates, social media posts, and real-time observations. One key update came three days after the initial breach when ICEYE satellite data became available. This data allowed for a detailed validation of the model, as discussed in Section 2.3 (Calibration and Validation). The comparison of simulated flood extents with ICEYE observations improved the model’s accuracy and provided a better match to real-world conditions. Figure 4 highlights how well the model predictions aligned with observed flooding, demonstrating the value of integrating satellite data in near real-time.

The ICEYE data, along with crowd-sourced information from social media, further refined the model, enhancing its accuracy over time. Updates on model changes and results were shared publicly through social media, including posts from the Presidium Network (Figure 8), which highlighted how the flood forecasts aided in coordinating evacuations and field assistance. The simulation data, accessible through an interactive web viewer, provided emergency responders with timely and reliable flood risk information, enabling them to make informed decisions during the critical stages of the crisis (also shown in Figure 8). During the emergency response period, the authors engaged with NGOs such as the Impact Collective and UNICEF, as well as network organizations like the Ukraine Water Platform, as well as local government organizations such the Dutch Embassy in Ukraine. Moreover the information was shared in a professional network via LinkedIn.



Presidium Network
132 followers
13h • Edited •

We are profoundly grateful for the data generously provided by the Arcadis-Tygron team. With their flood forecasts, we gain the power to prioritise evacuations, extend assistance, and safeguard the lives of countless individuals.

2. Select modelling results (flooding, arrival time, water dept, etc)

1. Select modelrun 20 days or 2 days

3. Use the buttons to move in time

4. The legend shows what the colours mean

Figure 8: Web viewer with explanation and an example of a post by an NGO that coordinates emergency response.

4 Discussion

This case study exemplifies a successful application of technology that could potentially shift the paradigm of flood risk management and emergency response. Traditional approaches, which typically rely on pre-event scenario analyses based on historical data, often fail to align with real-time events due to increasing uncertainties brought about by climate change (Sayers, 2022; Grigorieva & Livenets, 2022). Climate change leads to more frequent and severe weather events that deviate from past patterns, making predictive models based on historical data less reliable. The limitations of traditional methods are evident as they cannot accurately predict unforeseen variables such as the exact locations of extreme rainfall, the specifics of dike failures, or the precise points of breach. Such unpredictability necessitates a flexible and dynamic response. In contrast, the technology employed in this study allows for rapid model construction and analysis within a few hours, making the results immediately actionable and better suited to addressing the challenges posed by a changing climate.

However, while this modeling effort facilitated an ad-hoc, real-time simulation providing accurate and immediate insights during the emergency, it also underscores the need for more experience and enhanced preparedness for handling large-scale disasters. Access to and utilization of detailed source data—enabled by technologies such as daily satellite observations—are crucial, but this raises important questions about data management, such as how to ensure the timely availability of high-quality data, how to process and integrate diverse datasets efficiently, and how to maintain data accuracy under time constraints. Based on our experience, the authors recommend establishing standardized protocols for data handling that include predefined data sources, automated data retrieval systems, and real-time data validation techniques.

Ensuring that data are readily available and actionable involves developing strategies for data readiness and integration. This includes setting up data pipelines in advance to automate the collection and preprocessing of essential datasets like topography, land use, and hydrological parameters. By doing so, the time required to initiate modeling during an emergency can be significantly reduced.

To effectively respond to large-scale emergencies, significant requirements exist for well-prepared teams. Such teams must be always ready to anticipate and react to unfolding events. This necessitates clear roles and responsibilities for creating, validating, and communicating system updates during crises. Ensuring that a resolute team of high-caliber experts, who not only operate the system but also deeply understand the input data's granularity and the model's predictive accuracy, is crucial. These professionals are essential for accurately assessing results and providing meaningful interpretations.

Moreover, establishing an effective process to gather feedback is vital. In our case, leveraging social media and engaging with local experts provided invaluable real-time data that enhanced model accuracy. The authors recommend creating dedicated communication channels or platforms to facilitate the collection of crowd-sourced information during emergencies.

Informing key actors during emergency situations is another critical aspect. Pre-establishing connections with emergency response organizations and setting up protocols for information dissemination can ensure that vital model outputs reach decision-makers promptly. Developing interactive platforms, such as web-based GIS viewers, in advance can facilitate this process, allowing stakeholders to access and interpret the data efficiently.

The ongoing challenge in emergency management technology involves facilitating the swift and accurate integration of new model insights. This process of validation and verification is critical to ensuring that the models stay relevant and reliable as the situation evolves. Continuous operation of the system is imperative. The ability to adjust to new insights quickly—integrating fresh data and recalibrating predictions—requires a full-time commitment. This commitment ensures that the system remains a robust tool in the arsenal of emergency response strategies, capable of adapting to and effectively managing the dynamics of a crisis.

For future research and development, key challenges include enhancing data integration methods, improving real-time modeling capabilities, and developing user-friendly interfaces for both data input and output dissemination. Refining modeling structures to accommodate various types of flood events and optimizing computational efficiency are also important areas to explore.

This discussion not only highlights the need for flexibility and adaptability in emergency response strategies but also emphasizes the importance of leveraging the latest technological advancements, including social media, to enhance the responsiveness and efficacy of disaster management efforts. By addressing these requirements and challenges, future applications can become even more effective, ultimately contributing to better preparedness and response in flood risk management.

5 Conclusions

The Kakhovka Dam breach demonstrates a successful case where real-time flood risk information was effectively shared with emergency responders. Leveraging high performance computing, open-source data, including insights from crowd-sourced social media feedback, the authors were able to deliver precise and timely information during the crisis, which was of use for effective disaster response.

However, the deployment also highlighted the need for improvements. Effective disaster response not only requires access to detailed flood risk data but also systems capable of integrating this information swiftly to adapt to the rapidly evolving nature of emergencies. In our implementation, the authors optimized data management processes by establishing automated data collection and processing workflows. This included setting up data pipelines that continuously gathered and updated essential datasets such as DEMs, satellite imagery, and hydrological data. The authors utilized high-performance computing to process and integrate these large datasets efficiently, allowing for rapid model updates. Additionally, the authors applied real-time data validation and integration, ensuring that new information via the emergency community and social media could be seamlessly incorporated into the model as it became available during the emergency.

Moreover, the necessity for well-prepared response hydrology teams is evident. These teams must be experienced with the hydrodynamic model and possess a thorough understanding of the data and expert judgement to manage the complexities of real-time information delivery during disasters.

This case study highlights the potential of near-real-time modelling approaches in disaster management but also calls for ongoing efforts to refine this approach for better real-time communication of flood risks to emergency responders.

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Author contributions (CRediT)

Bas Agerbeek[1]: Conceptualization, Investigation, Methodology, Resources, Validation, Writing first version Visualization, Writing – review & editing. Maxim Knepflé: Methodology, Resources, Software, Validation. Florian Witsenburg[3]: Conceptualization, Methodology, Resources, Validation, Visualization. Bas Jonkman[4]: Conceptualization.

Data access statement

The data acquired in the study and used/analyzed/reported in this paper can be shared with by contacting the authors.

Declaration of interests

The author reports no conflict of interest.

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