An Impact-Based Flood Forecasting System for Citizen Empowerment

Alfredo Mahar Francisco Lagmay[1,2], Gerry Bagtasa[3], Dinnah Feye Andal[4], Fritz Dariel Andal[4], Janice Aldea[4], Dianne Charmaine Bencito[4], Kenneth Liporada[4], and Patricia Anne Delmendo[4]

[1]Executive Director, University of the Philippines Resilience Institute (UPRI), Diliman, Quezon City, Philippines; [2]UP National Institute of Geological Sciences, Diliman, Quezon City, Philippines; [3]UP Institute of Environmental Science & Meteorology, Diliman, Quezon City, Philippines; [4]UPRI

ABSTRACT

This work addresses the critical issue of flooding, a significant natural hazard, consistently ranked highest in the 2023 World Risk Index. The annual onslaught of tropical cyclones and the associated abnormal rainfall threaten lives, and destroy crops and property, thereby causing great economic damage, demanding urgent and science-based decision-making. We introduce an impact-based flood forecasting system as a proactive anticipatory action (i.e., AA) measure, linking climate services and disaster risk management to mitigate extreme weather impacts. Developed by the University of the Philippines Resilience Institute, the National Operational Assessment of Hazards (NOAH) Center, and Gerry Bagtasa of the Institute of Environmental Science and Meteorology, this system advances disaster resilience efforts, leveraging science-based forecasts to prioritize vulnerable *barangays* (villages). Unlike traditional early warning systems, the proposed automated system predicts flooding one day in advance and assesses exposure levels based on population distribution. By utilizing global weather forecast models locally calibrated for Philippine conditions and 100-year rain return flood hazard maps for the Philippines, the system forecasts river inundated areas, enabling local government units (LGUs) and humanitarian organizations to prioritize preparations for communities and allocate resources during flooding events effectively. This system enhances the efficiency of disaster response planning, fostering a proactive and impactful strategy to address the recurring threat of flooding in the country. The system also underscores the role of open data in disaster resilience, exemplified by NOAH's system to disseminating big data, which aligns with open governance principles. By encouraging transparency and stakeholder collaboration, data exchange is promoted, providing actionable

Keywords: flooding, anticipatory actions, disasters, open data
JEL codes: Q54, Q25

Asian Journal of Agriculture and Development (AJAD)
Vol. 21 | 20th Anniversary Issue October 2024
Complete Lineup

Contact A.M.F. Lagmay ✉ aalagmay@up.edu.ph https://doi.org/10.37801/ajad2024.21.20AI.8

information that fosters collaboration between the LGUs, humanitarian organizations, and other stakeholders. Cognizant of the importance of community engagement in disaster resilience, the newly developed impact-based flood forecasting system encourages community involvement by providing easily accessible information, which can be used to validate the forecasts based on local knowledge and experience. This research contributes to the urgent call for anticipatory action in the face of escalating extreme weather events globally.

INTRODUCTION

Flooding, triggered by extreme weather events, is one of the most devastating natural hazards globally, posing a substantial threat to human life and economic stability through tremendous damage to crops, livelihoods, infrastructure, and property. From 1900 to 2015, over USD 7 trillion worth of economic losses have been incurred, with approximately 40 percent attributed to flooding events (James, Friedemann, and Schaefer 2016). The Philippines experiences an annual precipitation of 965 to 4,064 mm, and accompanying floods damage hundreds of thousands of hectares of crop lands yearly. As global temperatures continue to rise, the likelihood of severe weather events escalates, leading to abnormal rainfall patterns in the future (IPCC 2018).

Additionally, the 2023 World Risk Index Report (Bündnis Entwicklung Hilft 2023) ranks the Philippines first in the list of countries most affected by extreme weather events. Around 20 tropical cyclones enter the Philippine Area of Responsibility (PAR) each year, which comprises more than 25 percent of the typhoons that enter PAR, making landfall, and potentially causing floods and other related hazards. These events are recurrent during the wet season, owing to the influence of the southwest monsoon, spanning July to November across the Philippines, excluding the southern region (Matsumoto et al. 2020). These result in the loss of lives and properties, impeding economic progress. Consequently, there is an imperative need for swift and science-based decision-making to assess inundated areas, prioritizing considerations of public safety and environmental sustainability (Lagmay and Racoma 2018).

Anticipatory actions (AA), forecast-based financing (FbF), and forecast-based action (i.e., FbA), build upon climate services (Hansen et al. 2022) to forecast extreme weather events and their corresponding impacts, thus facilitating actions for the communities. The AA systems allow actions between the forecast and the predicted disaster to mitigate the hazard's impact on the communities (Coughlan de Perez et al. 2014). Through AA, actions and responses are prepared, actions and areas are identified based on science-based forecasts, and funding is guaranteed in advance (Anticipation Hub 2022).

While the Philippines currently lacks a government-led, streamlined platform for AA, the University of the Philippines Resilience Institute (i.e., UPRI), through its core component, the UP Nationwide Operational Assessment of Hazards Center (UP NOAH Center) and the Academic Alliance on Anticipatory Action (i.e., 4As), is forging ahead with an impact-based flood forecasting system, which is integrated into the NOAH website (Lagmay et al. 2017). It represents a significant step forward in disaster resilience and is firmly rooted in the principle of AA, a critical approach to mitigate the impact of disasters proactively.

The system can predict flooding in specific regions based on the country's accumulated rainfall forecast and 100-year rain return flood[1] hazard maps. By utilizing data from global forecast models locally calibrated to account for the country's

---

[1] The term "100-year rain return flood" is used in an attempt to simplify the definition of a flood that statistically has a one percent chance of occurring in any given year. In the Philippine context, because of the scarcity of river flood gauge data, the return period of the rain, as determined from rainfall intensity duration frequency (i.e., RIDF) by the Philippine Atmospheric Geophysical and Astronomical Services Administration (PAGASA), is used instead to approximate the return period of the flood (DPWH and JICA 2003).

geographic and meteorological conditions, the system allows disaster managers to accurately monitor and identify potential river inundation areas at the local level, at least a day in advance.

Unlike general early warning systems, the system will be able to determine which barangays will most likely be affected by flooding based on the rainfall accumulation forecast and probabilistic flood hazard maps and identify their exposure levels based on their population. The LGUs and humanitarian organizations can use the system and include data to determine which communities must be prioritized during flood events. Furthermore, these organizations can use the information to estimate flood damage in a *barangay* (village) and calculate the resources needed for disaster response allocation. Although the current system is for risk assessment of exposed populations, the same system can easily be converted to an impact-based flood forecasting financing system that can be used to provide aid or advanced insurance payments to those that will incur property damage and/or agricultural losses.

METHODOLOGY

The methodology employed in this research is designed to comprehensively address the impact of flooding in the Philippines through a multifaceted approach. The process involves the simulation of hazards, rainfall forecasting, preparation of population data, a thorough assessment of the exposed population, and seamless integration of the system into the UP NOAH website. Each step is crucial in developing a robust understanding of flood risk factors to implement AAs effectively. This section details the systematic procedures undertaken to achieve accurate hazard simulations, reliable rainfall forecasts, population-centric data preparation, and the subsequent assessment and integration processes, contributing to a holistic methodology for enhancing disaster resilience.

Simulation of Hazards

Catchment delineation

The river and stream systems within the river basins are interdependent, and each river basin should be modeled to represent the water flow accurately. The boundaries of the river basins were generated by analyzing the digital elevation model (DEM). DEM obtained through LiDAR or IfSAR technology[2] was used to create shapefiles of streams and catchments. The size of the catchments depends on the volume of water the stream can drain. The catchment shapefiles were used to delineate the boundaries of the river basins.

The entire river basin is subdivided into smaller watersheds, with the water flowing generally in one direction to account for the limitations of the software capabilities and overall simulation time.

Data preparation

Factors such as rainfall, soil characteristics, and land cover affect the amount of water and overland flow for flood modeling. Elevation is important, as it dictates the flow direction, speed, and water accumulation.

Simulation of models

Flo-2D GDS Pro is the modeling software used for flood simulations. The volume conservation flood-routing software generates flow depth and flood hazard maps. It uses the Saint-Venant continuity and dynamic wave momentum equations to quantify the flow of water across the model area:

$$\frac{\partial h}{\partial t} + \frac{\partial hV}{\partial x} = i \tag{1}$$

$$S_f = S_o - \frac{\partial h}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \tag{2}$$

---

[2] LiDAR - light detection and ranging; IfSAR- interferometric synthetic aperture radar

where h is flow depth, t is time, V is the depth-average velocity in one of the eight flow directions x, S_f is friction slope component based on Manning's equation, S_o is bed slope pressure gradient, and g is the acceleration due to gravity.

Rainfall Forecasts

Rainfall forecasts are based on the Global Forecast System (GFS) of the National Centers for Environmental Prediction of the US National Oceanic and Atmospheric Administration (NOAA). The GFS is the operational global forecast model of NOAA that uses coupled atmosphere-ocean, land/soil, and sea-ice models to generate forecasts of short-term (~2 weeks) weather conditions. The GFS forecast is downscaled for the Philippine domain using the Weather Research and Forecasting (WRF) model (Skamarock et al. 2008) from a 27 km x 27 km grid of the global GFS model to a 3 km x 3 km grid covering the whole Philippines. The WRF model is a nonhydrostatic numerical weather prediction model developed by the National Center for Atmospheric Research and used for atmospheric research and operational forecasting. A suite of physical parameterization schemes representing processes such as hydrometer microphysics, cumulus convection, radiative transfer, planetary boundary layer, and land surface are available. The Advanced Research WRF solver uses the Arakawa-C grid as the computational grid and the Runge-Kutta 3rd-order time integration schemes. The same WRF model is also used by the national weather agency PAGASA.[3] The model configurations used in this study are as follows: WRF single-moment 6-class microphysics scheme, the Kain-Fritsch convective cloud parameterization scheme, the Yonsei University planetary boundary layer, NOAH Land Surface Model, Rapid Radiative Transfer Model (i.e., RRTM) radiation schemes, and with spectral nudging turned on. Furthermore, the Kain-Fritsch model was calibrated to better suit Philippine conditions, the details of which are found in Tolentino and Bagtasa (2021). This calibration scheme makes the rainfall forecast model used here different from other forecast models available in the country.

Preparation of Population Data

This study utilizes the population density from Facebook Connectivity Lab and the Center for International Earth Science Information Network (i.e., CIESIN) released in 2019, derived using various machine learning techniques to determine the building footprints from commercially available satellite images and publicly available census data (Tiecke et al. 2017).

The Facebook data was corrected using a Geographic Information System (GIS) to ensure accuracy for this study's analysis. To minimize area distortion, the spatial projection was changed to Universal Transverse Mercator (i.e., UTM) Zone 51N. Reprojected data were then overlaid with Philippine Statistics Authority (PSA) administrative boundaries to compute the land area of each city and municipality. The 2020 PSA census data were spatially joined to the attributes of the administrative boundary to compute population density and to account for the latest population data in the country. The output was then overlayed against the 100-year rainfall return flood hazard data to calculate the exposed population at the barangay level.

Assessing the Most Exposed Barangays to Flood Hazard

This threshold was compared against the 24-hour accumulated rainfall forecast value per river basin. If the average rainfall accumulation per river basin is equal to or greater than the computed 75-year threshold, it indicates exposure to a 100-year return period for flooding within the watershed. Subsequently, the population data for barangays falling within these affected watersheds was calculated and extracted to comprehensively understand the potential impact on local communities.

---

[3] Philippine Atmospheric, Geophysical and Astronomical Services Administration

Integration of the Flood Forecasting System to the NOAH Website

The system has been seamlessly integrated into the NOAH website,[4] enhancing accessibility for various stakeholders. This integration ensures a user-friendly access to crucial information regarding rainfall and flood forecasts and their corresponding affected population. To streamline and automate all processes, open-source tools were employed in the backend, with Python and Django as the primary technologies. The backend processes were designed to automate data management, processing, and visualization. The following programming languages and libraries were utilized to develop the backend processes:

a. Python

Python is a programming language that can be applied to build software, develop a website, analyze data, and automate tasks. Three libraries are mostly used in this process: Fiona, GeoPandas, and Boto3.

Fiona is a Python library for reading and writing geospatial data formats, such as shapefiles and TIFF files. It facilitates the reading of geospatial data and provides an interface to work with vector data, which is crucial for handling geographic information.

The process also used GeoDataframe, which is integrated with Pandas. This allows efficient manipulation and analysis of the rain forecast data in a spatial context, providing a comprehensive approach to processing and visualizing the information.

Boto3 is a Python library that manages Amazon Web Service (AWS) services like Amazon Elastic Compute Cloud (i.e., AWS EC2) and Amazon Simple Storage Service (AWS S3). It allows us to create, update, and delete AWS data using Python scripts. It is used to regularly upload and update the TIFF and PNG rain forecast files to AWS S3 to keep the website's forecast data updated.

b. Django

The system also has a web framework to build web APIs (Application Programming Interfaces), which allows communication between two or more computer programs. In Django, displaying the list of affected barangays after processing a rain forecast typically involves utilizing viewsets, templates, and models. The models represent the structure of the data. At the same time, viewsets show and identify what data should be displayed in a certain endpoint and templates that define the representation of the API. Once the affected barangays are identified, the viewsets send this information to the template, which dynamically renders the list of affected barangays in a JSON output. The output is written in a JSON format because it is the most popular and convenient way to compile the geographic information to the HTTP request used by the front end for user interface display (see Figure 1).

c. PostgreSQL

PostgreSQL is an open-source database management system that stores and manages data for web, mobile, and geospatial applications. It can be extended to PostGIS for spatial databases and geographic objects for maps, making it suitable for handling the results of identified affected barangays from processed rainfall forecasts. After the rainfall forecast data is processed and the affected barangays are identified, the information is stored in a PostgreSQL database. The database schema includes tables representing the identified barangays, their associated attributes (such as timestamp, province, total population, exposed to moderate and high hazard, percentage of exposed population), and any additional relevant information.

Moreover, the system's front end has been crafted for optimal user experience, utilizing Angular services, Tailwind CSS, HTML,5 Typescript, and Mapbox technologies. Angular

---

[4] https://noah.up.edu.ph

[5] CSS - cascading style sheets; html - hypertext markup language

Figure 1. Sample API output for affected barangay

```
HTTP 200 OK
Allow: GET, HEAD, OPTIONS
Content-Type: application/json
Vary: Accept

{
    "count": 41379,
    "next": "http://127.0.0.1:8000/affected_brgy/?page=2",
    "previous": null,
    "results": [
        {
            "psgc": "PH160202069",
            "prov": "AGUSAN DEL NORTE",
            "muni": "BUTUAN CITY (Capital)",
            "brgy": "Port Poyohon Pob. (Bgy. 17 - New Asia)",
            "total_pop": 6607,
            "total_aff_pop": 6607,
            "exposed_medhigh": 6607,
            "perc_aff_medhigh": 100.0,
            "affected": "no"
        },
```

services provide a way to separate the application data and functions that can be used by multiple components in the NOAH app. Tailwind CSS enhances the aesthetic appeal and responsiveness of the system's user interface, while Mapbox presents maps and dashboards visually and intuitively. This harmonious integration of front-end and back-end technologies ensures a smooth user experience and maximizes flood forecasting and information dissemination efficiency and accuracy through the NOAH platform.

d. Angular services

Angular is a JavaScript-based front-end web application framework for building dynamic, single-page applications. To use Angular for front-end development, one defines project requirements, sets up the development environment, designs and implements application structure, implements the user interface, tests and debugs the application, and finally deploys and maintains it.

When new features are integrated into the NOAH website, such as the Impact-Based Flood Forecasting system, a service is created using the Angular CLI.[6] Once the services file is created, the service logic is defined and then added to the providers of the NOAH studio, where the new feature is added. Finally, the methods or properties of the service within the components are being called to enable seamless communication and data sharing across the NOAH website.

e. Tailwind, HTML, and Typescript for UI/UX

Tailwind CSS is an innovative front-end framework that simplifies the creation of custom user interfaces. Focusing on utility-first design, it offers a comprehensive collection of predesigned CSS classes that developers can easily combine to generate visually appealing and functional designs instead of writing a vast amount of custom CSS code.

HTML is a standard markup language used to create the structure of web pages. In Angular, HTML defines the user interface (UI) structure for components. Angular extends HTML with additional syntax and features, allowing developers to create dynamic and data-driven views. Angular templates, written in HTML, include binding expressions, directives, and components that enable the creation of interactive and responsive user interfaces.

TypeScript is a superset of JavaScript that adds static typing and other features to the language. Angular is built with TypeScript and is used to write code for Angular applications. TypeScript provides benefits like type checking during development, which helps catch errors early in development. It also introduces features from ECMAScript standards (the standard JavaScript adheres to), making it a powerful language for building large-scale applications. Angular applications are typically written in TypeScript to exploit their additional features and provide a better development experience.

HTML defines the structure of the UI in Angular, while TypeScript is the language used to write the application logic and behavior. Combining these technologies and other Angular

---

[6] CLI - command line interface

features enables the development of robust and scalable NOAH web applications.

f. Mapbox GL JS

Mapbox GL JS is a JavaScript library that embeds interactive and customizable maps into web applications. Mapbox GL JS enables the creation of dynamic, data-driven maps with features like zooming, panning, and real-time updates. Key features of Mapbox GL JS include support for custom map styles, integration with various data sources, and the ability to add interactive markers, pop-ups, and layers. This library is often used in web mapping applications for various purposes, such as location-based services, data visualization, and geospatial analysis. Developed by Mapbox, it utilizes WebGL technology to render high-performance, vector-based maps directly in the browser.

Utilizing Mapbox technologies enables us to create a more involved and interactive user experience. Mapbox also fosters a unique collaborative environment integrating OpenStreetMap[7] data, Microsoft's AI-generated[8] building footprints, and its three-dimensional extrusion, enabling optimal utilization of diverse datasets to communicate disaster risk further and better.

RESULTS

Flood Hazard Mapping

Assessing potential flood hazards relies on simulation results encompassing flood depth and velocity (Table 1). These hazards are categorized into three levels—low, medium, and high—reflecting the degree of danger posed to individuals and structures. These levels are denoted by yellow, orange, and red, corresponding to low, moderate, and high danger levels (Table 2). The classification system delineates a progression from low to high hazards, with moderate and high levels representing a heightened threat to both lives and properties. While low-level hazards may induce property damage, they are not deemed life-threatening. However, they remain inconvenient, causing street flooding and substantial traffic disruptions.

The flood hazard maps are then ingested and displayed on the NOAH website so that the public can easily access the hazard data and help assess their exposure to flooding-related disasters (Figure 2).

Table 1. Classification of flood hazard levels

Flood Hazard Level	Maximum depth *h* (m)		Maximum depth *h* times maximum velocity *v* (m^2/s)
High	h >= 1.5	OR	vh >= 1.5
Moderate	0.5 <= h < 1.5	OR	0.5 <= vh < 1.5
Low	0.2 <= h < 0.5	AND	0 <= vh < 0.5

Table 2. Description of flood hazard levels

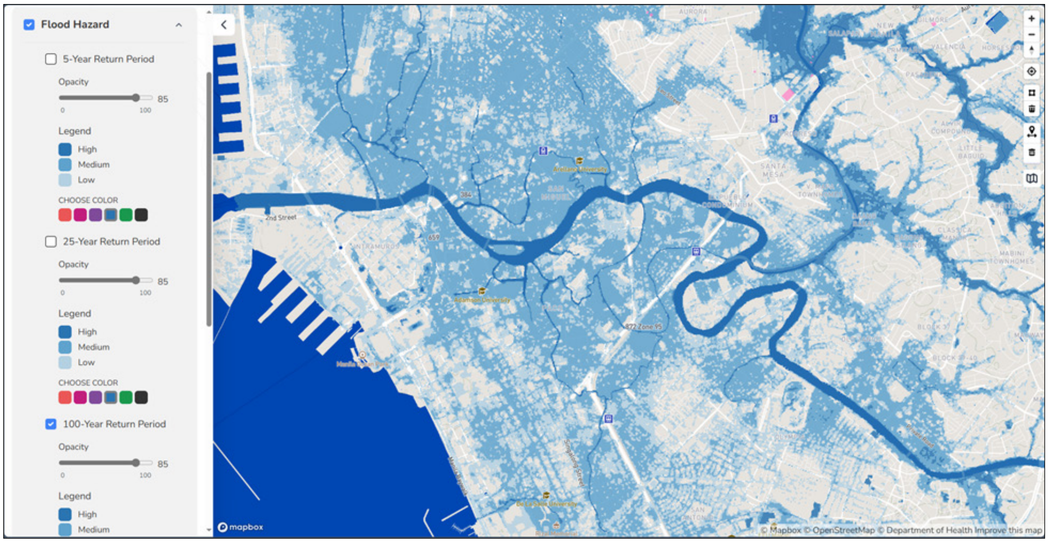
Hazard Level	Map Color	Description
High	Red	Persons are in danger both inside and outside their houses. Structures are in danger of being destroyed.
Moderate	Orange	Persons are in danger outside their houses. Buildings may suffer damage and possible destruction depending on construction characteristics.
Low	Yellow	Danger to persons is low or nonexistent. Buildings may suffer little damage, but flooding or sedimentation may affect structure interiors.

---

[7] https://www.openstreetmap.org/

[8] AI - artificial intelligence

Figure 2. Flood hazard 100-year rainfall return



☑ Flood Hazard

☐ 5-Year Return Period
Opacity 85 (0–100)
Legend
🟦 High
🟦 Medium
🟦 Low
CHOOSE COLOR

☐ 25-Year Return Period
Opacity 85 (0–100)
Legend
🟦 High
🟦 Medium
🟦 Low
CHOOSE COLOR

☑ 100-Year Return Period
Opacity 85 (0–100)
Legend
🟦 High
🟦 Medium

Rainfall Forecast

The rainfall forecasts from the WRF-downscaled GFS global model are generated every six hours at approximately 8:00 a.m., 2:00 p.m., 8:00 p.m., and 2:00 a.m. PST[9] and have forecast lead times of 120 hours. Rainfall forecasts are displayed as 12-hour accumulated rainfall from 8:00 a.m. to 8:00 p.m. of the first forecast day, 8:00 p.m. of the first forecast day until 8:00 a.m. of the second forecast day, and so on for the next five days. Figure 3 shows an example of the 24-hour lead time forecast during the passage of Typhoon Goring in August of 2023. Only rainfall over landmass is displayed in the rainfall forecast visualization for easier and more straightforward interpretation.

Figures 4 and 5 assess forecast rainfall amounts using observed rainfall data from PAGASA synoptic stations for Typhoon Vamco (Ulysses) in November 2020 and Tropical Storm Nalgae (Paeng) in 2022. These tropical cyclone events were two of the wettest tropical cyclones to traverse Luzon recently. In the case of Typhoon Ulysses, almost the whole of Luzon had significant rainfall in the forecast, with November 11 as the daytime in Bicol and southeastern Luzon regions and the rest of Luzon during the following 12 hours. This rainfall consequently caused widespread flooding in the Marikina and Cagayan River basins. The one-day lead time forecasts (maps) compared to observations (texts over the maps) show that the color scheme of the forecasts generally captured well the actual rainfall amount and distribution. The severe flooding due to Typhoon Ulysses was hypothesized (Macalalad et al. 2023) to be mainly due to rainfall over the mountainous regions, where no observation data was available. In the forecast maps, it can be seen that the heaviest rains are found along the Sierra Madre Mountain range. In the case of Tropical Storm Paeng, rainfall was more concentrated in the national capital (Metro Manila) and Southern Luzon regions. The 24-hour accumulated rainfall estimated from the sum of the two 12-hourly rainfall forecast maps also correlates well with the observed rainfall a day later.

An assessment of rainfall forecasts for all tropical cyclones that made landfall in the Philippines between 2016 and 2022 revealed a mean dry bias of 38 mm; after systematically adjusting for this bias, the new mean bias was reduced to 20 mm, with a probability of detection

---

[9] PST - Pacific Standard Time

of 65.6 percent and hit rates of 57.1 percent and 63.0 percent for the 50–100 mm and 100–150 mm rainfall ranges, respectively (Bagtasa 2021).

Affected Population

As outlined in Table 3, Metro Manila is the province most exposed to medium and high flood hazards, with the highest concentration of potentially affected individuals. Cavite and Rizal provinces closely follow.

Metro Manila has the highest number of individuals residing in areas prone to moderate and high flood hazards, considering the high population density across the area. Cavite is the second most exposed to flood hazards, with almost 26 percent of its population exposed to the hazard. Meanwhile, Rizal ranked third in the number of exposed populations to moderate and high flood hazards. The difference between the number of people exposed to moderate and high flood hazards in Cavite and Rizal is small but huge when comparing their exposed population to their overall population (25.81% and 32.97%, respectively).

All of Manila city's 280 barangays are affected by medium and high flood hazards; this means that 100 percent of the populace within the city's jurisdiction are exposed to floods with a height of 0.5 m and above.

This granular approach benefits the local authorities, humanitarian organizations, and the public by enabling them to take preemptive measures tailored to their specific barangays and communities. They can use this information to prioritize the communities at highest exposure, ensuring that limited resources are directed where they are needed most, estimate potential flood damages, and allocate resources and funds efficiently and effectively, leading to a more coordinated and impactful disaster response.

Figure 3. 12-hr accumulated rainfall forecast of the calibrated WRF model from 8:00 a.m. to 8:00 p.m. on 29 August 2023 and 8:00 pm on 29 August to 8:00 a.m. on 30 August 2024 during the onslaught of Typhoon Saola (Goring 2023)

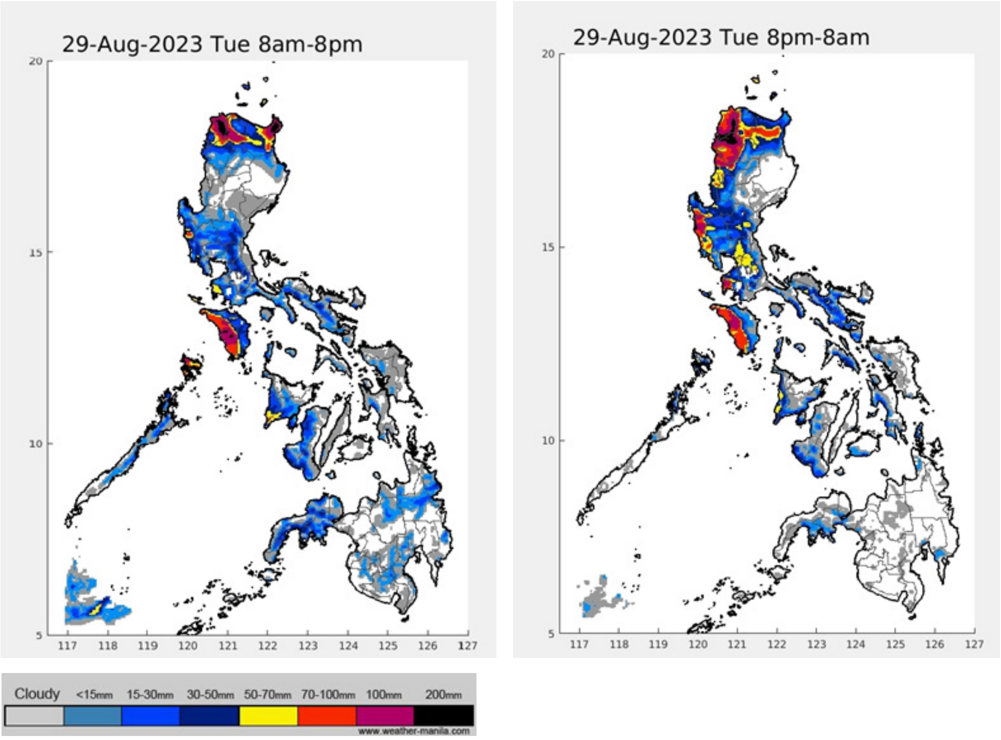
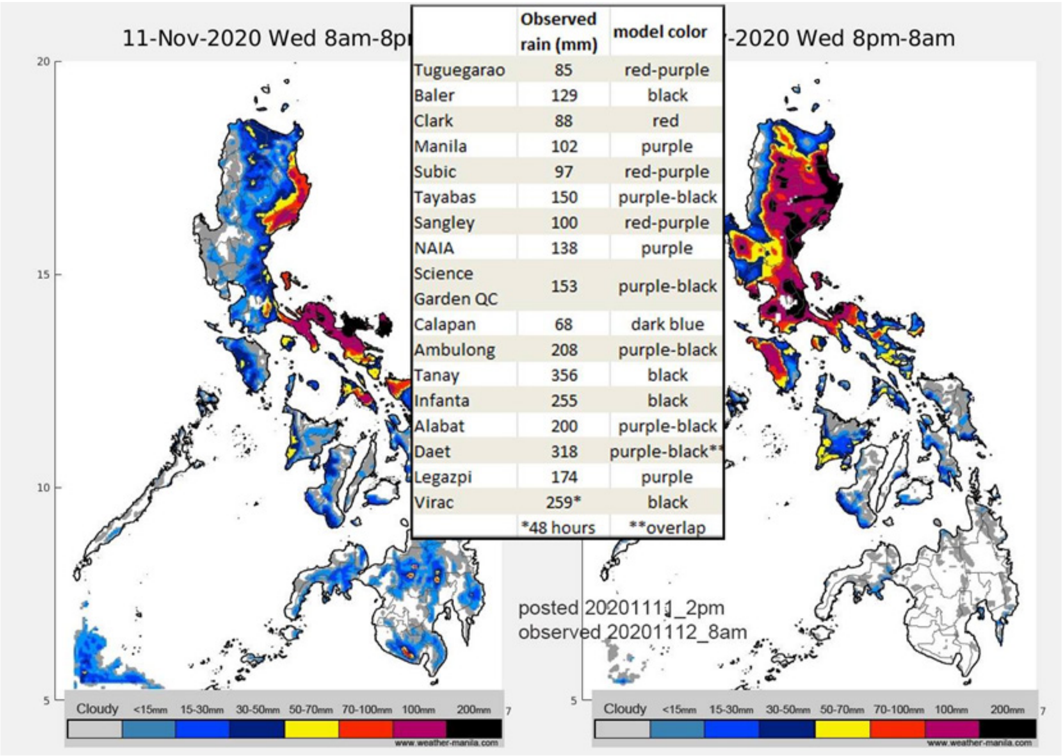


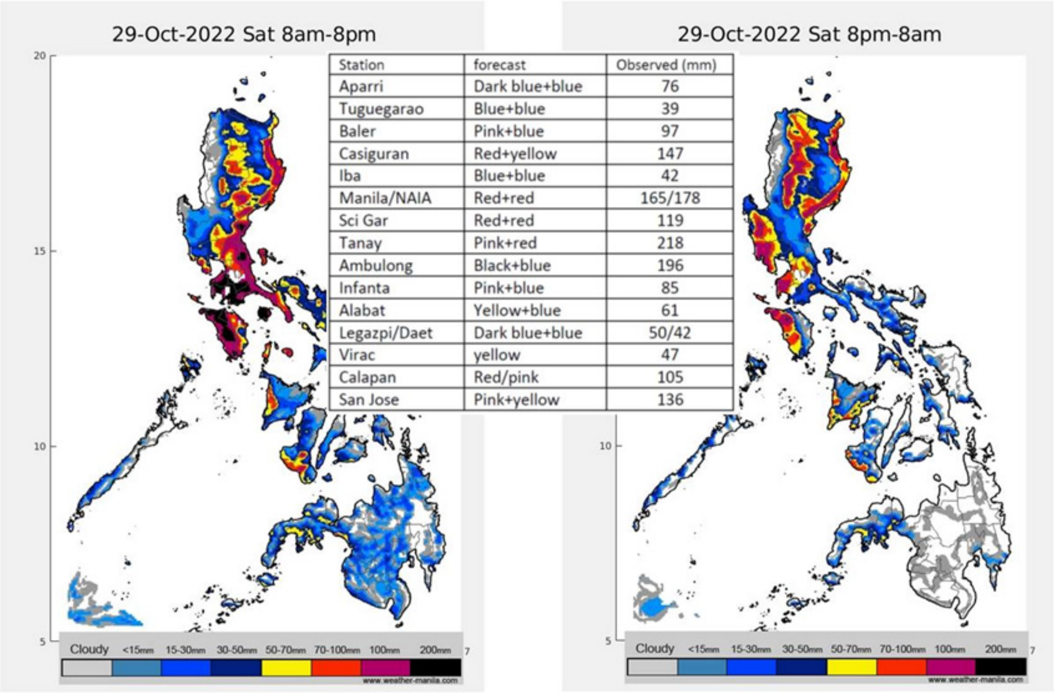
Figure 4. Typhoon Vamco (Ulysses) in November 2020



	Observed rain (mm)	model color
Tuguegarao	85	red-purple
Baler	129	black
Clark	88	red
Manila	102	purple
Subic	97	red-purple
Tayabas	150	purple-black
Sangley	100	red-purple
NAIA	138	purple
Science Garden QC	153	purple-black
Calapan	68	dark blue
Ambulong	208	purple-black
Tanay	356	black
Infanta	255	black
Alabat	200	purple-black
Daet	318	purple-black**
Legazpi	174	purple
Virac	259*	black
	*48 hours	**overlap

posted 20201111_2pm
observed 20201112_8am

Figure 5. Assessment of tropical storm Nalgae (Paeng) in October 2022



Station	forecast	Observed (mm)
Aparri	Dark blue+blue	76
Tuguegarao	Blue+blue	39
Baler	Pink+blue	97
Casiguran	Red+yellow	147
Iba	Blue+blue	42
Manila/NAIA	Red+red	165/178
Sci Gar	Red+red	119
Tanay	Pink+red	218
Ambulong	Black+blue	196
Infanta	Pink+blue	85
Alabat	Yellow+blue	61
Legazpi/Daet	Dark blue+blue	50/42
Virac	yellow	47
Calapan	Red/pink	105
San Jose	Pink+yellow	136

Table 3. Description of flood hazard levels

Rank	Province	Total Population	Exposed to Moderate and High Hazard	Percentage of Exposed Population
1	Metro Manila	13,400,412	4,429,640.4	33.06
2	Cavite	4,344,829	1,121,490.4	25.81
3	Rizal	3,327,337	1,097,186.2	32.97
4	Laguna	3,382,193	987,584.8	29.20
5	Negros Occidental	3,223,955	791,493.0	24.55
6	Cebu	5,151,274	781,099.5	15.16
7	Pangasinan	3,163,190	708,281.0	22.39
8	Quezon	2,226,539	661,136.5	29.69
9	Nueva Ecija	2,130,134	636,415.3	27.55
10	Pampanga	2,900,637	597,917.8	20.61

However, it is essential to note that the actual impact on the barangays and population remains contingent on the specifics of the rainfall event. The impact-based flood forecasting system dynamically assesses the situation, with outcomes dependent on whether the threshold of the respective river basins surpasses the intensity of the rainfall event in question. This dependency underscores the system's dynamic nature and the need for ongoing monitoring and validation during varying weather conditions.

Impact-Based Flood Forecasting System

The system establishes a dynamic connection to real-time data sources, specifically the rainfall forecast, provided at intervals every six hours and accumulated for 24 hours. Our system is designed to fetch and process data periodically, synchronizing with the six-hour forecast updates. This responsive approach allows for real-time computation based on the most recent rainfall forecast, maintaining the accuracy and relevance of flood hazard assessments. The backend processes, triggered by the scheduled accumulated rainfall data updates, execute threshold matching dynamically, providing an updated evaluation of potential flood hazards.

The system's results are reflected in the NOAH Studio and presented in a detailed dashboard. This dashboard, offering key metrics such as total population, number of affected individuals, and the corresponding percentage of the affected population, ensures that stakeholders are equipped with the most current and relevant information. This holistic integration, which includes timed data fetching and on-demand computation, fortifies the system's capacity to support informed and timely decision-making in response to evolving flood scenarios.

Expanding on the system's commitment to public service, our platform upholds transparency and accessibility that is publicly available on GitHub. This aligns with the vision of fostering collaboration and knowledge sharing within the academic and practitioner communities. This open-source approach enhances the system's credibility and invites valuable contributions for continuous improvement and adaptation in addressing dynamic challenges posed by evolving flood scenarios.

Validation

In our pursuit of developing a reliable and robust tool for exposure assessment tailored to the Philippines, validation emerged as an important component of our study. Validation through citizen engagement ensures that the forecasts and outcomes generated by our tool align with real-world scenarios. Hence, a comprehensive validation process utilizing the latest forecasted data is essential.

Integral to the validation process was using reported flooding events sourced from social media channels such as Facebook and X (formerly Twitter). By cross-referencing the forecasted data with real-time reports of flooding incidents during the specified period, we gained invaluable insights into the results of our tool. Identifying flooding events through citizen engagement served as tangible evidence that corroborated our forecast data's accuracy and effectiveness.

The results of our validation exercise revealed a significant alignment between our tool's forecast and the occurrence of flooding events in Mindanao. On 30 January 2024, rainfall was forecasted to commence from 12:00 a.m. (Figure 6), with one municipality (Baganga, Davao Oriental) specifically identified as likely to experience flooding (Figure 7).

Subsequent monitoring through social media channels confirmed reports of flooding in the

Figure 6. Recorded 24-hour accumulated rainfall forecast on 30 January 2024, 12:07 a.m.

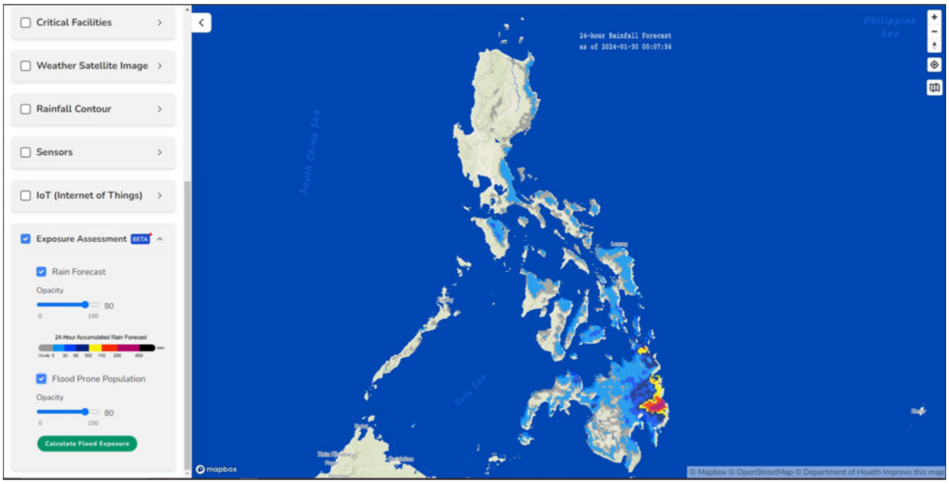
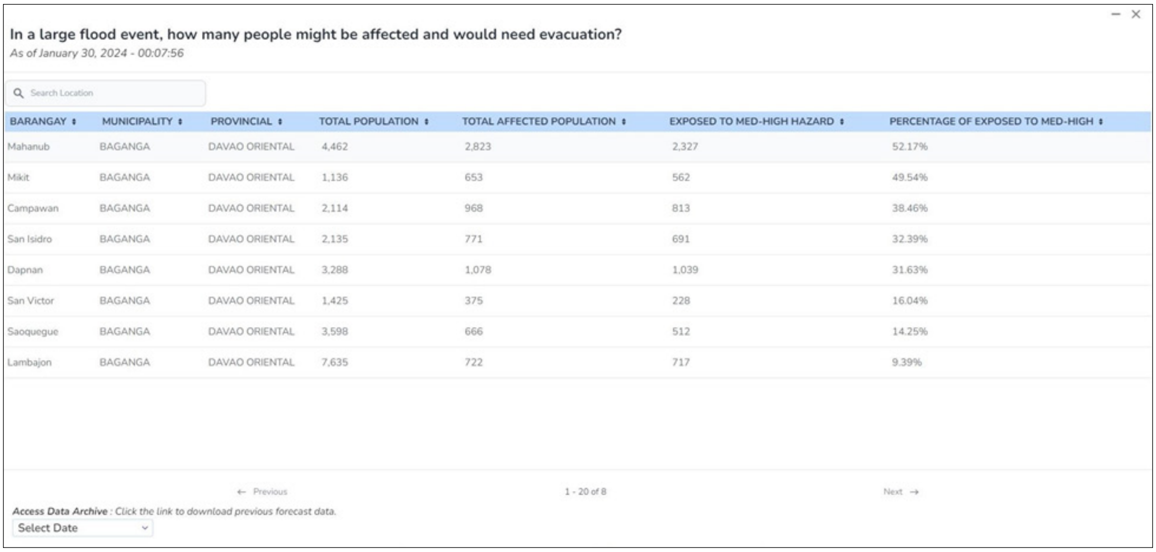


Figure 7. List of identified barangays tagged in the system (forecast last 30 January 2024, 12:07 a.m.)



In a large flood event, how many people might be affected and would need evacuation?

As of January 30, 2024 - 00:07:56

BARANGAY	MUNICIPALITY	PROVINCIAL	TOTAL POPULATION	TOTAL AFFECTED POPULATION	EXPOSED TO MED-HIGH HAZARD	PERCENTAGE OF EXPOSED TO MED-HIGH
Mahanub	BAGANGA	DAVAO ORIENTAL	4,462	2,823	2,327	52.17%
Mikit	BAGANGA	DAVAO ORIENTAL	1,136	653	562	49.54%
Campawan	BAGANGA	DAVAO ORIENTAL	2,114	968	813	38.46%
San Isidro	BAGANGA	DAVAO ORIENTAL	2,135	771	691	32.39%
Dapnan	BAGANGA	DAVAO ORIENTAL	3,288	1,078	1,039	31.63%
San Victor	BAGANGA	DAVAO ORIENTAL	1,425	375	228	16.04%
Saoquegue	BAGANGA	DAVAO ORIENTAL	3,598	666	512	14.25%
Lambajon	BAGANGA	DAVAO ORIENTAL	7,635	722	717	9.39%

Access Data Archive : *Click the link to download previous forecast data.*

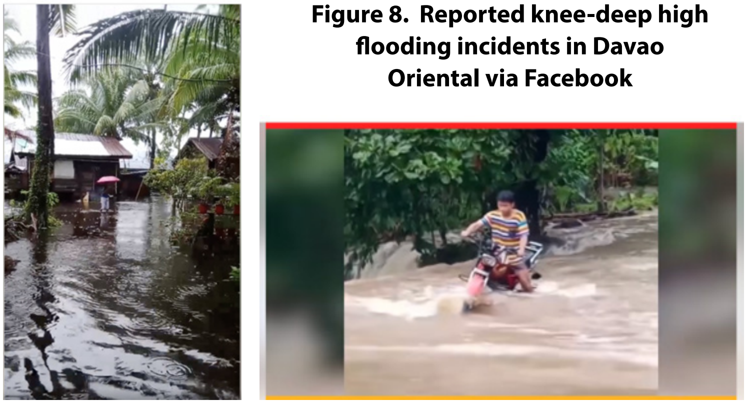
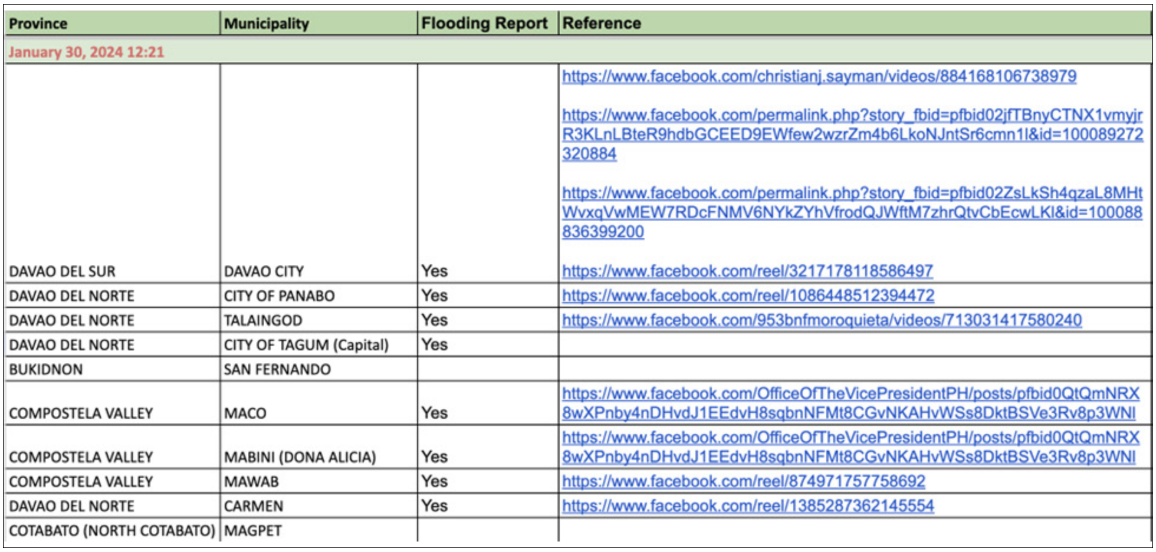


Figure 8. Reported knee-deep high flooding incidents in Davao Oriental via Facebook

Figure 9. List of identified barangays tagged in the system against the flooding report incidents scraped from Facebook (forecast last 30 January 2024, 12:21 p.m.)



Province	Municipality	Flooding Report	Reference
January 30, 2024 12:21			
DAVAO DEL SUR	DAVAO CITY	Yes	https://www.facebook.com/christianj.sayman/videos/884168106738979 https://www.facebook.com/permalink.php?story_fbid=pfbid02jfTBnyCTNX1vmyjrR3KLnLBteR9hdbGCEED9EWfew2wzrZm4b6LkoNJntSr6cmn1l&id=100089272320884 https://www.facebook.com/permalink.php?story_fbid=pfbid02ZsLkSh4qzaL8MHtWvxqVwMEW7RDcFNMV6NYkZYhVfrodQJWftM7zhrQtvCbEcwLKl&id=100088836399200 https://www.facebook.com/reel/3217178118586497
DAVAO DEL NORTE	CITY OF PANABO	Yes	https://www.facebook.com/reel/1086448512394472
DAVAO DEL NORTE	TALAINGOD	Yes	https://www.facebook.com/953bnfmoroquieta/videos/713031417580240
DAVAO DEL NORTE	CITY OF TAGUM (Capital)	Yes	
BUKIDNON	SAN FERNANDO		
COMPOSTELA VALLEY	MACO	Yes	https://www.facebook.com/OfficeOfTheVicePresidentPH/posts/pfbid0QtQmNRX8wXPnby4nDHvdJ1EEdvH8sqbnNFMt8CGvNKAHvWSs8DktBSVe3Rv8p3WNl
COMPOSTELA VALLEY	MABINI (DONA ALICIA)	Yes	https://www.facebook.com/OfficeOfTheVicePresidentPH/posts/pfbid0QtQmNRX8wXPnby4nDHvdJ1EEdvH8sqbnNFMt8CGvNKAHvWSs8DktBSVe3Rv8p3WNl
COMPOSTELA VALLEY	MAWAB	Yes	https://www.facebook.com/reel/874971757758692
DAVAO DEL NORTE	CARMEN	Yes	https://www.facebook.com/reel/1385287362145554
COTABATO (NORTH COTABATO)	MAGPET		

municipality, validating the results of our initial forecast. For instance, barangays Lambajon and Mikit in Baganga, Davao Oriental, were among the identified barangays affected based on the accumulated rainfall forecast from 30 January 2024 at 12:07 a.m. Through reports on social media, we validated the flooding situation in these barangays, confirming our models' results (Figure 8).

Further forecasts were issued at 12:00 p.m. and 6:00 p.m. on January 30, identifying several municipalities exposed to flooding, given the forecast accumulated rainfall. Verification through social media channels revealed a high correspondence between our forecasts and reported flooding events (Figure 9). Most municipalities highlighted in the forecasts indeed experienced flooding, further affirming the reliability and effectiveness of our tool in anticipating and identifying areas prone to large flooding.

The validation process, particularly leveraging flood reports from social media, offers a valuable opportunity for calibrating our models. We can identify discrepancies and fine-tune our models by comparing our forecast models with real-time reports of flooding events sourced from social media. This calibration process enables us to enhance the accuracy and reliability of our predictive models, ensuring they remain aligned with community experiences.

DISCUSSION

Implication of Digitalization

Digitalization refers to integrating digital technologies into various aspects of societal, economic, and governmental functions to enhance efficiency, accessibility, and transparency (World Bank 2016). The surge in digital technologies has recently been transformative, proving particularly instrumental in bolstering disaster resilience efforts. The intersection of digital technology and big data has significantly enhanced our ability to predict, prepare, and respond to disasters (Kitchin and McArdle 2016).

The synergy among digital technologies, disaster risk reduction, and climate change adaptation efforts is significant in the Philippines. The availability and accessibility of precise, localized, and data-driven risk assessments are essential in saving lives and mitigating disaster risk. Accurate data, as outlined in initiatives such as local disaster risk reduction and management plans (i.e., LDRRMP) and local climate change action plans (i.e., LCCAP), serves as the bedrock for informed decision-making, aiding in formulating and enhancing DRR and CCA-related tools and policies such as the Philippine Disaster Risk Reduction and Management Act of 2010 (RA 10121) and the Climate Change Act of 2009 (RA 9729) (Official Gazette of the Philippines 2010; 2009).

Our tool spearheads digitalization by harnessing cutting-edge technology and utilizing open and available datasets to enhance disaster preparedness and response. Besides its technical capabilities, our tool contributes to open data and governance principles. By providing a platform for accessible and transparent flood forecasting information, it mirrors global trends advocating for open and collaborative data practices. It also aligns with the visionary directives outlined in the National Disaster Risk Reduction and Management Plan 2020–30 (NDRRMC 2020). Acknowledging the pivotal role of data in successful disaster response efforts worldwide, our tool underscores the power of open data, information management, sharing, and e-governance in shaping effective disaster resilience strategies.

Beyond data provision, our tool contributes to the broader digitalization landscape by actively promoting open data practices. In line with the UP Diliman's commitment to an open data policy (UPD 2016), the system's availability on GitHub reflects our dedication to transparency and collaborative knowledge dissemination. This strategic alignment emphasizes the institution's broader ethos of promoting accessibility and encouraging a shared culture of learning and innovation.

Our approach fosters collaboration and shared responsibility by enabling local stakeholders, including the LGUs, to access and contribute to the data ecosystem. This participatory model aligns with the principles of open governance, empowering local communities to actively engage in decision-making processes related to disaster preparedness and response (Ibrahim, Salifu, and Peprah 2023).

In the unique context of the Philippines, where economic disparities among the LGUs are apparent, the impact-based flood forecasting system plays a pivotal role in supporting open governance. By democratizing access to accurate and enhanced flood forecasting data, even resource-limited LGUs can actively engage in decision-making processes related to disaster resilience. This aligns with the principles of open governance by fostering transparency, inclusivity, and accessibility in decision-making, ensuring that even those with limited resources can actively participate in disaster resilience efforts (Ahmed, M., S.N. Nawal, and P. Bhangle 2021).

Capacity Building and Citizen Science Initiatives

As an integral component of our overarching strategy, capacity-building activities assume a central role in amplifying the impact of our tool. By conducting training activities with various and diverse stakeholders, we enhance users' proficiency in navigating the tool and cultivate more inclusive and widespread participation in disaster response and mitigation efforts. Capacity-building efforts serve as a cornerstone in building resilience at the local level, enhancing a community-driven approach to disaster response and mitigation efforts (Tadele and Bernard Mayena 2009).

Moreover, capacity building extends beyond mere learning; it empowers stakeholders to acquire skills and validate information based on their experiences and the data shared and presented with them. These competencies ensure a more robust system, as the stakeholders' validation efforts contribute to the overall sustainability of our tool. When harnessed properly and effectively, this knowledge becomes a catalyst for encouraging citizen science initiatives. Stakeholders validate information, and their contributions refine the accuracy of exposure and flooding data, which could stimulate a general sense of community engagement and ownership.

The sustainability of our system primarily relies on the continuous update of exposure data through OpenStreetMap. By fostering citizen science initiatives, wherein local communities actively engage in data collection and validation processes, we contribute to developing and enhancing population density from Facebook's Data for Good in the Philippines. This approach refines the accuracy of our exposure data and empowers citizens to play an active role in their community's disaster resilience efforts.

In the dynamic landscape of data availability, the potential unavailability of critical data sources, such as Facebook's Data for Good, necessitates proactive planning. The absence of predefined alternative sources emphasizes the importance of collaborations that support the open data movement. Engaging with various agencies and communities ensures the collective effort to maintain a sustainable platform.

Collaborative efforts with national government agencies (NGAs) facilitate the integration of authoritative data sources, ensuring the comprehensive and validated nature of the information utilized in our forecasting model (Mobasheri, Zipf, and Francis 201). In doing so, we leverage the collective expertise and resources of various stakeholders to enhance the accuracy and effectiveness of our flood forecasting system.

Enabling Disaster Resilience Across Various Sectors

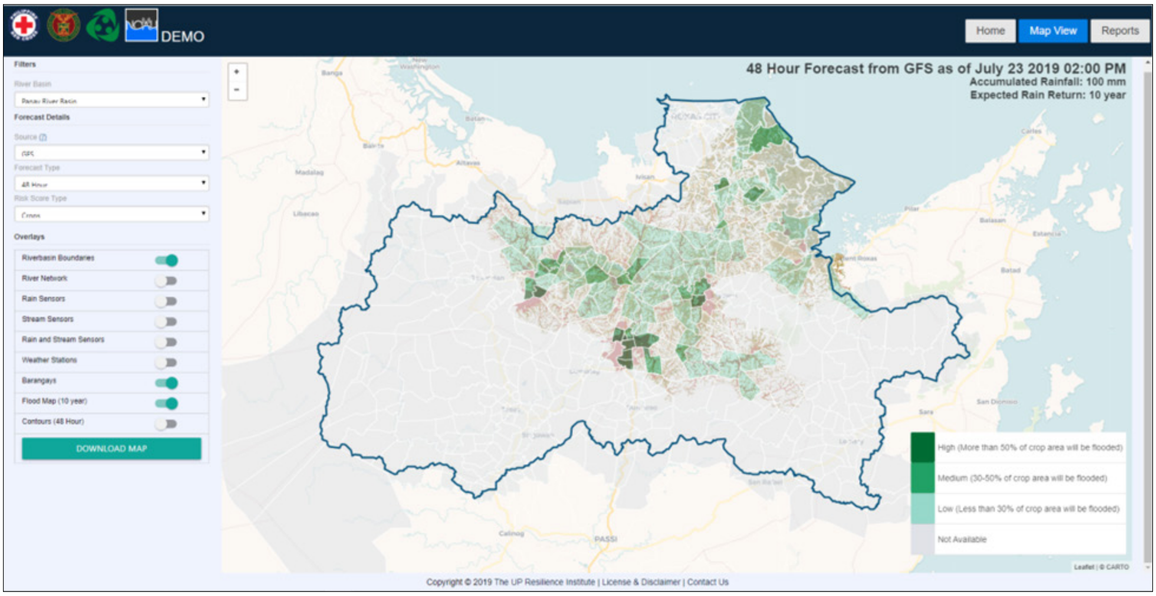
Implementing our impact-based flood forecasting system marks a significant milestone in disaster resilience. This system revolutionizes various sectors with its tailored applications and emphasis on AAs.

This system evolves from our previous project in partnership with the German Red Cross, the Philippine River Inundation System (PRINS), and represents a pioneering adaptation, building upon PRINS's foundational principles. Originally developed to forecast river inundation and aid in disaster response, PRINS also served a vital role in agricultural assessment, providing crucial insights into flood impacts on agricultural lands. Moreover, this system integrates FbF mechanisms tailored for the agriculture sector, providing a basis for delivering aid or advanced insurance payments to those facing property damage and/or agricultural losses (Figure 10).

Our system produces barangay-level data, enabling the LGUs to implement more targeted and effective responses to potential flood events. This can include localized evacuation plans, resource allocation, and coordination with other stakeholders. Cutter, Ash, and Emrich (2014) emphasize the importance of localized disaster planning, advocating for strategies that account for each community's unique characteristics and vulnerabilities. For instance, during the monsoon and typhoon season in the Philippines, our system enables the LGUs to identify exposed barangays and implement localized strategies preemptively, minimizing the impact of flooding.

Humanitarian organizations can benefit from our system by enabling swift responses to emerging crises. The study by Trogrlic et al. (2022) highlights the significance of timely interventions in reducing disaster impacts. This is particularly crucial in the aftermath of typhoons, where our system could facilitate efficient resource deployment and aid distribution. Following the impact of super

Figure 10. PRINS facilitates the assessment of crop area flood risk by leveraging data from installed sensors across the region, incorporating accumulated rainfall measurements, including global forecast models



Filters

River Basin: Panay River Basin

Forecast Details

Source (?): GFS

Forecast Type: 48 Hour

Risk Score Type: Crops

Overlays

- Riverbasin Boundaries ●
- River Network ○
- Rain Sensors ○
- Stream Sensors ○
- Rain and Stream Sensors ○
- Weather Stations ○
- Barangays ●
- Flood Map (10 year) ●
- Contours (48 Hour) ○

48 Hour Forecast from GFS as of July 23 2019 02:00 PM
Accumulated Rainfall: 100 mm
Expected Rain Return: 10 year

🟩	High (More than 50% of crop area will be flooded)
🟩	Medium (30-50% of crop area will be flooded)
🟩	Low (Less than 30% of crop area will be flooded)
⬜	Not Available

Copyright © 2019 The UP Resilience Institute | License & Disclaimer | Contact Us

typhoon Haiyan in the Philippines, where valuable insights were gained, humanitarian organizations like UNOCHA[10] emphasized the importance of AAs in disaster response strategies to mitigate the impact of disasters on vulnerable communities.

Furthermore, OCHA's report discusses how FbF mechanisms enable humanitarian organizations to take proactive measures before disasters occur. By using forecast information to trigger funding and response activities in advance, organizations can reduce the severity of disasters and enhance the efficiency of their response efforts.

Continuous engagement with the academic community ensures a robust and evolving research framework. The feedback loop from ongoing research contributes to refining and improving the forecasting model over time. Moreover, academic partnerships facilitate rigorous evaluation and validation of our system, ensuring it meets the highest scientific integrity and reliability standards. By subjecting our methodologies and outputs to peer review and scrutiny within the academic community, we enhance the credibility and trustworthiness of our system, fostering greater acceptance and adoption among stakeholders.

Our system heightened public awareness, empowering individuals and communities to take proactive measures. This includes educating the public on interpreting forecast data, preparedness measures, and community-based response strategies. Research by Lindell and Perry (2012) underscores the role of public awareness and preparedness in reducing the impacts of disasters. In the Philippines, community-centered workshops and awareness campaigns are practiced to educate residents on the signs of impending floods, enabling them to take timely precautions and evacuate when necessary.

By integrating lessons learned from PRINS and leveraging advancements in technology and methodology, our new system enhances disaster resilience by offering stakeholders more precise and actionable information. The LGUs and humanitarian organizations benefit from this evolution, as the system equips them with the tools needed to respond to disasters with targeted responses and swift interventions.

---

[10] The United Nations Office for the Coordination of Humanitarian Affairs

Moreover, the academic community and public awareness play essential roles in ensuring further research, refinement, and validation of the system's methodologies, contributing to its continuous improvement. Furthermore, the current system has the potential to integrate FbF techniques designed for the agriculture sector, thereby providing timely financial support in the event of flood-related losses.

CONCLUSION

By pioneering a multifaceted system grounded in cutting-edge technologies, open data principles, and collaborative engagement, we have endeavored to address the pressing challenges of disaster resilience and AAs in the Philippines.

The methodology employed is rooted in AAs, harnessing the power of climate risk management, rainfall thresholds, and the active involvement of stakeholders. Through capacity-building initiatives, local governments, disaster response teams, humanitarian organizations, and community leaders are empowered to navigate and utilize the tool effectively, contributing to a more inclusive and proactive disaster management framework. The emphasis on citizen science initiatives further strengthens the platform, as local communities actively contribute to data collection and validation processes. This participatory model refines exposure data and instills a sense of ownership and engagement at the grassroots level.

The study underscores the transformative potential of our tool within the digitalization landscape of the Philippines. Aligned with the National Disaster Risk Reduction and Management Plan 2020–30, our platform recognizes the centrality of data in successful disaster response efforts. Collaboration with multiple stakeholders, including the NGAs, is emphasized, ensuring the integration of authoritative data sources and validating the information used in our forecasting and data models.

However, amidst our strides, potential challenges in data availability, notably exemplified by external and global sources like Facebook's Data for Good and climate models, must be seriously considered. Proactive planning and collaboration are deemed essential to address these challenges, ensuring a robust and collective effort toward maintaining a sustainable platform.

Our study marks a pioneering effort to develop a tool to enhance disaster resilience in the Philippines, firmly rooted in the concept of AAs. This has especially profound implications for the resilience of the agriculture sector and the livelihoods of farmers and their families. Our platform, designed as a dynamic data source, lays the groundwork for an improved disaster preparedness and response framework. However, it is imperative to acknowledge that the success of our tool represents only the initial phase. Achieving a more profound transformation in disaster response demands concerted and genuine collaboration among stakeholders, embracing open data and governance principles. This collaborative endeavor emerges as the fundamental element for attaining comprehensive and enduring success in disaster risk management. We can achieve a disaster-resilient future in the Philippines through collective commitment and unified action guided by the anticipatory concept.

REFERENCES

Ahmed, M., S.N. Nawal, and P. Bhangle. 2021. "Impact of Good Governance on Disaster Risk Management." In L. Filho, et al., eds., *Peace, Justice and Strong Institutions: Encyclopedia of the UN Sustainable Development Goals*. Springer, Cham. https://doi.org/10.1007/978-3-319-71066-2_95-1

Anticipation Hub. 2022. "How Anticipatory Action Makes a Difference." Berlin: Anticipation Hub. https://www.anticipation-hub.org/Documents/Briefing_Sheets_and_Fact_Sheets/How_AA_makes_a_difference_policy_brief_FINAL.pdf

Bagtasa, G. 2021. "Analog Forecasting of Tropical Cyclone Rainfall in the Philippines." *Weather and Climate Extremes* 32: 100323. https://doi.org/10.1016/j.wace.2021.100323

Bündnis Entwicklung Hilft. 2023. *WorldRiskReport 2023*. Berlin: Bündnis Entwicklung Hilft.

Coughlan de Perez, E., B. van den Hurk, M. van Aalst, B. Jongman, T. Klose, and P. Suarez. 2014. "Forecast-Based Financing: An Approach for Catalyzing Humanitarian Action Based on Extreme Weather and Climate Forecasts." *Natural Hazards and Earth System Sciences Discussions* 2: 3193–218. https://doi.org/10.5194/nhessd-2-3193-2014

Cutter, S.L., K.D. Ash, and C.T. Emrich. 2014. "Urban-Rural Differences in Disaster Resilience." *Annals of the American Association of Geographers* 104(6): 1236–58. https://doi.org/10.1080/24694452.2016.1194740

DPWH and JICA (Department of Public Works and Highways, and Japan International Cooperation Agency). 2003. *Manual on Flood Control Planning.* https://www.jica.go.jp/Resource/project/philippines/0600933/04/pdf/Manual_on_FC_Planning.pdf

Hansen, J., G. List, S. Downs, E.R. Carr, et al. 2022. "Impact Pathways from Climate Services to SDG2 ('Zero Hunger'): A Synthesis of Evidence." *Climate Risk Management* 35(2022): 100399. https://doi.org/10.1016/j.crm.2022.100399

Ibrahim, A., A.-H. Salifu, and C. Peprah. "Does Governance Matter When Disaster Looms? Zooming into Proactive Institutional Measures for Flood Risk Management." *International Journal of Disaster Risk Reduction* 97: 104021. https://doi.org/10.1016/j.ijdrr.2023.104021

IPCC (Intergovernmental Panel on Climate Change). 2018. "Summary for Policymakers." In V. Masson-Delmotte et al., eds., *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, 3-24. UK: Cambridge University Press, and NY, USA. https://doi.org/10.1017/9781009157940.001

James, D., W. Friedemann, and A. Schaefer. 2016. "The Economic Costs of Natural Disasters Globally from 1900–2015: Historical and Normalised Floods, Storms, Earthquakes, Volcanoes, Bushfires, Drought and Other Disasters." EGU General Assembly 2016, 17–22 April 2016, Vienna, Austria. https://ui.adsabs.harvard.edu/abs/2016EGUGA..18.1899D/abstract

Kitchin, R., and G. McArdle. 2016. "What Makes Big Data, Big Data? Exploring the Ontological Characteristics of 26 Datasets." *Big Data & Society* 3(1): 1–10. https://doi.org/10.1177/2053951716631130

Lagmay, A.M.F.A., and B.A.B. Racoma. 2018. "Lessons from Tropical Storms Urduja and Vinta Disasters in the Philippines." *Disaster Prevention and Management* 28(2): 154–70. https://doi.org/10.1108/DPM-03-2018-0077

Lagmay, A.M.F.A., G. Bagtasa, I. Crisologo, and B.A.B. Racoma. 2015. "Volcanoes Magnify Metro Manila's Southwest Monsoon Rains and Lethal Floods." *Frontiers in Earth Science* 2(2014). https://doi.org/10.3389/feart.2014.00036

Lagmay, A.M.F.A., B.A. Racoma, K.A. Aracan, J. Alocnis-Ayco, and I.L. Saddi. 2017. "Disseminating Near-Real-Time Hazards Information and Flood Maps in the Philippines through Web-GIS." *Journal of Environmental Sciences* 59: 13–23. https://doi.org/10.1016/j.jes.2017.03.014

Lindell, M.K., and R.W. Perry. 2012. "The Protective Action Decision Model: Theoretical Modifications and Additional Evidence." *Risk Analysis* 32(4): 616–32. DOI: 10.1111/j.1539-6924.2011.01647.x

Macalalad, R.V., R.J.P. Delfino, R.A. Badilla, and S.F. Paat Jr., and G. Bagtasa. 2023. "Role of Historical Warming on the Extreme Flooding Event Due to Typhoon Vamco (Ulysses) 2020 in the Philippines." *Philippine Journal of Science* 152(S1): 197–212.

Matsumoto, J., L.M.P. Olaguera, D. Nguyen-Le, H. Kubota, and M.Q. Villafuerte II. 2020. "Climatological Seasonal Changes of Wind and Rainfall in the Philippines." *International Journal of Climatology* 40(11): 4843–57. https://doi.org/10.1002/joc.6492

Mobasheri, A., A. Zipf, and L. Francis. 2018. "OpenStreetMap Data Quality Enrichment through Awareness Raising and Collective Action Tools—Experiences from a European Project." *Geo-Spatial Information Science* 21(3): 234–46. https://doi.org/10.1080/10095020.2018.1493817

NDRRMC (National Disaster Risk Reduction and Management Council). 2020. *National Disaster Risk Reduction and Management Plan 2020-2030*. Quezon City: Office of Civil Defense-Policy Development and Planning Services. https://ndrrmc.gov.ph/attachments/article/4147/NDRRMP-Pre-Publication-Copy-v2.pdf

Official Gazette of the Philippines. 2009. "Republic Act No. 9729: Climate Change Act of 2009." https://www.officialgazette.gov.ph/2009/10/23/republic-act-no-9729/

———. 2010. "Republic Act No. 10121: Philippine Disaster Risk Reduction and Management Act of 2010." https://www.officialgazette.gov.ph/2010/05/27/republic-act-no-10121/

Skamarock, W.C., J.B. Klemp, J. Dudhia, et al. 2008. "A Description of the Advanced Research WRF Version 3." *NCAR Technical Note* 475: 113. http://dx.doi.org/10.5065/D68S4MVH

Tadele, F., and S. Bernard Manyena. 2009. "Building Disaster Resilience through Capacity Building in Ethiopia." *Disaster Prevention and Management* 18(3): 317-26. https://doi.org/10.1108/09653560910965664

Tiecke, T.G., X. Liu, A. Zhang, et al. 2017. "Mapping the World Population One Building at a Time." *arXiv.* https://doi.org/10.48550/arXiv.1712.05839

Tolentino, J.T., and G. Bagtasa. 2021. "Calibration of Kain–Fritsch Cumulus Scheme in Weather Research and Forecasting (WRF) Model over Western Luzon, Philippines." *Meteorology and Atmospheric Physics* 133(1):771–80. DOI:10.1007/s00703-021-00779-0

Trogrlic, R.S., M. van den Homberg, M. Budimir, C. McQuistan, A. Sneddon, and B. Golding. 2022. "Early Warning Systems and Their Role in Disaster Risk Reduction." In B. Golding, ed., *Towards the "Perfect" Weather Warning*. Springer, Cham. https://doi.org/10.1007/978-3-030-98989-7_2

UPD (University of the Philippines Diliman). 2016. "UP Diliman Data Privacy Portal." https://upd.edu.ph/data-privacy-portal/

World Bank. 2016. *World Development Report 2016: Digital Dividends.* Washington, DC: World Bank.