Operational impact-based flood early warning in Lao PDR and Cambodia

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Abstract

Operational flood forecasting and early warning systems are key tools for disaster risk prevention, with implementation rates steadily increasing worldwide. Yet, most operational systems focus on detecting only the hazard characteristics of upcoming floods, rather than the likely impacts on the society, which are the variables of highest interest for warning centers and emergency responders. This work describes the implementation of FloodPROOFS, a physically based modelling framework to predict the occurrence and the consequent impacts of riverine floods in five river basins in Cambodia and in Lao People's Democratic Republic. The system is updated twice daily with four numerical weather predictions for the next 5 days. It uses a modeling cascade to produce estimates of river discharges, water levels, exceedance of flood thresholds, inundation depth and extent, socio-economic impacts for seven exposure categories, and impact-based warnings at the district level. The latter are included in a semi-automated warning bulletin application co-designed with the two national meteo-hydrological services for daily monitoring and dissemination of alert messages ahead of impending disasters. The system is operational from summer 2024 and has already shown significant value in rising preparedness ahead of some moderate-magnitude floods, including the floods of the Prek Thnot river near Phnom Penh in July 2024.

Keywords
Flood risk, early warning system, impact-based forecasting, hydrological modeling, risk assessment, warning bulletins

Highlights

- FloodPROOFS delivers 5-day flood impact forecasts for five pilot basins
- Impact-based warnings help prioritize emergency response efforts
- Workflow automation and a web visualization platform are key for effective monitoring
- Expanding coverage to all of Cambodia and Lao PDR is a future goal
- Addressing data-sharing challenges is key to transboundary disaster management

1. Introduction

Floods are among the most destructive natural hazards globally, and their impacts are particularly severe in Southeast Asia, a region characterized by high vulnerability due to socioeconomic and climatic factors. The region's vulnerability to floods is exacerbated by the foreseen effects of climate change, which are projected to cause more frequent and intense flooding events [1,2]. Southeast Asia is thus a hotspot for increasing flood risk, with millions of people and critical infrastructures at heightened risk of exposure to weather-related hazards, with implications to disaster preparedness and response mechanisms.

To mitigate flood risk, early warning systems (EWS) have traditionally been set up by national meteo-hydrological services (NMHS) to monitor and forecast the ongoing and future hazard conditions. These systems primarily rely on parameters such as river levels, peak discharges, and the statistical probability of flood occurrence based on historical data, commonly expressed through their return periods (e.g., the 1-in-50 year flood event) [3–7]. While such hazard-based forecasting has proven valuable, it often leads to incorrect mapping of the most critically affected locations, as it does not directly incorporate information on the people and assets exposed, their vulnerability, and often even on the likely inundation scenarios (i.e., the flood extent and its depth). In response to such a gap, there is an ongoing shift in disaster risk management from focusing on "what the weather will be" to the more impact-oriented "what the weather will do." This transition marks a critical evolution from hazard forecasts to impact-based forecasts, which provide actionable information that can better inform early warnings and emergency response efforts [8].

The growing emphasis on impact-based forecasting (IBF) stems from the need to prioritize minimizing the consequences of natural hazards, particularly in terms of protecting human lives and reducing damage to critical infrastructure. In this approach, the focus is on predicting the likely consequences of a flood event, such as the number of people affected, the degree of disruption to transportation networks, or the potential for damage to homes and essential services. By shifting from a purely meteorological perspective to a more holistic risk assessment, impact-based EWS enable more targeted early actions and decision-making that aim to mitigate harm.

This shift toward impact-based EWS is strongly supported by international initiatives such as the Sendai Framework for Disaster Risk Reduction 2015-2030 [9], which emphasizes reducing disaster risk through a people-centered approach. Another key initiative is the Early Warnings for All (EW4All) campaign, launched by the United Nations [10] to ensure that everyone on the planet is protected by EWS by 2027, and with specific recommendations on promoting IBF systems. These frameworks advocate for a comprehensive understanding of risk that integrates hazard monitoring with the social, economic, and environmental factors that determine vulnerability and exposure. In this context, the move toward IBF represents a critical step in advancing disaster risk management practices to meet the challenges posed by climatic changes.

This paper presents an operational impact-based flood forecasting and early warning system developed for five pilot river basins in Cambodia and the Lao People's Democratic Republic (PDR). This system, implemented by the CIMA Foundation in collaboration with the World Meteorological Organization (WMO) and the NMHS of Cambodia and Lao PDR, proposes an innovative approach to flood risk management in the region. By integrating automation into the forecasting process, the system enables both a quantitative and objective estimation of flood impacts and a significant reduction in the time required to produce and disseminate early warning information. Automation is crucial not only for reducing the effect of biased interpretation of results in areas where the forecasters have lower/higher local knowledge but also for ensuring that early warning information reaches decision-makers and the general public quickly and efficiently.

A key objective is to forecast riverine flood impacts up to five days in advance thanks to a modeling chain of hydrological, hydraulic, and risk assessment framework based on multiple numerical weather predictions (NWP), updated twice daily to ensure continuous monitoring. This early and automated detection allows for timely activation of flood warning procedures and the initiation of early actions to mitigate impacts. Additionally, the system includes the development of a platform that facilitates the coproduction of standardized and detailed warning bulletins, which can be disseminated rapidly to ensure that stakeholders have the information they need to act promptly. This feature allows the actors involved to focus specifically on the most critical aspects, such as i) the overall evaluation of the ongoing situation and its evolution; ii) the advisories for the population and early actions to trigger; and iii) the prioritization of resources for emergency response, hence reducing the chances of taking wrong decisions due to stress and time pressure which are common during disasters.

This operational impact-based flood forecasting and early warning system represents a significant advancement in flood risk management in Southeast Asia. By shifting the focus from hazard forecasting to impact forecasting, it aligns with international best practices and initiatives aimed at reducing disaster risk and building resilience in vulnerable regions. This work provides innovative solution to support the NMHS with:

1. an automated system to forecast the impacts of riverine floods in the coming 5 days and with a frequent updating system, to enable effective monitoring and trigger early warning procedures.
2. A tool to improve the dissemination of flood warning information through a web-platform to co-produce standardized and detailed warning bulletins within a short timeframe to expedite early action for impact reduction.

2. Material

2.1. Study area

Five case studies were selected by the two NMHS, according to in-situ data availability, current challenges in flood EWS and connections with local stakeholders. These are the Prek Thnot, Pursat, and Sen river basins in Cambodia and the Xe Kong and Xe Done river basins in Lao PDR (Figure 1), all sub-basins of the greater Mekong River system, in Southeast Asia. These basins experience a tropical monsoonal climate, with distinct wet and dry seasons. The wet season, typically from May to October, brings heavy rainfall due to the southwestern monsoon, resulting in high river flows, flash floods, and increased sediment transport. The dry season, from November to April, sees reduced precipitation and lower river discharge. Geographically, the three Cambodian basins drain the central plains, bordered by low-lying mountains such as the Cardamom and Dangrek ranges. In contrast, the Xe Kong and Xe Done rivers in Laos flow through the Annamite Range, featuring steeper topography and higher elevation. The economy in the five basins depend heavily on agriculture, particularly rice farming and fishing. They have relatively low industrialization rates, with livelihoods closely tied to the rivers' seasonal cycle. In the three Cambodian basins, communities engage in small-scale farming, fishing, and forestry, while in Laos, similar practices dominate, with additional reliance on hydropower development. Except for the Cambodian capital Phnom Penh, the economic sector is constrained by limited infrastructure, poverty, and relatively high vulnerability to flooding. However, hydropower projects, especially in the Laotian basins, have become increasingly significant for regional economic development.

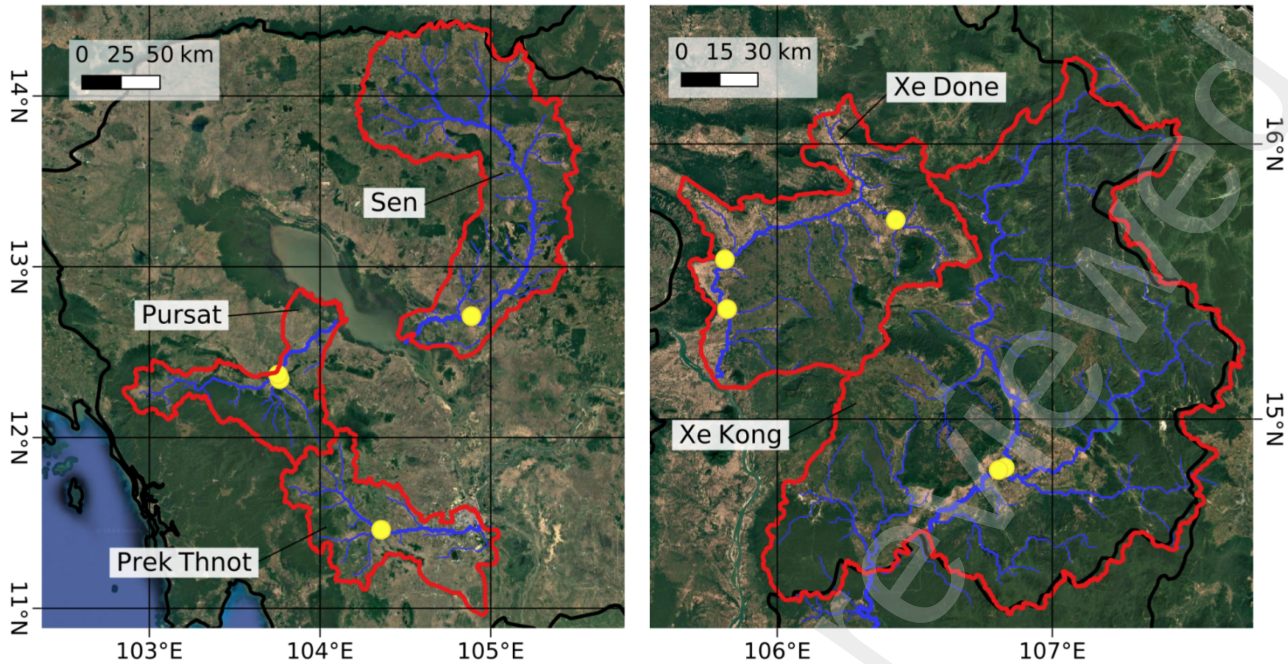

Figure 1: The five river basins considered in this work (in red), three of them in Cambodia (left) and two in Lao PDR (right). The modeled river network is shown in blue, while the nine calibration points are shown with yellow circles. Country borders are shown in black. Map data: © Google 2024.

2.2. Static data for hazard modeling

The set up of an operational impact forecasting chain involves the collection of several datasets from different sources, which are needed to produce information on hazard, exposure and vulnerability. The hydrological modeling requires the use of a Digital Elevation Model (DEM), which was taken from the Hydrologic Derivatives for Modeling and Applications (HDMA) database [11], with spatial resolution of 3 arc-second (~90 m at the equator). For the production of inundation maps, two additional DEM were used, the Copernicus Global DEM [12] and the FABDEM [13], both at 30 m resolution. Land use and land cover maps were derived from the ESA-CCI Land Cover map v2 [14] at 300 m resolution. Such data was used to estimate the soil characteristics and the vegetation cover. We applied the USDA method for soil texture identification and hydrologic soil type classification [15] by combining the ISRIC SoilGrids [16] maps of soil fraction in sand and clay at 250 m spatial resolution.

2.3. Exposure and vulnerability data

Grid-based estimates of population density are taken from the Global Human Settlement (GHS) population grid (R2023) for the year 2020 at 100 m resolution [17]. Information on the built-up area refers to two main aspects: i) the description of the physical exposure of buildings in flood-prone areas in terms of their economic value and spatial location; ii) the elements influencing its vulnerability - such as occupancy, presence of basements, and type of construction materials. The built-up data used for the pilot basins are obtained from the Global Exposure Socio-Economic and Building Layer (GESEBL) [18,19], derived from the Global Infrastructure Risk Model and Resilience Index (GIRI) project[1]. This exposure dataset includes country-specific building typology, usage, and value in both urban and rural settings. The dataset relies on the count of individuals categorized by socio-economic conditions, construction type and geographic area as the basis to distribute the exposed economic value of the building stock. People and built-up were divided into three sector classes, according to the exposure

[1] https://giri.unepgrid.ch/

categories reported in the Sendai Framework Indicators: housing sector distribution, service sector distribution and industrial sector distribution.
All data (socio-economic, building type and capital stock) are provided through a uniform geographical unit at about 1x1 km at the equator and were then downscaled proportionally to the population density to match the resolution of the inundation maps (i.e., 30 m). Critical infrastructures data refer to spatial location of educational and health facilities, as well as the transport network combined with their economic values related to the rehabilitation cost. The educational and health infrastructures were derived from OpenStreetMap combined with information from national datasets where available. Transport networks were obtained from the GESEBL dataset. The agricultural exposures, including cropland and grazing land, are derived from the JRC's Anomaly hot Spots of Agricultural Production (ASAP) [20].
Vulnerability functions to determine the percent damage for increasing water levels for the built up sector are taken from the CAPRA dataset of the Global Assessment Report (GAR) [18]. All other exposure classes are computed through stepwise functions defining each exposed element as affected for flood depth exceeding specific thresholds.

2.4. Dynamic data

Dynamic data used in the system development and in the operational runs is mainly represented by meteo-hydrological data, in the form of in situ observations, satellite products, atmospheric reanalysis and numerical weather predictions. The hydrological model Continuum requires five dynamic input variables: 10m wind speed, relative humidity, 2m temperature, downward short-wave radiation, and precipitation. Observed precipitation data is taken from the IMERG-Late V07 dataset [21] at 0.1° resolution (~10 km) and aggregated from the original 30 minute resolution to the hydrological model resolution of 1 hour. IMERG data was downloaded from its first year of complete availability (i.e., 2002) to the present and is updated as soon as new maps are made available (with latency of about 14 hours), for the updating of the hydrological model states. The other four variables needed to run the hydrological reanalysis are taken from the ERA5 atmospheric reanalysis [22] of the European Centre for Medium-Range Weather Forecasts (ECMWF).
Four different NWP products are acquired twice per day (00 and 12 UTC runs) and used as input to produce an ensemble of hydrological forecasts:

- The High Resolution (HRES) global model by the ECMWF Integrated Forecasting System (IFS) at 0.1° (~11 km)
- The GFS global model by the US National Centers for Environmental Prediction (NCEP), at 0.25° (~27 km) resolution.
- The ICON global model by the Deutscher Wetterdienst (DWD), at about 13 km resolution.
- The WRF regional model by the Viet Nam National Center for Hydro-Meteorological Forecasting (NCHMF), which covers the entire Southeast Asia peninsula and the South China Sea at the spatial resolution of 3 km.

For all NWP, the first 5 days of forecast are acquired at their original temporal resolution (between 1 and 3 hours, depending on product and forecast range), except from the WRF Vietnam, which has a constant 1 hour resolution and maximum lead time of 3 days.
Time series of daily water level observations at 15 stations across the 5 basins were shared by the two NMHS, together with rating curves to estimate river discharges from water levels at a subset of stations, yet raising the need to verify the accuracy of such curves.

3. Methods

3.1. Discharge measurements and rating curves

To calibrate the hydrological model, accurate time series of river discharges for a minimum duration of three years are needed at key cross sections. A dedicated discharge measurement campaign was arranged from late 2023 to the entire 2024 in the test basins, resulting in 51 data pairs discharge-water level at 13 river sections, with an average of 4 measurements per section. The new data, taken during a range of different flow conditions, was used to confirm the validity of the available rating curves or update them in case of minor shifts. In the six stations where the 4 new measures were the only valid data (i.e., due to unavailable curves or to significant mismatch with the curves provided), stations were discarded due to large uncertainty in the resulting discharge time series. Discharge time series suitable for model calibration within the test basins could be produced at 9 river sections by combining observed water levels with the corresponding rating curves: 7 were updated with new measurements (e.g., Figure 2), and the remaining 2 were considered reliable by the local hydrologists.

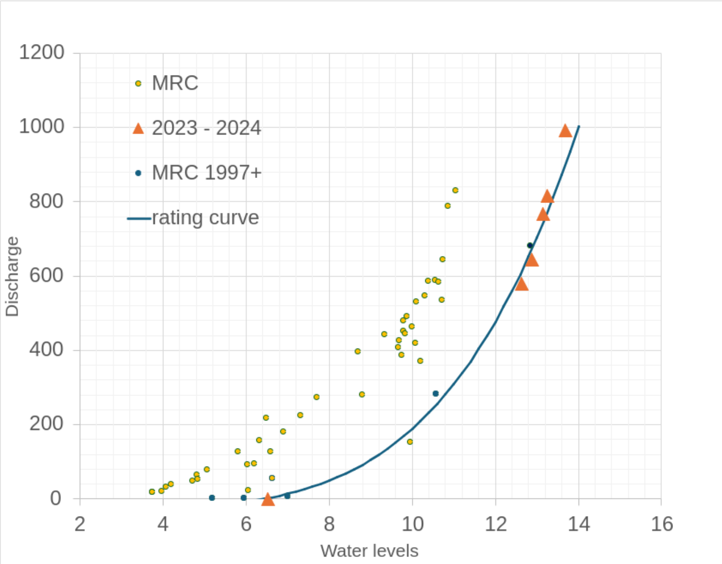

Figure 2: Updated rating curve for the Sen river at Kampong Thom, obtained by combining recent measurements (triangles) with pre-existing ones taken from 1997 onwards (blue circles). Older measurements taken before 1997 (yellow dots) were discarded due to an evident shift in the rating curve.

3.2. Hydrological modeling and calibration

Hydrological simulations are performed with Continuum [23], a physically based distributed hydrological model, that was set up on two separate domains at regular grids of 1 km and hourly time steps to cover the 3 Cambodian and the 2 Laotian basins respectively. Continuum uses numeric equations to simulate all the main hydrological processes and completely solves the mass and energy balance at each grid element. The 4 largest reservoirs with total storage larger than 100 Mm^3, all within the Xe Kong basin, were included in the model, with information extracted from the Global Dam Watch [24], the HydroLAKES [25] dataset, and with additional data shared by the Laotian NHMS. A set of four model parameters was calibrated independently for each of the five pilot basins through a semi-automated procedure based on an iterative search of the parameter set that minimizes the difference between observed and simulated discharges at the calibration stations. The calibration period was set to July 2016 to December 2019 for the Pursat basin and July 2019 to December 2022 for the other four basins, to include 3.5 years of observed discharge data in the most recent period of availability, considering the quality of the data and possibly including both periods of high and low flows. Each model simulation had a 4-year duration, to include a warmup of 6 months at the start of each run and to improve the representation of the model states. Each pilot basin was calibrated using between 1 and 3 discharge time series along its river network, using the normalized root mean square error (nRMSE) as the objective function to optimize at each iteration. The number of parallel model runs was set to 50 in the first iteration, then reduced by 20% at each further iteration up to a maximum of 5 iterations to reach the optimum, hence a maximum of 169 simulations per river basin. Calibration runs were terminated earlier if the objective function performance between one iteration and the previous one improved by less than 1%, thus indicating that an optimum was reached. Further information on the Continuum model implementation for operational hydrological forecasting can be found in Alfieri et al. [26], together with details on the lake and reservoir modules and on the semi-automatic calibration routine.

Once all basins were calibrated, we run the updated model setup over 2002 to 2023 forced by observed meteorological input (i.e., IMERG Late for precipitation and ERA5 for the other variables) to obtain a continuous hydrological reanalysis. Generalized extreme value (GEV) distributions were then fitted with L-moments [27] on the time series of annual maximum peak discharges at each grid point of the model river network, to generate univocal analytical relations between simulated peak discharges and their annual recurrence interval.

3.3. Hydraulic modeling (REFLEX) and map interpolation

We used the REFLEX model [28] to generate maps of inundation depth and extent with constant probability of occurrence corresponding to return periods of the peak flow of 5, 10, 20, 50, 100, 200 and 500 years. REFLEX is a hydro-geomorphological model based on the concept of the Height Above the Nearest Drainage (HAND), where flood volumes are estimated through a physically coherent approach based on the travel time of the flood waves and on peak discharges with chosen recurrence intervals, which for this work were taken from the statistical analysis on the Continuum long term hydrological reanalysis. Inundation maps were produced using the Copernicus DEM [12] at 30 m grid resolution as well as with the FABDEM [13] at the same resolution. To increase the level of details between maps with consecutive return periods, we used a physically based spatial interpolation technique based on the Piecewise Cubic Hermite Interpolation (PCHIP) [29] to produce maps with return periods with increasing spacing, from 1 year for smaller values, up to 25 years for the highest values, resulting in a set of 80 maps with return periods of 2, 3, 4, 5, ..., 450, 475, 500 years. The same algorithm enables to remove from each original inundation map the flood volume which is considered to correspond to bankfull conditions, here assumed as the 1-in-2-year event as in [30], thus enabling an operational modeling of inundation and the consequent impacts only above that specific recurrence interval and imposing no inundation for smaller flow magnitudes.

3.4. Impact assessment model and warning levels

The proposed impact assessment procedure aims to estimate the potential impacts of upcoming river flooding events in the pilot basins on different asset categories, by combining information of hazard, exposure and vulnerability. Impact estimates are implemented and routinely performed for the following seven classes: Direct damage on built-up in USD, Population affected, Crop land affected in hectares, Grazing land affected in hectares, Roads affected in km, Education facilities and Health facilities affected. Hazard is the main dynamic information in the impact calculation, and in this approach is defined by the maximum inundation depth and extent, in any considered 5-day forecast window.
The impact calculation is performed per pixel at the resolution of the inundation maps (i.e., 30 m). To enable efficient computation of forecast event impacts and provide fast updates during each new forecast cycle, flood impacts are pre-calculated for all the 80 return periods of the flood maps and aggregated into Pertinence Areas (PAs), so that results for each flood impact category are saved into tables rather than maps. PAs are polygons defined at the resolution of the inundation model and result from the intersection of administrative areas (the lowest level considered in the impact assessment) and of hydrological units over which the maximum return period of discharges can be assumed constant during a flood event (i.e., each sub-catchment area between two consecutive river confluences).
In each PA, impacts are calculated for all exposure types, using the vulnerability curves described in Sect. 2.3, at the resolution of the inundation maps (30 meters), through a mosaic of flood intensity identified with their return period. The pre-computation of flood impacts for all return periods enables rapid estimation of forecast impacts and a consequent rapid update of results for display in the monitoring webportal.
A further layer of warning levels is generated by classifying estimates of relative population affected (RPA) with thresholds corresponding to selected percentiles, where RPA is obtained as the ratio between population affected in the forecast range and the resident population in each district (Table 1).

Table 1: Thresholds to classify warning levels

Relative Population Affected (RPA)	Warning level	Severity
RPA=0	1	No event
0 < RPA < 0.5%	2	Medium
0.5% ≤ RPA < 5%	3	High
RPA ≥ 5%	4	Extreme

3.5. Product visualization in the myDewetra web portal

FloodPROOFS output products are visualized as soon as they are generated in myDewetra (https://www.mydewetra.world/). myDewetra is a geospatial web platform developed by CIMA Foundation for the Italian Civil Protection Department. It is designed as an integrated system providing a single point of access to environmental information for hazard monitoring, forecasting and early warning, supporting duty officers and decision makers in disaster risk management as well as during emergencies. Each user in myDewetra can access the platform through dedicated credentials, enabling the display of a customized set of static and dynamic information including FloodPROOFS, when implemented, as well as ancillary external datasets to support a comprehensive evaluation of hazard and risk information. The myDewetra geospatial platform allows users to choose the layers of interest, and includes a calendar option to enable visualizing past forecast and observation data, for model evaluation and case study review, particularly useful for training modules on products.

3.6. Operational forecasts

Operational hydrological and flood impact forecasts for the five basins are updated twice per day as soon as new NWP are available for download from the respective weather centers. The 00 UTC forecasts are tipically received between 5 and 7 UTC for the three global models and around 8 to 9 UTC for the WRF local model, as it uses ECMWF forecasts as initial and boundary conditions. The FloodPROOFS chain takes about 1 hour to complete, from the download of the NWP data to the production of the impact forecast layers. Each NWP product is run independently and results are pushed to myDewetra for visualization as soon as each of them is completed. 00 UTC forecasts generated from the global models are usually visualized within 8 UTC, while those depending on the WRF model within 10 UTC, corresponding to 15:00 and 17:00 local time in Cambodia and Laos. Similarly, 12 UTC forecasts become available within 3:00 AM (global models) and 5:00 AM (WRF) local time, making the 12 UTC the most important of the two production cycles for daily monitoring by the duty officers based in the NHMS of the two countries.

Discharge forecasts are displayed in myDewetra through a map of reporting points, placed along the river network to enable a comprehensive inspection of river conditions in all parts of the basins. Figure 3 shows an example of the reporting point layer for the Lao PDR basins on 27 October 2024, the same day when Tropical Storm TRAMI made landfall in central Vietnam causing severe flooding. Reporting points are color coded according to the highest of three discharge thresholds exceeded in the upcoming 5 days: white if no threshold is exceeded, and yellow, orange or red if the forecast peak flow exceeds respectively the 2, 5 or 20-year return period, taken from the analytical distribution fitted at each location (see Sect. 3.2). The most severe among the four deterministic forecasts (one for each NWP) is considered for color coding the reporting points.

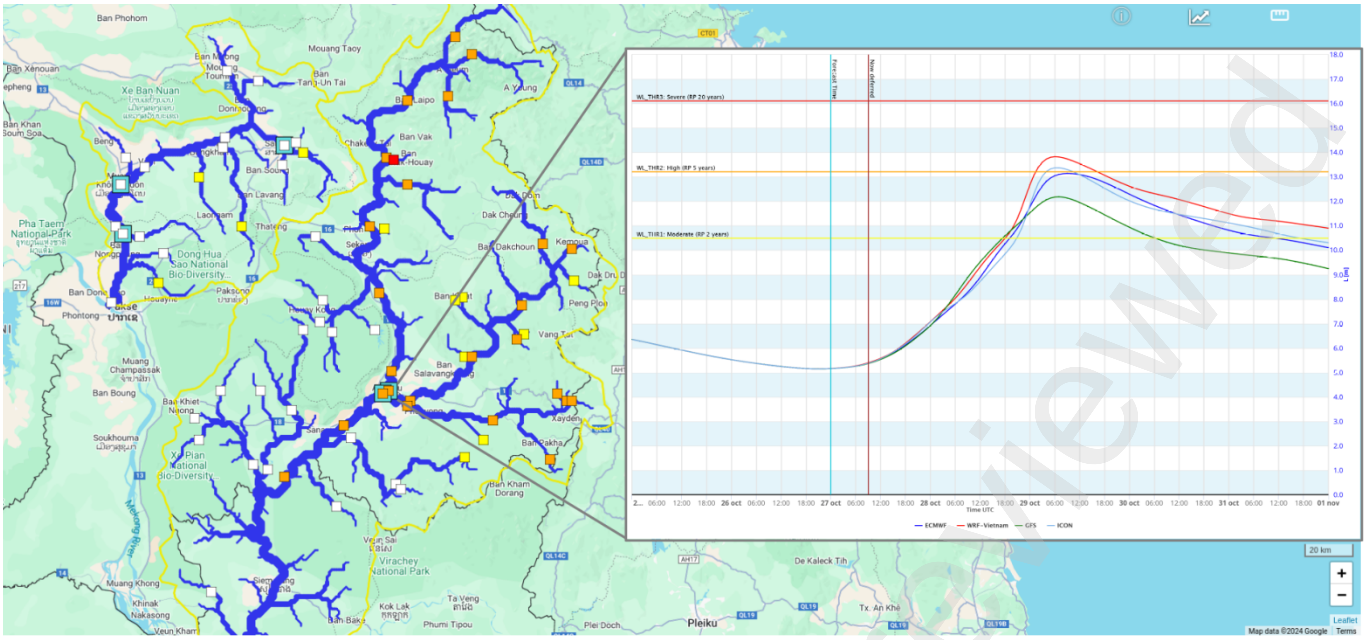

Figure 3: FloodPROOFS reporting points in the two Lao PDR basins for the forecasts of 27 October 2024 00 UTC and 5-day water level forecast in Attapeu. Adapted from myDewetra. Map data: © Google 2024.

Flood hazard and impact forecast maps are generated using only hydrological simulations driven by ECMWF forecasts, which—based on consultations with the local NMHS—are considered the most reliable numerical weather prediction model for this region. The first product in the forecast chain is a map representing the maximum return period of the predicted peak river discharge over the next five days. This layer conveys similar information to the color-coded reporting points but is derived by inverting the extreme value distribution at each river pixel. This allows for a precise estimation of the highest return period (rounded to the nearest integer) expected during the forecast period, serving as a direct indicator of flood magnitude (see Figure 4, left). This return period map serves as the basis for constructing a corresponding flood inundation scenario mosaic for the same 5-day period. For each catchment area, the algorithm selects the inundation map from a pre-computed catalogue of 80 maps (each associated with a fixed return period, as detailed in Section 3.3) that best matches the forecasted return period. The resulting maximum flood depth map (see Figure 4, right) reflects the anticipated flood severity along each river section and is used as the core hazard input for all subsequent impact forecast products.
The system then generates seven impact layers, all based on the maximum flood depth mosaic combined with corresponding data on exposure and vulnerability, and a map of warning levels. Impact estimates are calculated at a 30-meter pixel resolution and subsequently aggregated to administrative level 2 (districts) for visualization within the myDewetra platform.

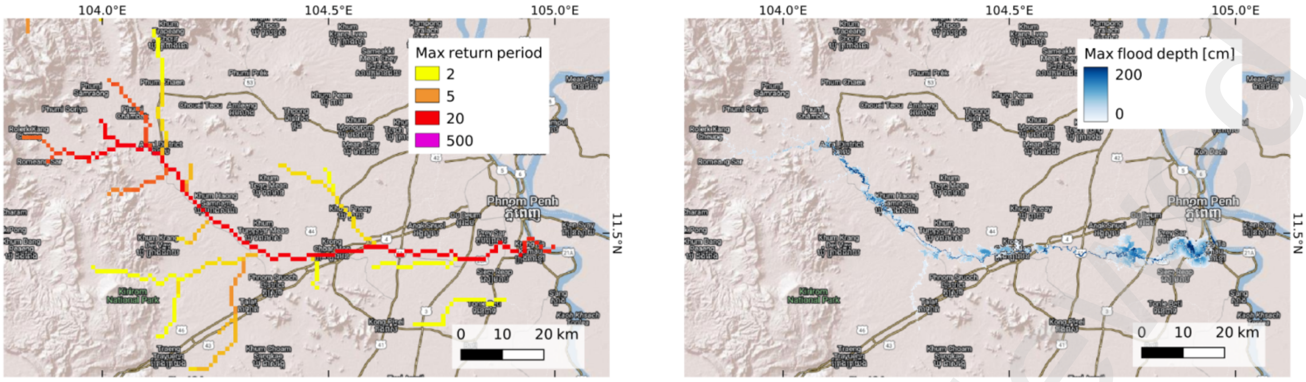

Figure 4: Maps of maximum return period of the forecast peak flow (left) and maximum flood depth (right) resulting from FloodPROOFS forced with ECMWF forecasts on the Prek Thnot basin, Cambodia, on 26 July 2024 and valid for the subsequent 5 days.

3.7. The myDewetra bulletin application

The myDewetra configuration for the users in Cambodia and Lao PDR includes a Bulletin tool, designed to produce early warning bulletins for impending riverine floods, to be distributed to the population or to key stakeholders who have the mandate of the warning dissemination. Bulletins thus generated can automate the inclusion of warning classes produced by the latest FloodPROOFS forecasts, in a map and in text format, as well as text boxes where the duty officers describe the current situation, an outlook on the risk levels in the coming days, and recommendations in case severe events are predicted for the next days. Both tools are designed to cover the respective national territory at the district level (administrative level 2), with warning classes proposed by FloodPROOFS in the pilot basins and the option to manually select a warning level elsewhere in the country based on expert evaluation, station monitoring, and the outlook shown by the latest weather forecasts. Similarly, the warning classes proposed by FloodPROOFS in the pilot basins can be manually changed by the forecasters on duty, to reflect the experience of the forecasters or any additional information that may become available ahead of or during emergencies.

Each bulletin begins with a cover page displaying the title and the validity period, which by default spans the upcoming five days but can be adjusted to reflect a different time range. Below this, a summary of the key messages is presented alongside a national map, where districts are color-coded according to the assigned warning levels. The map also outlines the boundaries of the pilot basins. A methodological disclaimer is included at the bottom of the page. The second page provides a detailed list of affected districts, automatically extracted from the map on page one and grouped by warning level. This is followed by three dedicated text boxes containing inputs from the relevant authorities: the meteorological outlook, the hydrological outlook, and civil protection advisories. Each section is completed by the designated national experts. Bulletins are authored by duty officers in the respective national languages—Khmer in Cambodia and Lao in the Lao PDR (see Figure 5). To enhance accessibility for international audiences—including NGOs, development partners, and donors—each bulletin is automatically translated into English. The English version is simultaneously created and displayed in the web application and can be further edited to improve clarity or the terminology resulting from the automated translation.

The Bulletin tool is designed to speed up the production of warning information, thanks to a predefined layout and input collection, so that information can reach the target users in the shortest time. Once a bulletin is completed, a dedicated button enables the saving to pdf format and direct sharing via email or selected social media channels, together with a precompiled accompanying text.

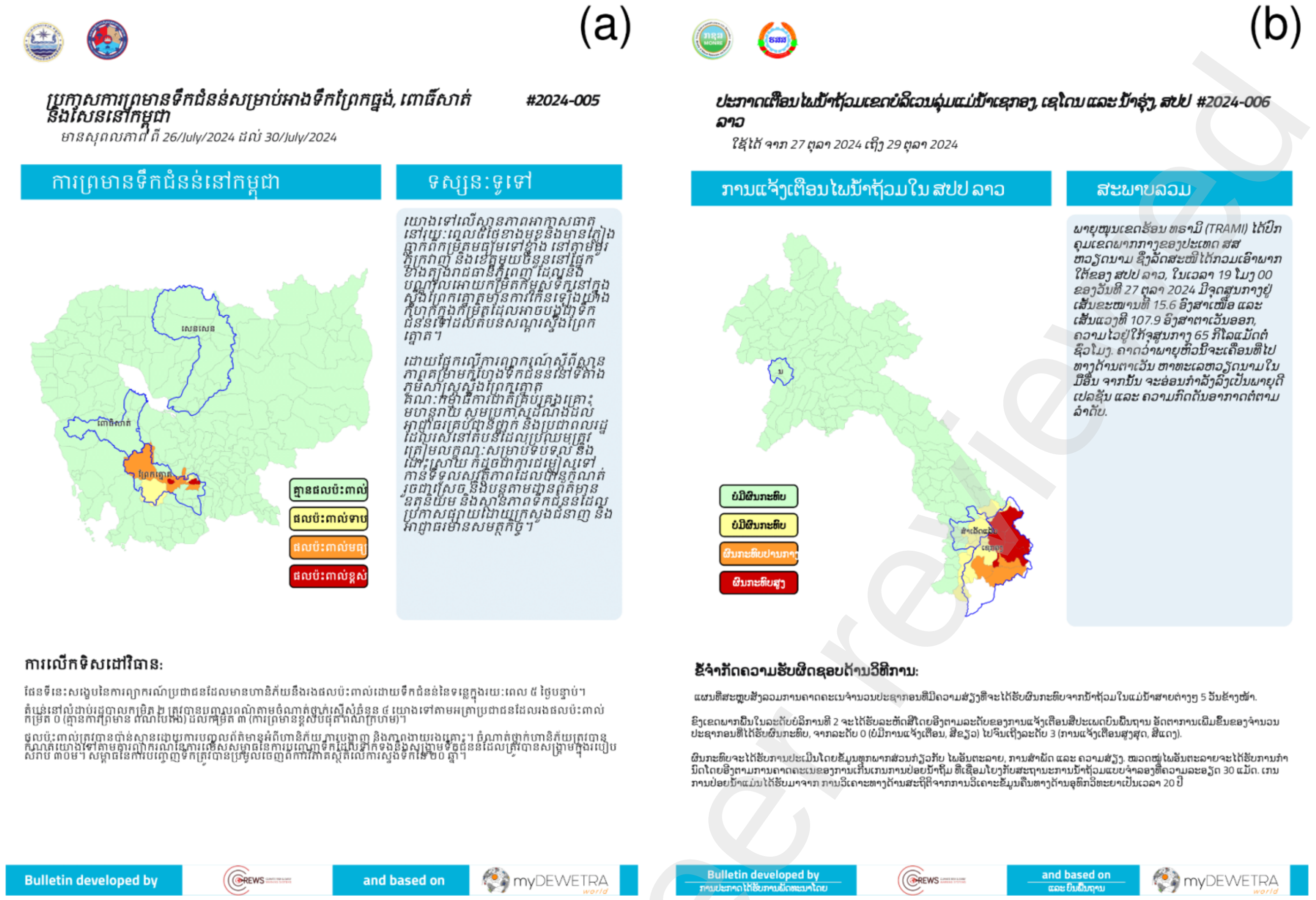

Figure 5: Page 1 of two sample bulletins produced in the respective local language for Cambodia on 26 July 2024 (a) and Lao PDR on 27 October 2024 (b).

4. Results

4.1. Calibration performance

Calibration results of the Continuum model for the five basins are shown in Table 2. The table summarizes the skill of the model in reproducing observed river discharges for each calibration station. Performance indicators are the Kling-Gupta Efficiency (KGE) [31] and its three decomposition terms, namely the correlation (r), the variability rate (CV rate), and the bias rate, all having their optimum at 1. Overall, results are skillful, with only Salavanh resulting in a KGE smaller than the climatological average (-0.41, see [32]), due to a significant positive bias. Interestingly, the least skillful performance both in terms of KGE and of bias rate are Salavanh and Bak Trakoun, the only two stations where the discharge rating curves could not be verified, and existing relatively old curves were used. Yet the two stations keep skillful correlation values. This suggests the possible occurrence of a shift in the respective rating curves (as observed in Kampong Thom, see Figure 2), which can cause a bias in the observed discharges, without affecting the relative ranking of measurements, hence with limited impact on correlation. Overall in the five basins, the average correlation is 0.76, with best performance in the most downstream stations. Despite the high correlation, negative bias is observed in both the calibration stations in the Sekong, especially during low flows, likely due to the influence of the upstream dams used mainly for hydropower production.

Table 2: performance at the 9 stations used to calibrate the Continuum model.

	Name	River Basin	Country	Lon	Lat	r	CV rate	bias rate	KGE
1	Peam Khley Dam	Prek Thnot	Cambodia	104.36	11.46	0.85	0.95	0.91	0.82
2	Bak Trakoun	Pursat	Cambodia	103.76	12.35	0.69	0.41	1.93	-0.14
3	Prey Khlong	Pursat	Cambodia	103.76	12.34	0.73	0.68	0.68	0.47
4	Kampong thom	Sen	Cambodia	104.89	12.72	0.91	1.18	0.89	0.77
5	Souvannakhili	Se Don	Lao PDR	105.82	15.40	0.76	0.87	1.03	0.73
6	Khongxedon	Se Don	Lao PDR	105.81	15.58	0.79	0.96	1.04	0.78
7	Salavanh	Se Don	Lao PDR	106.43	15.72	0.55	0.23	4.35	-2.46
8	Veunkhen	Sekong	Lao PDR	106.81	14.82	0.77	1.25	0.79	0.61
9	Attapeu	Sekong	Lao PDR	106.84	14.81	0.80	1.58	0.76	0.34

4.2. Case study - floods in the Prek Thnot in July 2024

On 28 July 2024, the Prek Thnot river basin experienced severe flooding as a result of an intense and prolonged meteorological event. A combination of heavy monsoonal rainfall and a slow-moving tropical disturbance associated with the typhoon Geami, led to widespread inundation in the basin. The extraordinary rainfall overwhelmed the local hydrological network, causing the river to breach its banks and submerge extensive areas downstream. The most heavily impacted districts were near Phnom Penh, including Dangkao, Takhmao City and Kandal Stung[2], where floodwaters caused significant damage to infrastructure and livelihoods, inundating homes and prompting evacuations (in Kandal Stung district and Takhmao city, near canals 94 and 96)[3]. Urban areas near the capital city experienced inundation of residential neighborhoods, schools, and healthcare facilities, yet no flood-related casualty was reported. Transportation networks were also heavily affected, with several major roads rendered impassable due to flooding. On the 28th morning, a warning was issued urging residents of Kandal Stung and Takhmao districts living along the river and the Prek Ho canal, to remain vigilant.

On the 25th of July, the rain gauge station of Thnous Loung recorded 52mm (Figure 6). During the three days prior to the flood event, the IMERG satellite product estimated maximum precipitation rates around 150mm/72h locally in the upstream parts of the basin. This led to the rise of water levels in the main reach of the Prek Thnot, exceeding the local yellow warning thresholds on the 26th of July, (5.38m at the Peam Khley), and reaching the orange warning level on the 27th and the red warning level on the 28th.

[2] https://www.nationthailand.com/news/asean/40040117
[3] https://cambodianess.com/article/cambodia-battles-widespread-floods-evacuations-underway

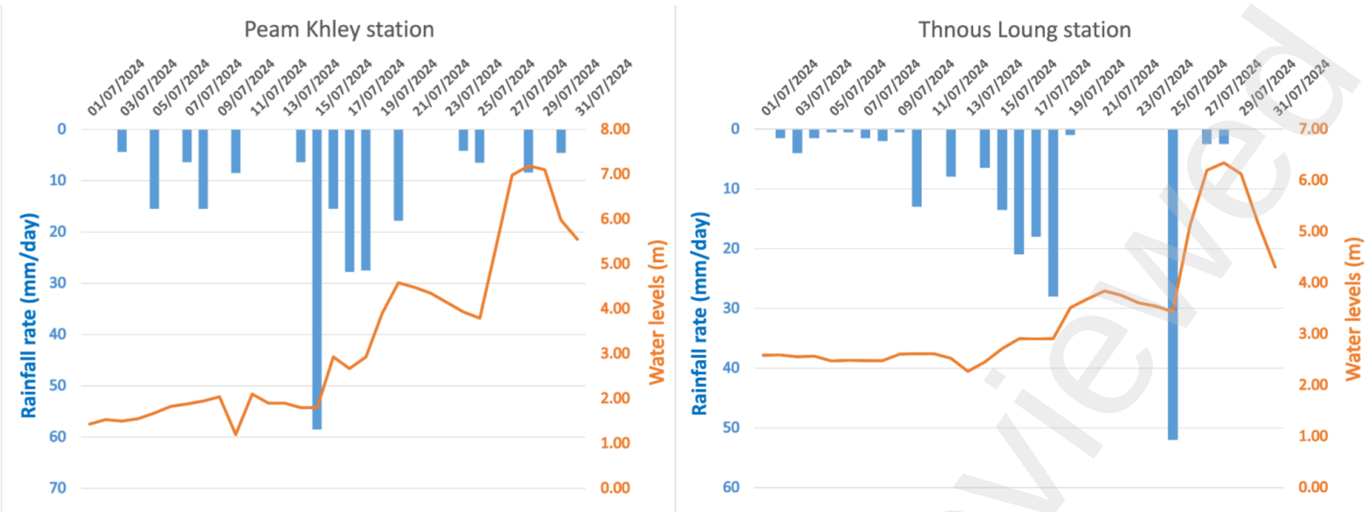

Figure 6: Daily rainfall and water levels for July 2024 at two gauging stations in the Prek Thnot river. The location of the two stations is shown in Figure 8.

Precipitation forecast over the Prek Thnot (basin average) by the ECMWF IFS model for 26 to 28 July 2024 increased from 51 mm (model run of 25 July 00 UTC), to 72 mm (run of 26 July 00 UTC). In the latter forecast, more than 100 mm of rainfall were predicted in the 3 days over a large portion in the northern part of the basin. As a consequence of the increase in predicted rainfalls, predicted peak discharges in the downstream part of the Prek Thnot river increased from a 2-year return period (ECMWF model run of 25 July 00 UTC), to 5 years (model run of 25 July 12 UTC), to about 20 years (model run of 26 July 00 UTC and in the following four 12-hourly updates, see Figure 7). The other deterministic runs show general agreement in magnitude and timing of the predicted peak discharges, yet with a smaller magnitude forecast by the WRF model in all updates (see Supplement figures).

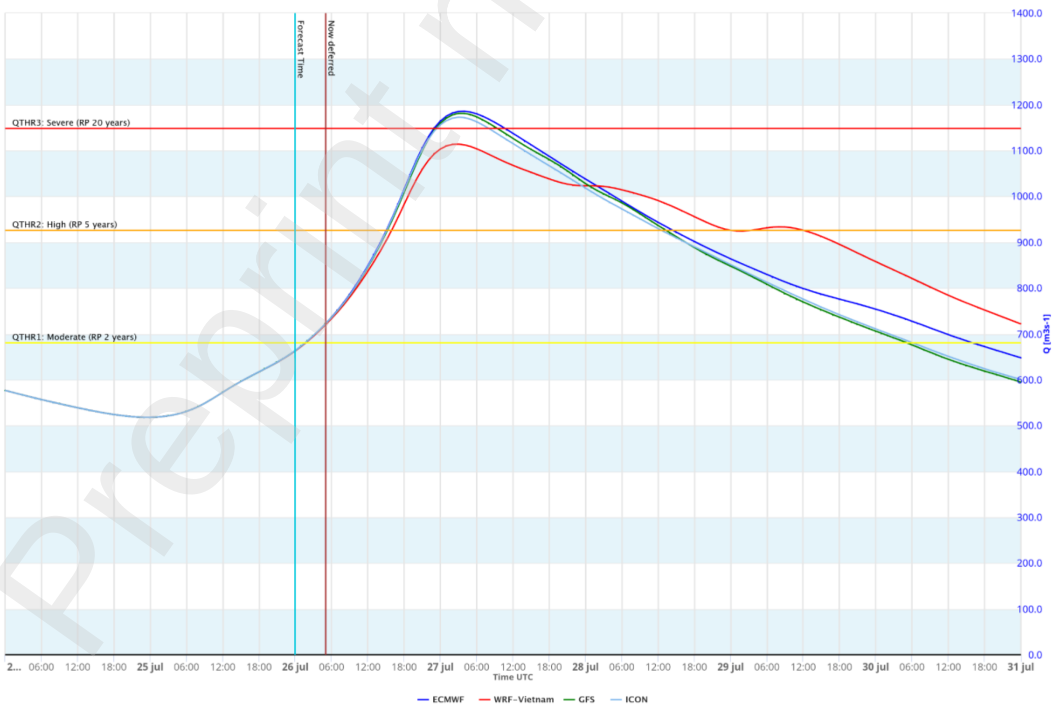

Figure 7: FloodPROOFS 5-day multimodel discharge forecast of 26 July 2024 00 UTC at Krang Mkak station in the lower Prek Thnot river.

The validation exercise shows that FloodPROOFS forecasts of the 26th of July at 00 UTC skillfully predicted magnitude and timing of peak discharges of the flood event. Indeed, the water level observations at the upstream Peam station confirmed the exceedance of the highest threshold exceedance predicted for the 28th of July by the FloodPROOFS System. Water levels at a more downstream automatic station (Trapeang Kong) confirmed the local orange warning level reached on the 27th at 00 UTC, and it exceeded by 25 cm the highest alert threshold on the 28th of July at 12 UTC.

The maximum magnitude of peak discharges and the related flood extent over the subsequent 5 days associated with ECMWF forecasts of 26 July 00 UTC are shown in Figure 4. The highest flood return periods around 20 years are located along the main reach of the Prek Thnot river, from the north-western headwaters down to the confluence with the Bassac River in Phnom Penh. Smaller peak magnitude within 2 and 5 years is predicted in the tributaries joining the Prek Thnot in the lower part of the river. As a result, the maximum forecast flood extent is the largest in the area of Phnom Penh, where the orography is relatively flat and the peak flow overtopping or breaching the levees can cause the highest impacts to settlements and economic activities. In the run of the 26 July at 00 UTC, FloodPROOFS estimated that about 200 thousand people could be potentially affected by the flood in the Prek Thnot river in the next 5 days. Dangkao and Takhmao districts were predicted to be the most affected, with respectively about 9% and 11% of the population likely to be affected. Together with Kandal Stung, media reports confirmed these districts as the most impacted by the event. For these three districts, medium and high impact-based warning levels were predicted (Figure 8). Impacts on buildings, road network and agriculture were also anticipated (Table S1 in the Supplement material).

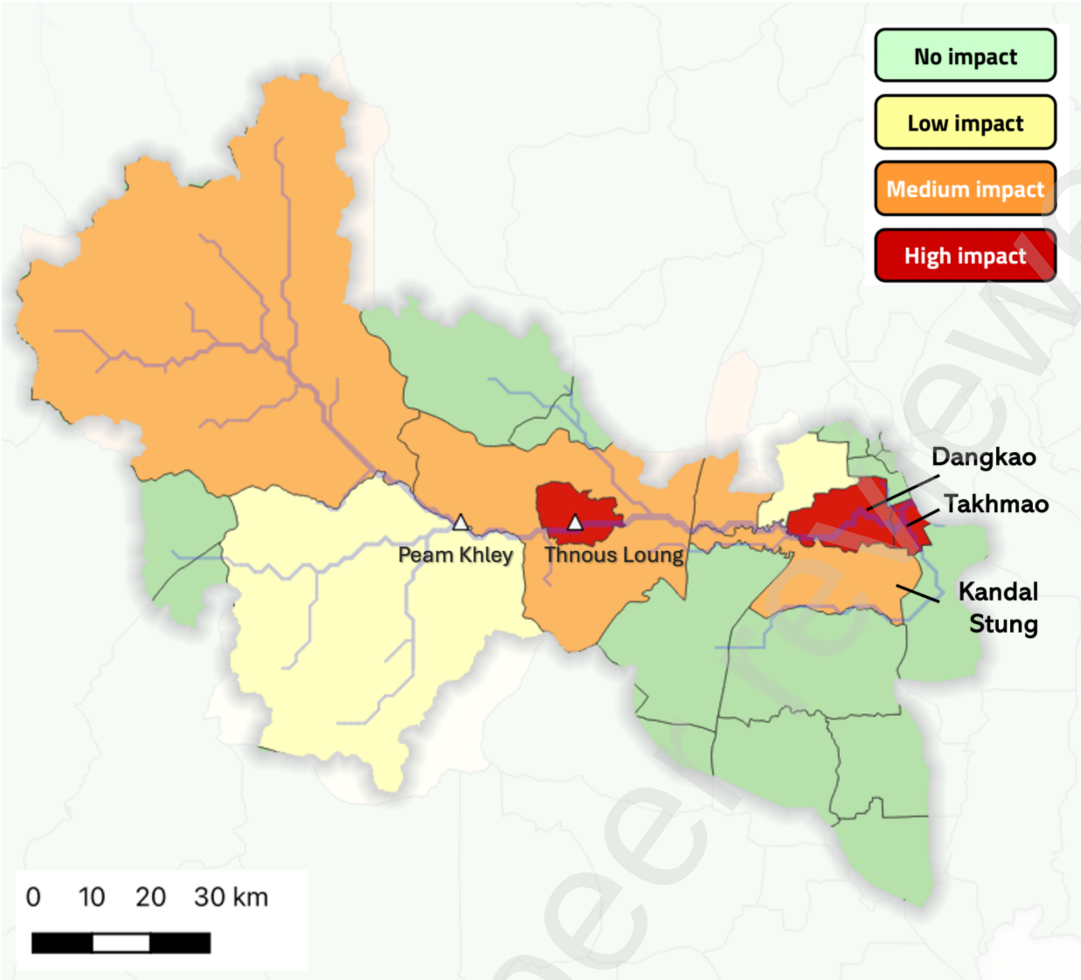

Figure 8: Predicted warning levels based on relative population affected at the district level in the Prek Thnot river basin on the 26th of July 2024, for the subsequent 5 days. The two triangles show the location of the gauging stations Peam Khley and Thnous Loung (see Figure 6).

5. Discussion

The system described in this document was built with constant feedback of the local NMHS and in coordination with key institutes and initiatives active in the region, thanks to the continuous support of WMO and its network of regional support centers. While the system is in operation, development work is ongoing to improve the current capabilities and performance, improve the usability through training, user manuals and tutorials, as well as to define communication channels and standard operating procedures so that flood warnings are efficiently disseminated and emergency risk prevention measures are put in practice.

Among the crucial activities needed to steer future developments is the performance evaluation of the FloodPROOFS system. Having a physically-based cascading approach enables the evaluation of the model output throughout the various forecasting steps. Common benchmark data for the evaluation are observed river discharges or water levels, satellite images of inundation extent, and flood impacts typically including people and cropland affected. A multi-step approach also means that the forecast uncertainty progressively increases for the most downstream system products, so that predicted flood impacts should be considered accurate if they are in the same order of magnitude of the observed ones. Nevertheless, the system implements various techniques to avoid the multiplication of bias throughout the model cascade, which enables keeping the output within meaningful ranges. Among these are 1) the focus on detecting anomalies in peak discharges compared to climatological values, rather than on absolute values; 2) the matching of the probability of occurrence of peak discharges (linked to

their return period) to inundation extent with similar probability, hence that can be created independently from the modeled flood hydrographs; 3) the definition of warning levels based on estimates of relative rather than absolute population affected.
In the current framework, warning thresholds based on relative population affected were defined through statistical criteria, to separate high-impact rare events from more frequent smaller ones. In emergency response procedures, each warning level is linked to a specific set of actions, which range from raising awareness or recommend avoiding unnecessary travels, to more incisive actions such as the closure of schools, street markets, and bridges, among others. Hence, quantitative thresholds need fine tuning with extensive consultations and testing by the local agencies responsible for early warning, to align warning levels produced by the system to emergency actions. This may also involve including additional variables to the warning class definition (e.g., number of critical infrastructures affected), or changes to the vulnerability information (e.g., different thresholds on flood depths, inclusion of social vulnerability data). The paradigm shift towards impact-based warnings implies a deeper involvement of civil protection agencies at the stage of the warning definition, which must coordinate with meteorological and hydrological services rather than being just a recipient of warning messages as in traditional weather-related EWS.
The current model was set up and calibrated using observed discharge data, hence partly taking into account the human influence on the discharge patterns. However, we expect higher challenges in making accurate predictions in the basins where the actual water cycle is most affected by anthropic activities. In this system, the Se Kong basin in Lao PDR is the one with the highest impact on the river flows due to the extensive presence of dams and consequent impact of flow regulation. While the four largest reservoirs are modeled in the system, there remains a substantial uncertainty on the actual filling level, which can largely modify the outcomes of a potential flood scenario in case the actual reservoir levels substantially differ from the modeled ones.
The use of a multi-model approach fed by four different NWP is a valuable quality of the system, not only to increase the chances to spot low-predictable extreme events, but also to provide a measure of the uncertainty of the upcoming meteorological patterns. Indeed, the first year of testing showed that events where the four models agreed the most were those with the highest chance to occur. The inclusion of the high resolution WRF model from the Vietnamese meteorological agency greatly enhances the capabilities to spot localized extreme events potentially causing flash floods. However, we noted a tendency to produce more frequent alerts in the headwater catchments, due to the finer grid resolution compared to the one of the IMERG precipitation dataset used to produce the hydrological reanalysis and the relative discharge thresholds. This is a foreseeable result, which needs to be taken into account by the forecasters in their daily model assessment, to avoid excessive false alarms.

6. Conclusion

In this study, we have described the current operational framework of FloodPROOFS in Cambodia and Lao PDR, an innovative impact-based flood forecasting and early warning system launched in the summer of 2024. FloodPROOFS integrates a meteo-hydrological modeling chain, utilizing Numerical Weather Predictions (NWP) as its primary input to provide twice-daily updates on flood impacts and warning levels. By focusing on five pilot basins, the system delivers forecasts with a five-day lead time, aiming to enhance preparedness and disaster risk reduction. Results from the first rainy season, including the July 2024 floods in the

Prek Thnot basin and other events of smaller severity, highlight the system's ability to skillfully detect moderate to severe flood events. Users have recognized the added value of FloodPROOFS impact-based forecasting approach, which identifies areas with the highest anticipated impacts. This feature allows emergency response efforts to be prioritized more effectively, representing a significant advancement over traditional early warning systems focusing on the prediction of high water levels or discharges without accounting for the possible consequences of the disasters. The effectiveness of FloodPROOFS relies on technological advances yet needs to better address the ability to disseminate warning messages efficiently. Collaboration with National Meteo-Hydrological Services (NHMs) and civil protection agencies remains essential to refine the communication of warning messages and to ensure that stakeholders can take immediate and effective actions upon the information provided. Such improvements are critical for minimizing disaster impacts and protecting vulnerable communities.

Looking forward, there is considerable interest in extending the system's coverage to encompass the full national territories of Cambodia and Lao PDR. This extension, tailored to the tributary basins of the Mekong River, would complement the existing flood forecasting activities produced by the Mekong River Commission for the main reach of the Mekong, which focus particularly on the propagation of the flood wave along the main river. The success of a hydrological forecasting system in the area strongly depends on the access to real-time hydrological data, including discharge and water level measurements, lake and reservoir storage, as well as the operation schemes in use at the dams. However, in the transboundary context of the Mekong River Basin, the availability of such data is often constrained by sensitivities around data sharing, due to the upstream/downstream relations of neighboring countries and the interest in optimizing the use of water resources at the local level. These limitations underscore the need for improved coordination among the basin countries, especially given the already large influence of human activities on water allocation, the ongoing socio-economic growth, and the potential impacts of climate change on water availability. Ultimately, FloodPROOFS demonstrates the potential for a paradigm shift in flood early warning systems, moving from a reactive hazard-based approach to one that is anticipatory and impact-based. By bridging the gap between hydrological modeling and actionable information, the system offers a powerful tool for mitigating the effects of flooding and increasing disaster preparedness in the region.

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Author contributions: CRediT

Lorenzo Alfieri: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Agathe Bucherie**: Project administration, Writing – review & editing, Methodology, Investigation, Visualization, Data curation, Conceptualization. **Andrea Libertino, Lorenzo Campo, Mirko D'Andrea, Tatiana Ghizzoni**: Data curation, Software, Writing – review & editing, **Simone Gabellani, Marco Massabò, Lauro Rossi, Roberto Rudari, Eva Trasforini**: Funding acquisition, Resources, Review & editing. **Bounteum Sisouphanthavong, Hun Sothy**: Data curation, Investigation. **Ramesh Tripathi, Jason Thomas Watkins**: Project administration, Supervision.

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Declaration of competing interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability
Model results can be provided by the corresponding author upon request.

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Operational impact-based flood early warning in Lao PDR and Cambodia

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