Design of an automatic hydro-meteorological observation network for a real-time flood warning system: a case study of Vu Gia-Thu Bon river basin, Vietnam

Liem D. Nguyen, Hong T. Nguyen, Phuong D. N. Dang, Trung Q. Duong and Loi K. Nguyen

ABSTRACT

This paper presents an interdisciplinary approach, along with Vietnam's legal frameworks, to design an automatic hydro-meteorological (HM) observation network for a real-time flood warning system in Vu Gia-Thu Bon (VGTB) river basin, Vietnam. The automatic HM monitoring network consists of weather-proof enclosures containing data loggers, rechargeable batteries, sensors for air temperature, air humidity, solar radiation, wind speed, water level with attached solar panels and mounted upon masts located at fixed ground stations. A total of 20 meteorological stations and five hydrological stations have been built in VGTB river basin. To capture changes in weather and stream flow in the basin, the 5-minute and half-hour recording frequency options were set for meteorological and hydrological variables, respectively. All HM data was transmitted every 30 minutes to the data server at the data processing centre via Global System for Mobile Communications (GSM)/General Packet Radio Service (GPRS) network. These data were then input into hydrological-hydraulic models for inundation simulation in the basin. The results showed that the performance of flood simulation at hourly time step has significantly improved during flood events in September and November 2015. Overall, near-real-time HM data recording from an automatic monitoring network proved beneficial for an flood early warning system.

Key words | data processing centre, flood warning system, general packet radio service, global system for mobile communications, hydro-meteorological observation network

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HIGHLIGHTS

- The automatic HM observation network has been designed based on coefficient of variation, spatial interpolation, spatial analysis, Vietnamese Standards, and WMO regulations.
- The density of the HM observation network on VGTB basin is increased due to the additional installation.
- The automatic meteorological observation network contributes to improving the accuracy of flood simulation.

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INTRODUCTION

Floods are major water-related disasters that affect millions of people, resulting in thousands of deaths and billions of dollars in losses each year worldwide. In order to minimize flood damage, adaptation and mitigation measures should be considered (Acosta-Coll *et al.* 2018). Possessing the ability to give advance notice of an impending flood and enable the implementation of emergency plans, early warning systems can be used appropriately to save lives and reduce other adverse impacts (Jha *et al.* 2012). Flood warning systems are currently operational in many countries such as the Flood Forecasting system of DELFT-FEWS (Deltares 2013), Automated Local Evaluation in Real Time (National Hydrologic Warning Council 2010), Central America Flash Flood Guidance (Christopher *et al.* 2010), and Flood Forecasting and River Monitoring System in the Mekong River Basin (Chayanis *et al.* 2005). The differences between types of flood warning system operating in developing and developed countries appear to be insignificant (Perera *et al.* 2019).

A flood warning system needs four key elements, including (Jha *et al.* 2012): (1) detecting flood potential; (2) forecasting flood hazards; (3) flood warning to authorities and/or public; (4) flood response. Failure in any essentials of a flood warning system will result in inefficiency. However, the utility of a flood warning system depends greatly on the underlying forecasting system, the quality of emergency plans and the level of preparedness of at-risk communities (Jha *et al.* 2012). Recently, developments in advanced technologies such as data assimilation, geospatial data mining, numerical modelling, artificial intelligence, decision support system, and wireless communication have contributed to improving flood warning systems on response time and accuracy. Nevertheless, challenges still exist which slow down or even hinder the prevalence of flood warning systems (Perera *et al.* 2019). First, inadequate hydrological network coverage and limited back-up equipment for monitoring of floods adds to inaccuracy of flood forecasts. The models used to produce early alerts are not accurate or advanced enough for this purpose. There is a lack of technical expertise and limited skilled manpower to perform flood forecasts.

HM variables such as rainfall, air temperature, air humidity, solar radiation, wind speed, water discharge, and water level are the key inputs in flood forecasting and warning. In the absence of rain observation stations, significant errors occurred in simulating flood peaks in a semi-arid basin (Jene 1994). Theoretical reliable rainfall-runoff models will not accurately predict if rainfall input data is incomplete or inaccurate (Keith 2002). A dense network of rain gauge stations gave better results of overflow forecast than sparse rainfall station density (Gregory *et al.* 2003). In theory, to collect HM data on a specific region, it is necessary to design an extensive monitoring network to fully and accurately cover the spatial heterogeneity of hydro-climate parameters on that area. However, when it comes to large basins or basins with high hydro-climatic variability, it is, in fact, unfeasible to install HM monitoring stations at all locations. To solve this problem, optimization approaches have been proposed to determine the minimum number of stations in the most appropriate locations while ensuring maximum collection of HM data. Coefficient of variation, key station network, spatial correlation and entropy were used to determine the number of additional rain gauge stations and the number of redundant stations (Panigrahy & Mani 2000). The optimal location of new monitoring stations in an existing rain monitoring network was evaluated using a geostatistical method and Geographic Information System (GIS) (Barca *et al.* 2008). Kriging was combined with entropy to determine the optimal number of rain gauge stations and spatial distribution of these stations (Yen *et al.* 2008; Afef *et al.* 2013). Numerical models, geostatistics and evolutionary strategies were integrated to design quasi-optimal monitoring networks in lakes and reservoirs (Jimênez *et al.* 2005). The non-dominated sorting genetic algorithm and Inverse Distance Weighting interpolation were applied to optimize groundwater-level monitoring networks (Mirzaie-Nodoushan *et al.* 2017). Geostatistical tools were coupled with genetic algorithm to design an optimal pressure sensor in water distribution systems (Soroush & Abedini 2019). An approach for optimally positioning water quality sensors based on the Bayesian decision network was developed for illicit intrusion identification in urban drainage systems (Sambito *et al.* 2020).

Vietnam is ranked number six among countries most affected by extreme weather events during the 1999–2018 period (Eckstein *et al.* 2019). Among extreme weather events, floods are listed at the top in terms of affected areas, severity, frequency and losses. All regions of the country are affected by floods, especially on the Central Coast. Therefore, most studies in Vietnam on flood warning are concentrated in this flood-prone area. Flood forecasting and warning models, as well as a network of hydro-meteorological observations, flood warning landmarks and telegraphs, were built for rain-flood forecasting in four river basins (Huong-Bo, VGTB, Ve-Tra Khuc, and Kon-Ha Thanh) (Du 2001). A daily online flood forecasting technology in the flood season was developed for Central river basins (Nhat Le, Ben Hai, and Thach Han) (Cam 2007). The risk of flooding in Huong river basin was predicted to prevent and minimize damages (Dan 2008). A short-term flood forecast model using rainfall downscaled from the global numerical weather prediction outputs was developed for Thu Bon river basin (Nam *et al.* 2011). At the national level, the National Centre for Hydro-Meteorological Forecasting under the Ministry of Natural Resources and Environment is responsible for region-specific hydrological forecasting with interactive maps providing river station information (water level and flood warning level) and weather (Ministry of Agriculture and Rural Development and United Nations Development Programme 2012). Overall, existing flood warning systems in Vietnam provide flood warnings based on three different methods: (1) monitoring and forecasting the formation and development of weather patterns causing heavy rains; (2) using estimated rainfall from optical satellite imagery, radar; and (3) analysing data on rainfall, relationship between rainfall and flood peak, surface characteristics of the basin using hydrologic and hydraulic modelling. Regardless of the method used to warn floods, inadequate HM network coverage has been a major challenge which adds to the inaccuracy of flood forecasts in Vietnam. With a total of 194 surface meteorological stations and 354 hydrological stations nationwide (Vietnamese Government 2016), the existing HM monitoring network is still sparse compared to the recommendations of the World Meteorological Organization (WMO).

This study aims to introduce an automatic HM observation network optimally designed for a real-time flood warning system in VGTB river basin, a large river system in the Central Coast of Vietnam. First, the flood regime of VGTB river basin is analysed to provide a conceptual HM observation network framework for this basin. Second, we use an interdisciplinary approach along with Vietnam's legal frameworks to optimally design an automatic HM observation network for a real-time flood warning system in VGTB river basin. Finally, we discuss advantages and disadvantages of the established HM observation network.

METHODS

Study area

The VGTB river basin is located in Central Vietnam with an area of approximately 10,350 km^2. It lies approximately between 14°55′–16°03′N in latitude and 107°15′–108°24′E in longitude, encompassing almost the whole of Quang Nam province, Da Nang city, and a part of Kon Tum and Quang Ngai provinces (see Figure 1).

The four major topography types in the basin are mountains (occupying most of the basin area, extending from the north to the west, the southwest and the south of the basin), hills (distributed in the east of the mountains), plains (mainly laying in the east of the basin, running in a north–south direction), and coastal sand dunes (stretching for hundreds of kilometers along the coastline). Complex topographic characteristics of the basin lead to the differences in river morphology between upstream and downstream. The upstream rivers have narrow beds, steep banks, and rapids. In the midstream area, river beds are relatively wide and shallow with lots of sand dunes. On the downstream region, the river network has unstable beds and gentle banks.

Due to its location in a tropical climate, VGTB river basin has a large annual average rainfall, ranging from 2,200 mm in the plains to over 3,000 mm in the mountains. Precipitation not only varies according to the topography of the basin, but also significantly changes between dry and rainy seasons. The rainy season starts in September and ends in December with the total rainfall accounting for 65–80% of the annual rainfall. Meanwhile, rainfall during the dry season that lasts from January to August accounts for only 20–35% of the annual rainfall.

Under the influence of topography, climate and land use activities, floods have occurred frequently in VGTB river basin (Loi *et al.* 2019). During the flood season, which generally lasts from October to December, there are on average 3–5 large flood events. Flood events often occur continuously in a short time, so the flood hydrograph has many peaks. In addition, the rise and fall of floods are quick in the upper and middle areas, but slow in the downstream areas. Hydropower plants

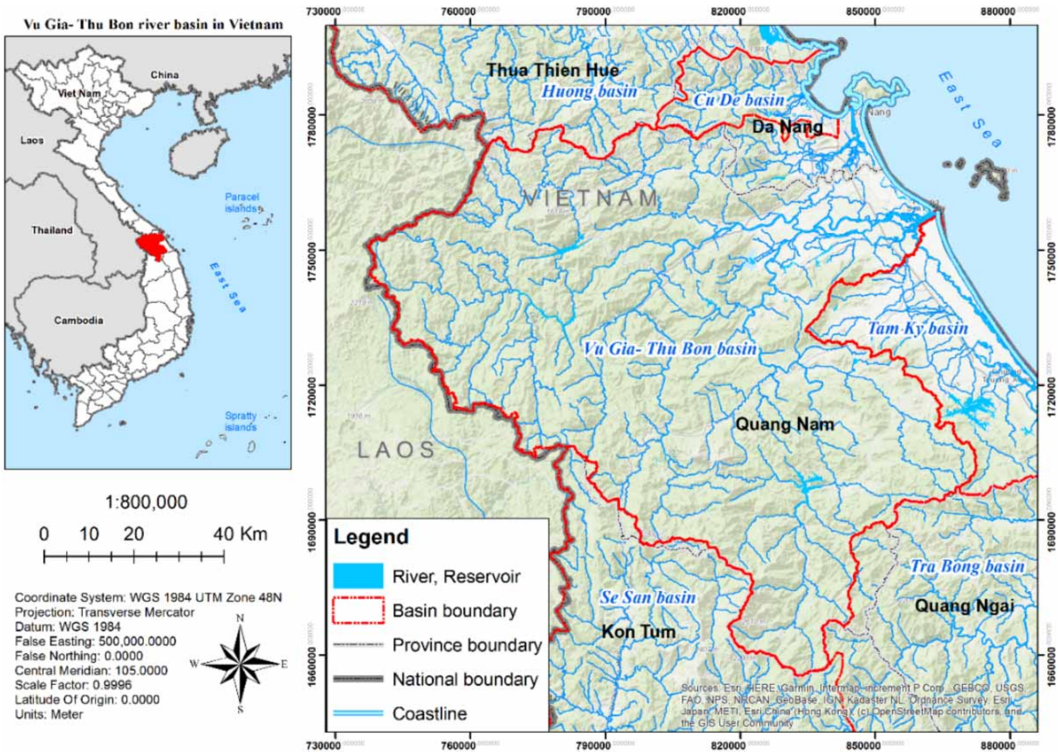

Figure 1 | Geographic location of VGTB river basin.

that have been operating or are under construction in the basin have not effectively reduced the risk of flooding. According to 19-year statistics from 1997 to 2015 (Luu & von Meding 2018), storms and floods in VGTB river basin left 726 dead and economic damage of 614.6 million USD (see Figure 2).

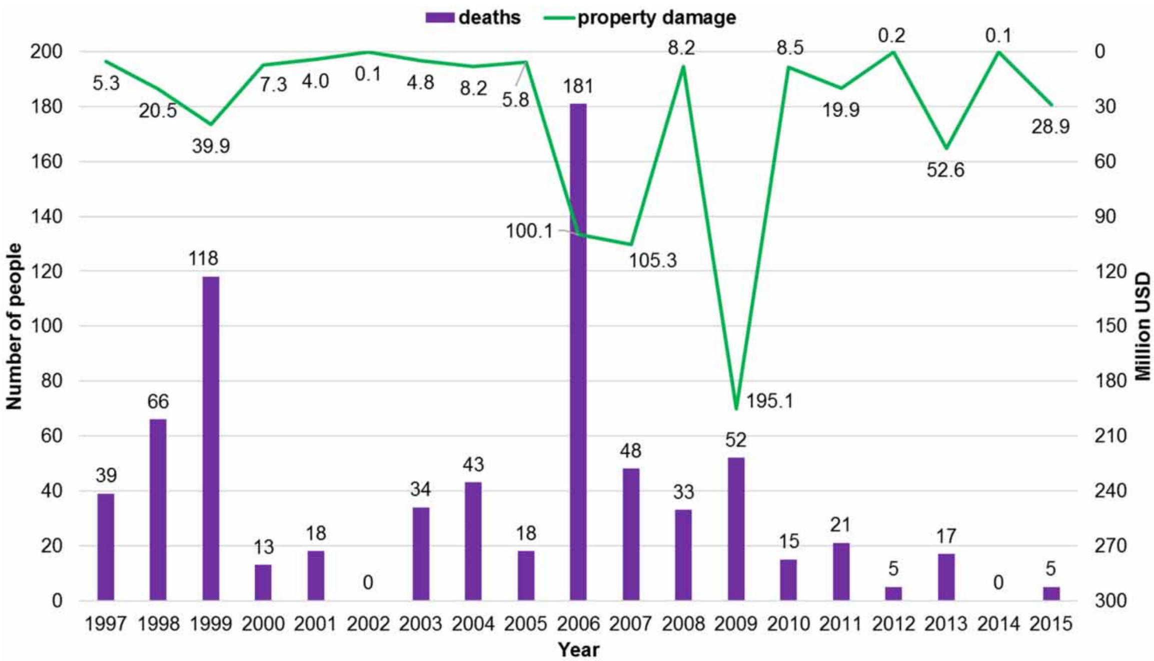

Figure 2 | Number of deaths and property damage caused by storms and floods from 1997 to 2015 in VGTB river basin.

The role of automatic hydro-meteorological observation network for real–time flood early warning system

We have developed a spatial decision support system for real-time flood warning in order to support vulnerable local communities downstream during extreme precipitation events upstream of VGTB river basin (Nguyen *et al.* 2020). The structure of this system consists of four components: automatic HM observation network, data processing centre, telecommunication infrastructure and end users (see Figure 3).

An automatic HM observation network records weather and stream flow data on a sub-daily basis in the basin, and transmits these data to a data processing centre via a GSM/GPRS network. At the data processing center, HM measurements (both historical data during 1980–2013 and real-time data since 2015), simulated flood maps, biophysical maps (hydrographical network, Digital Elevation Model, soil type, land use characteristic, road network, administrative unit) and socioeconomic information (end user) were stored in the Microsoft Structured Query Language Server database management system. For real-time flood forecasting, an automated module integrating the Soil and Water Assessment Tool (SWAT) hydrological model with the Hydrologic Engineering Centre's-River Analysis System (HEC-RAS) hydraulic model has been developed using a set of console scripts, HEC-RAS Controller (Goodell 2014) and mouse tracking. The reasons for selecting SWAT and HEC-RAS are that it is easy to use, free of charge and internationally accepted. There has been much effort to

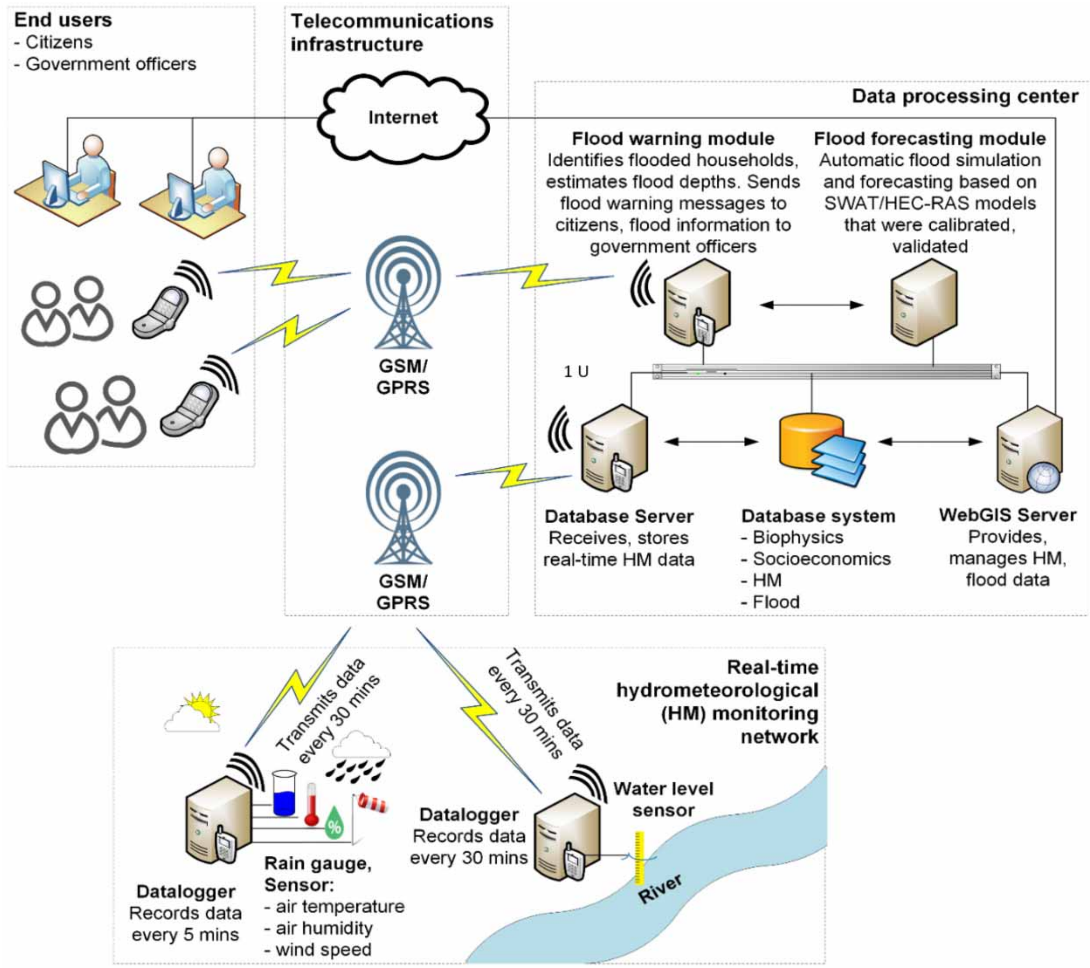

Figure 3 | The structure of real-time flood early warning system in VGTB river basin (Nguyen *et al.* 2020).

apply SWAT and HEC-RAS models for flood modeling and forecasting purposes (Divac *et al.* 2009; Santillan *et al.* 2012; Leon & Goodell 2016; Siqueira *et al.* 2016; Tiwary 2016). Both SWAT and HEC-RAS were calibrated and validated individually to ensure that flood events could be predicted 5 hours in advance with 80% accuracy. The simulation results of flood depth and flood time from the flood forecasting module had been stored in a WebGIS server before being displayed online using GeoServer. In the next step, a flood warning module was activated to send Short Message Service (SMS) flood alerts to citizens and flood information to government officers via GSM/GPRS network after identifying flooded households, and estimation of flood depths by comparing household information (geographic coordinates, full name, mobile phone number) with flood data.

End users are categorized into citizens and government officers, each having different access rights to the flood warning system database. Being a citizen account, the user can only view, query HM and flood data in the form of maps and charts and receive flood warning messages dependent on the specific situation. Meanwhile, as a government officer, the user not only owns the above functions, but also has the right to use advanced functions such as aggregating, exporting HM data, managing accounts and sending flood alert messages via SMS.

Design of automatic meteorological observation network

The process of optimising the number and location of weather stations on the VGTB river basin includes two phases: office work and field work (see Figure 4). The office work aims to allocate the optimal number of weather stations for each meteorological zone, and determine suitable areas for installing weather stations. The field work aims at examining field conditions (terrain, obstructions, and households), distances between stations and distances from weather stations to base transceiver stations to select

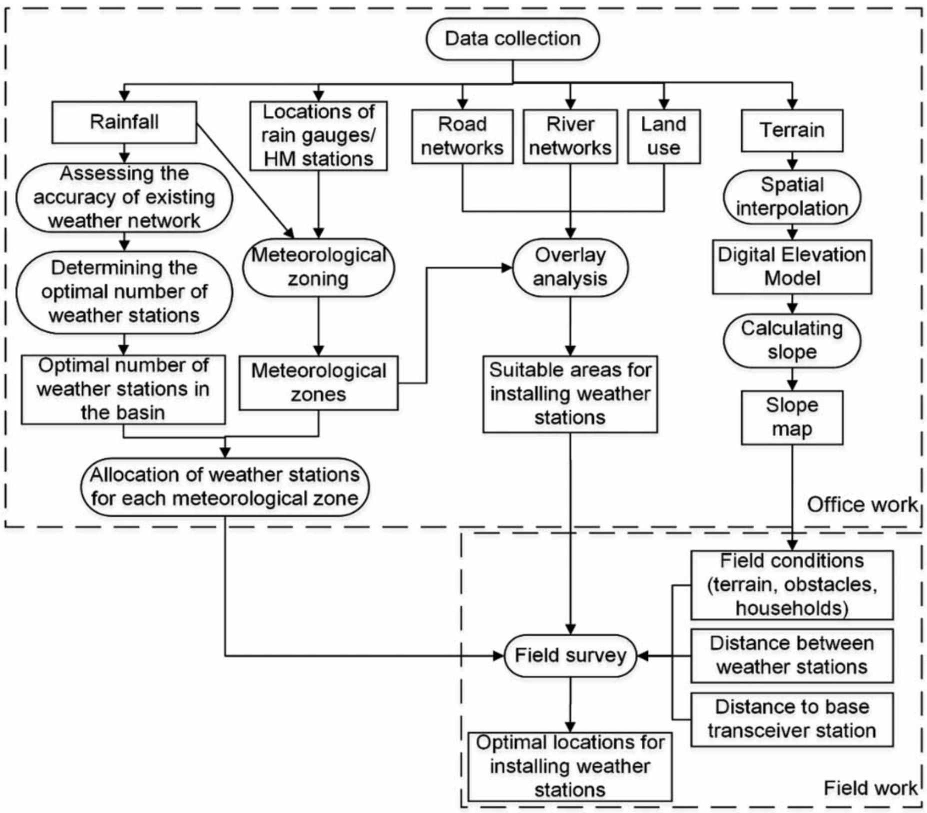

Figure 4 | The process for optimizing meteorological network on VGTB river basin.

the optimal location for installing weather stations that meet Vietnam's legal frameworks.

Based on the input data including geographic location and rainfall of rain gauges/HM stations, road networks, river networks and land use, the office work was carried out sequentially according to the following five steps. Step 1: Based on the rainfall measurement data at rain gauges, HM stations in VGTB river basin, we assessed the accuracy of the existing weather network by coefficient of variation. Step 2: Based on the coefficient of variation determined in the previous step, we calculated the optimal number of weather stations to be installed on the basin in order to meet the requirements of a flood warning system. Step 3: From the rainfall measurement data and geographic location of rain gauges/HM stations, we conducted meteorological zoning in the basin. Step 4: From the optimal number of weather stations (Step 2) and the meteorological zones (Step 3), we allocated weather stations for each meteorological zone. Step 5: Based on road networks, river networks and land use data, we overlaid these data to determine suitable areas for installing weather stations according to Vietnam's legal frameworks.

Design of an automatic hydrological observation network

Similar to meteorological networks design, the process of optimizing the number and location of hydrological stations on VGTB river basin also involves two phases: office work and field work (see Figure 5). The office work aims to determine the optimal number of hydrological stations, and find suitable river sections for installing these stations. The field work aims at examining field conditions (terrain, road accessibility and households), and distances from hydrological stations to base transceiver stations to select the optimal location for installing hydrological stations that meet Vietnam's legal frameworks.

Based on the input data including terrain, satellite images and river networks, the office work was carried out sequentially according to the following three steps. Step 1: Based on topographic map, we classified the topography of VGTB river basin into two types: hills/plains and mountains. Step 2: Based on WMO regulations on the minimum density for stream gauges by terrain, we determined the optimal number of hydrological stations. Step 3: Based on satellite images and river networks, we identified suitable river sections for installing hydrological stations meeting two groups of criteria according to WMO regulations and Vietnam's legal frameworks. Moreover, the location of the hydrological station must support the calibration and validation of SWAT model for upstream streamflow and HEC-RAS model for the downstream water level.

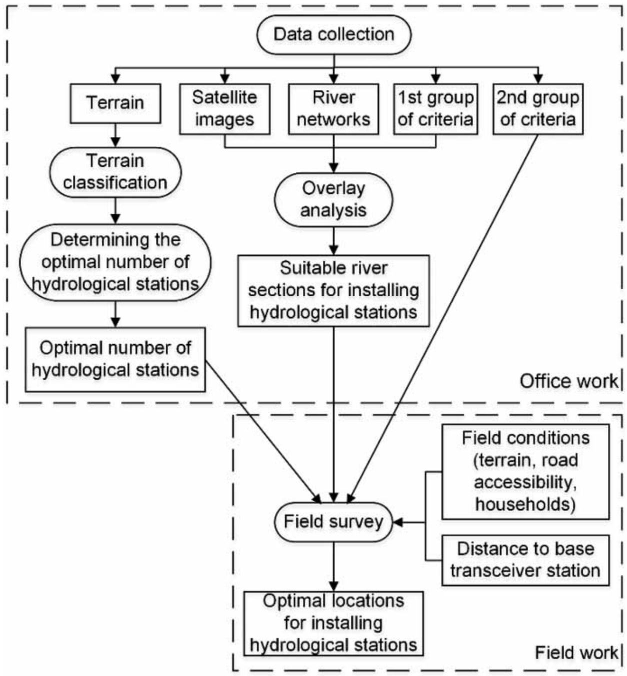

Figure 5 | The process for optimizing a hydrological network on VGTB river basin. The first group of criteria are: (1) river section must be straight, far away confluence of rivers or reservoirs, avoiding rapids; (2) Satisfy data demand of SWAT and HEC-RAS models. The second group of criteria are: (1) river section is relatively straight with a stable bank, without confluence or bifurcation, and less compromised by human activities; (2) river bed is relatively stable, water surface is without sudden changes (expansion or contraction); (3) near road networks for convenient construction; (4) construction areas must be at least 4 m^2, flat (with a slope of less than 15°) and have a stable ground structure; (5) construction areas must be covered with mobile coverage to ensure signal transmission.

RESULTS AND DISCUSSION

Automatic meteorological observation network

Optimal number of weather stations

Currently, there are two rain gauge systems operating independently on VGTB basin: one includes rain gauges located upstream of large reservoirs under the management of the reservoir owners, the other includes rain gauges and hydrometeorological stations installed throughout the basin managed by the Mid-Central Hydro-Meteorological Centre. However, due to the privacy of the reservoir owners, we cannot access their precipitation data. Therefore, only rainfall data provided by the Mid-Central Hydro-Meteorological Centre was used. According to the Mid-Central Hydro-Meteorological Centre, there are 13 rain gauges and HM stations in operation on VGTB river basin (see Figure 6). Among them, nine stations have complete and valid data for optimal analysis of HM stations. The multi-annual average rainfall from 1980 to 2013 of these stations is shown in Table 1. Based on rainfall measurement data at rain gauges and HM stations, we

Table 1 | The multi-annual average rainfall from 1980 to 2013 of rain gauges and HM stations on VGTB river basin

No.	Rain gauges/HM stations	Multi-annual average rainfall (mm)
1	Thanh My	2,278.88
2	Hoi Khach	2,235.82
3	Ai Nghia	2,430.10
4	Hiep Duc	3,171.79
5	Nong Son	3,047.96
6	Tra My	4,160.78
7	Kham Duc	3,280.00
8	Tien Phuoc	3,308.50
9	Hien	2,293.90

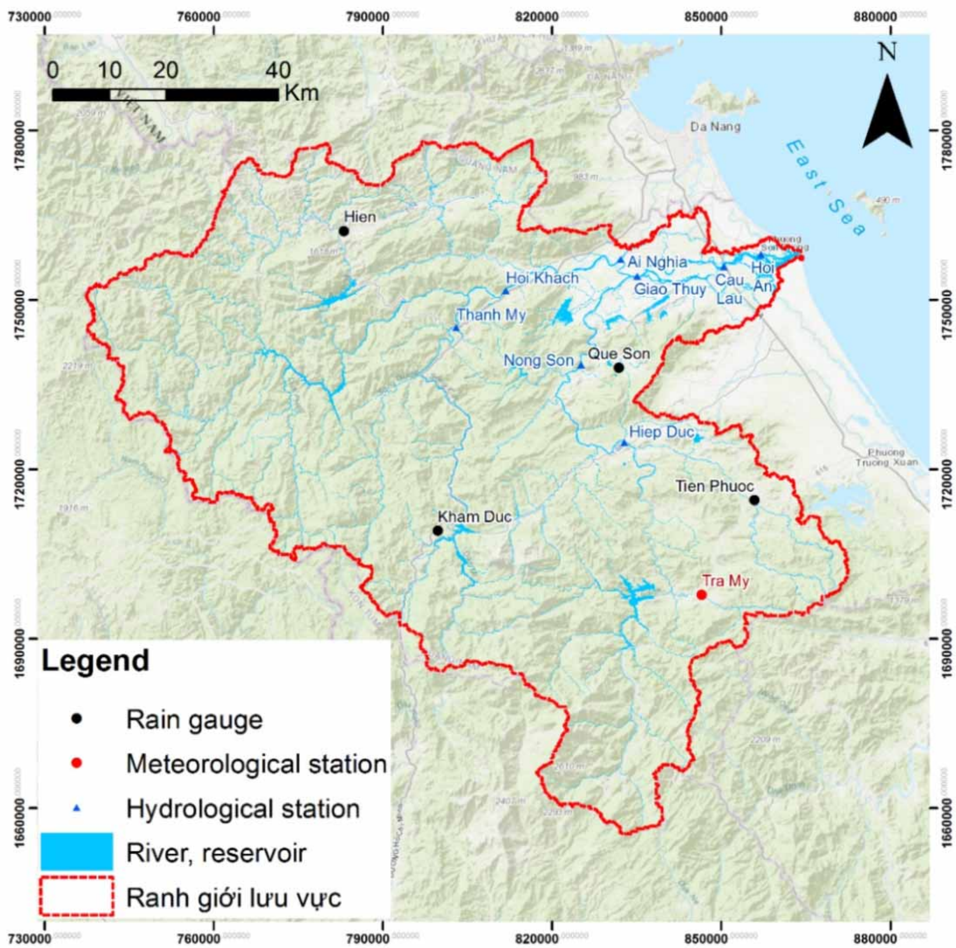

Figure 6 | Rain gauges and HM station network on VGTB river basin.

evaluated the accuracy of the existing weather network using the following equation (Mazdoor *et al.* 1994):

$$p = \frac{C_v}{\sqrt{N}} \quad (1)$$

where p is the current error in estimating rainfall over the basin, C_v is the coefficient of variation of rainfall and N is the number of existing weather stations in the basin. The results showed that the error of the existing weather network was about 7.47%.

Based on C_V determined in the previous step, we calculated the optimal number of weather stations to be installed on the basin with an error of 5%. To meet the requirements of the flood warning system, the accuracy of the weather network must be at least 95%. As a result, the required number of weather stations should be 20.

Spatial interpolation of multi-annual average rainfall in the study area was based on rainfall data series in the period 1980–2013 by Spline algorithm with a regularized option. The result presented in Figure 7 reflects the spatial

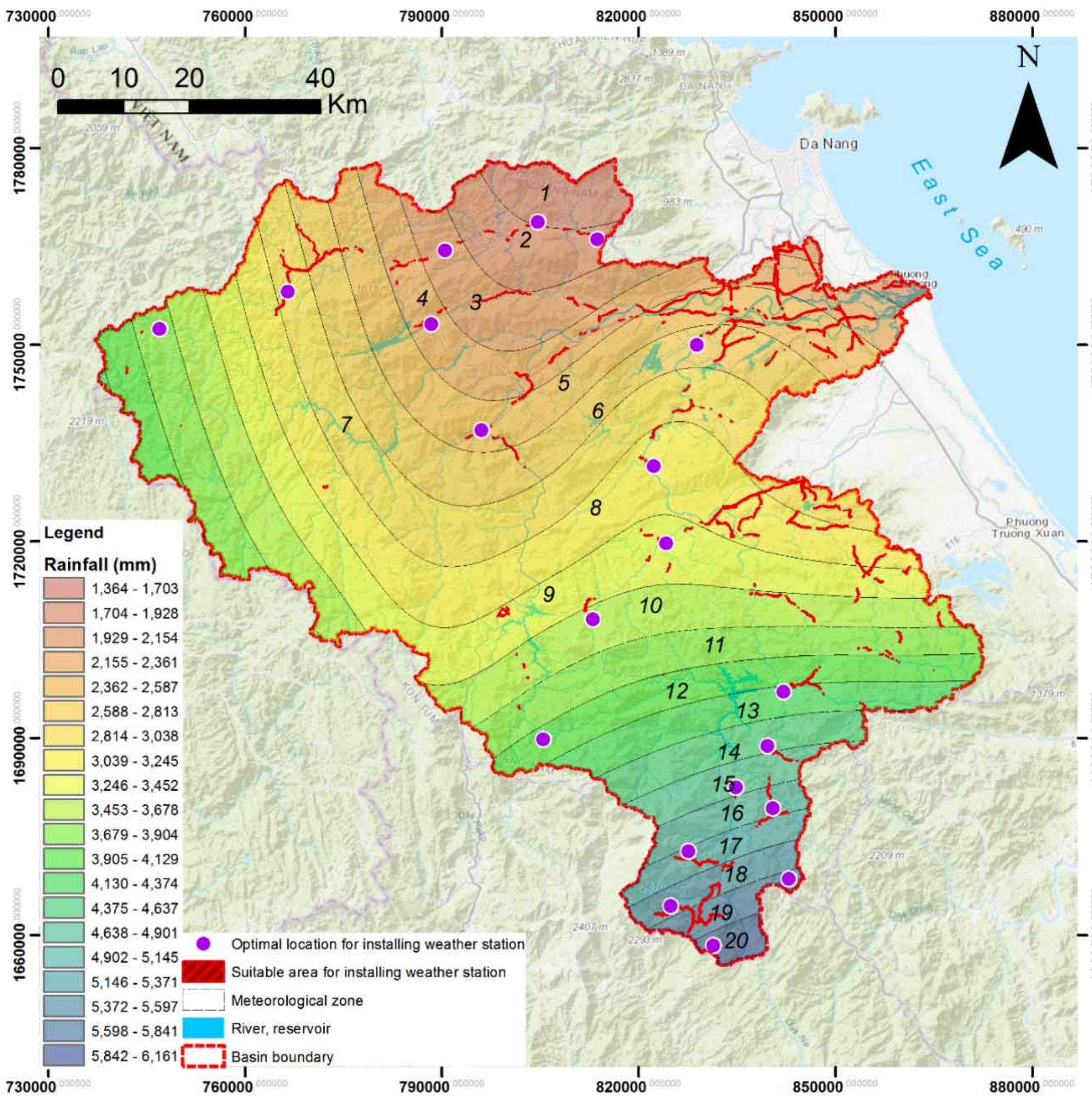

Figure 7 | The suitable areas and optimal locations for installing weather stations on VGTB river basin.

distribution of rainfall on the basin as previous studies have shown (Duong & Gourbesville 2014; Hanh & An 2018). The average annual rainfall increases gradually from the plain to the mountainous region and gradually increases from north to south. Next, meteorological zoning using Jenks' Natural Breaks algorithm resulted in the number of meteorological zones equal to the optimal number of weather stations to be installed on the basin (see Figure 7). Jenks' Natural Breaks algorithm is the recommended classification method for cases of unevenly distributed values because it seeks to reduce the variance within classes and maximize the variance between classes. This feature is consistent with the constraint for optimizing the location of weather stations, which is the less similar the rainfall values measured at the stations, the richer the amount of data collected. From the results of meteorological zoning, we allocated one weather station for each meteorological zone.

Suitable areas for installing weather stations

We overlaid road networks, river networks and land use data to determine suitable areas for installing weather stations based on Vietnamese Standards in meteorology (Ministry of Natural Resources and Environment 2012a) and irrigation (Ministry of Science and Technology 2009). Specifically, weather stations must be within the 100 m buffer zone of road networks and be at least 100 m away from river networks, preferably located at office buildings and residential land. The result showed suitable areas for installing 20 weather stations on VGTB river basin (see Figure 7).

Optimal locations for installing weather stations

According to Vietnamese Standards in meteorology (Ministry of Natural Resources and Environment 2012a) and irrigation (Ministry of Science and Technology 2009), the selected locations for installing weather stations must satisfy the following requirements: (1) within suitable areas; (2) near road networks for convenient construction; (3) construction areas must be at least 4 m^2, flat (with a slope of less than 15°), have a stable ground structure and not covered in order to receive sunlight; (4) construction areas must have mobile coverage to ensure signal transmission; (5) distance between stations must be between 10 and 15 km (in mountainous areas) and 15–20 km (in midland and delta areas). The field trips that took place during December 3–5, 2014, identified 20 optimal locations for installing weather stations that met the above criteria (see Figure 7).

Components of an automatic weather station

The automatic weather station consists of a weather-proof enclosure containing data logger, rechargeable battery and meteorological sensors (rain gauge, thermometer, hygrometer, pyranometer and anemometer) with an attached solar panel and mounted upon a mast (see Figure 8). To capture changes in weather in the basin, the 5-minute recording frequency option was set. All meteorological data were transmitted every 30 minutes to the data server of the data processing centre via the GSM/GPRS network.

Automatic hydrological observation network

According to Kapos *et al.* (2000), hills/plains occupy an area of approximately 7,565 km^2 of VGTB river basin, while the remaining area of about 1,114 km^2 is mountains. Based on WMO regulations (World Meteorological Organization

Figure 8 | Automatic weather station installed on VGTB river basin. Photograph taken by authors.

1994) on the minimum density for stream gauges by terrain, it was necessary to install at least four stations for hilly/plain areas and one station for mountainous areas. Thus, the total number of hydrological stations that need to be installed on VGTB river basin was five.

Based on satellite images and river networks, we identified suitable river sections for installing hydrological stations meeting the first group of criteria (Ministry of Science and Technology 2009; World Meteorological Organization 2010; Ministry of Natural Resources and Environment 2012b): river section must be straight, without confluence or birfurcation, and has no rapids. In addition, the location of the hydrological station must satisfy data the demands of the SWAT and HEC-RAS models.

The suitable river sections for the installation of hydrological stations on VGTB river basin are shown in Figure 9. Accordingly, station TV1 was located in mountains behind A Vuong hydropower plant to monitor water discharges from this plant. The remaining four stations were located in hills or plains. Station TV2 was located near the outlet of the Vu Gia branch, in front of Ai Nghia station to monitor the streamflow of the Vu Gia branch before joining with the Thu Bon branch; station TV3 was located near the outlet of the Thu Bon branch, in front of Giao Thuy station to monitor the streamflow of the Thu Bon branch before joining with the Vu Gia branch. Both TV2 and TV3 stations served for calibration and validation of the SWAT model. The others (TV4, TV5) were located to coincide with Giao Thuy and Hoi An hydrological stations in order to monitor the downstream water level and serve for calibration and validation of the HEC-RAS model.

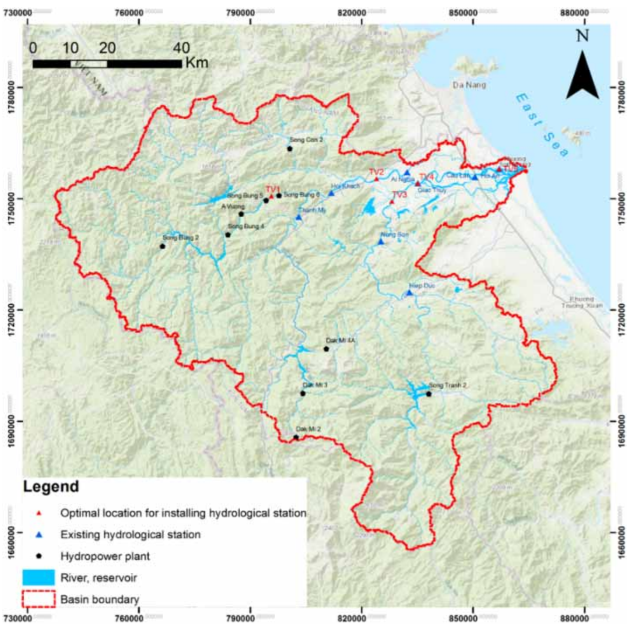

Figure 9 | The optimal locations for installing hydrological stations on VGTB river basin.

According to Vietnamese Standards in hydrology (Ministry of Natural Resources and Environment 2012b), irrigation (Ministry of Science and Technology 2009) and WMO (World Meteorological Organization 2010), the selected locations for installing hydrological stations must satisfy the second group of criteria (Ministry of Science and Technology 2009; World Meteorological Organization 2010; Ministry of Natural Resources and Environment 2012b): (1) river section is relatively straight with a stable bank, without confluence or the place where the stream splits apart and is less affected by human activities; (2) river bed is relatively stable, water surface is without sudden changes (expansion or contraction); (3) near road networks for convenient construction; (4) construction areas must be at least 4 m^2, flat (with a slope of less than 15°) and have a stable ground structure; (5) construction areas must be have mobile coverage to ensure signal transmission. Thanks to field surveys with on first trip from December 3–5, 2014, and the second trip from May 24–26, 2015, we identified five optimal locations for installing hydrological stations that met the above criteria.

The automatic hydrological station consists of a weatherproof enclosure containing a data logger, rechargeable battery, and ultrasonic water level sensor with an attached solar panel and mounted upon a mast (see Figure 10). To capture changes in stream flow in the basin, the half-hour recording frequency option was set. All hydrological data was transmitted every 30 minutes to the data server of the data processing centre via the GSM/GPRS network.

The effect of automatic meteorological observation network on flood simulation in the basin

In this study, flood simulation was performed using an integrated SWAT and HEC-RAS modeling system (Loi et al. 2019) to confirm the effect of the automatic meteorological observation network. Specifically, weather data were

Figure 10 | Automatic hydrological station installed on VGTB river basin. Photograph taken by authors.

imported into the SWAT model to generate stream flow. These simulated stream flow values were then input to the HEC-RAS model to simulate water level. Two cases of using weather data were examined, namely, nine stations (meaning nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre) and 29 stations (meaning nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre plus 20 automatic weather stations). The hourly water levels simulated for these two cases were compared with the observed values at Ai Nghia and Giao Thuy hydrological stations in the flood season of 2015. As shown in Figures 11–14, both weather cases effectively simulated the flood duration and water level change pattern. However, with regard to flood peak and lag time, the simulation results in the case of using 29 stations were better than those when using nine stations as demonstrated by Nash–Sutcliffe efficiency (NSE) (see Table 2). In two flood events of 2015, if nine stations were used, the simulated water levels were only acceptable at Ai Nghia station in the flood of November 2015. The remaining cases were not acceptable. Meanwhile, if using 29 stations, water level values were well simulated. This suggests that the integration of traditional and automated meteorological observation networks has contributed to improving the accuracy of flood simulation in VGTB basin.

CONCLUSIONS

Although VGTB river basin is ranked number eight among the largest river basins in Vietnam, with an area of over 10,000 km^2, there are currently only four rain gauges, one

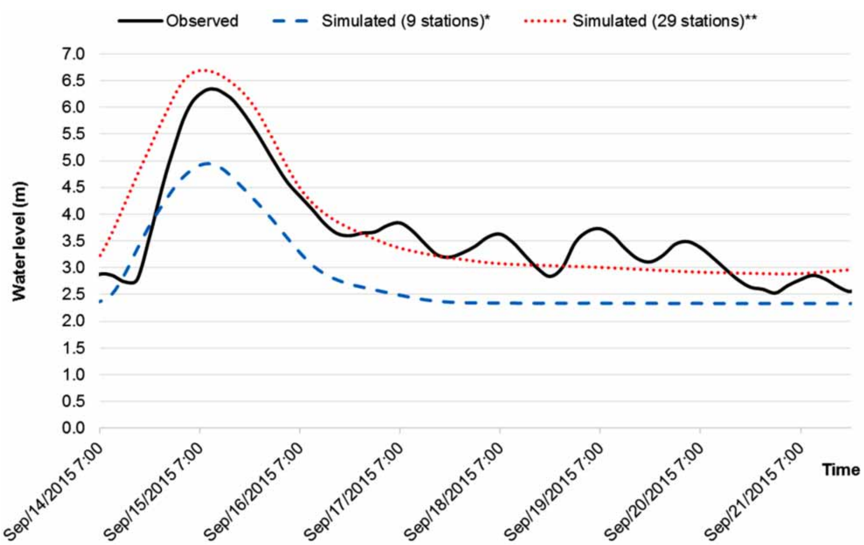

Figure 11 | Comparisons between observed and simulated water levels on hourly timestep at Ai Nghia stream gauge during a flood event in September 2015. (*nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre; **nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre plus 20 automatic weather stations).

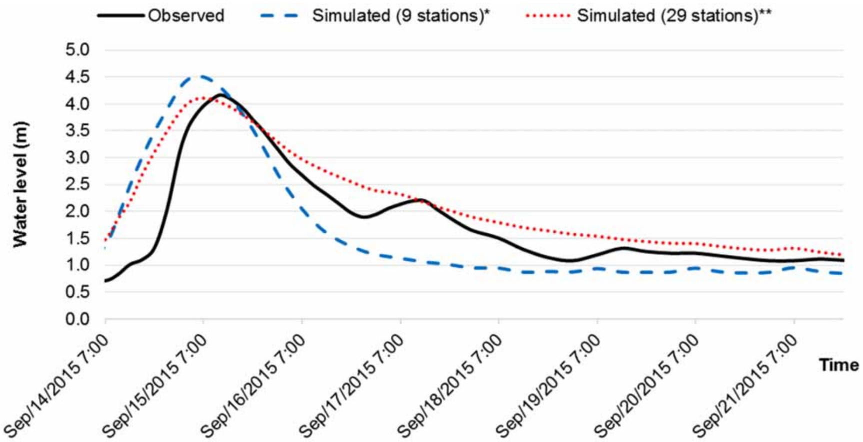

Figure 12 | Comparisons between observed and simulated water levels on hourly timestep at Giao Thuy stream gauge during flood event in September 2015. (*nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre; **nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre plus 20 automatic weather stations).

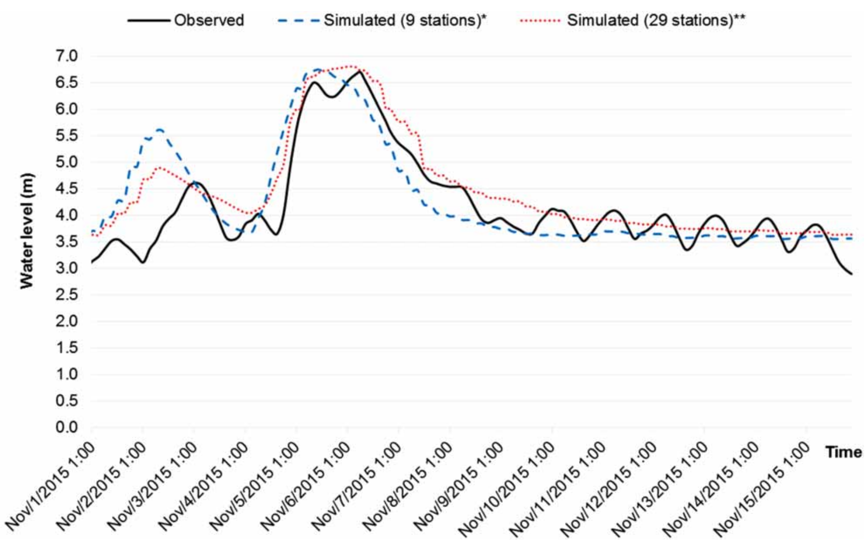

Figure 13 | Comparisons between observed and simulated water levels on hourly timestep at Ai Nghia stream gauge during flood events in November 2015. (*nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre; **nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre plus 20 automatic weather stations).

surface meteorological station and eight hydrological stations in operation on this basin. Most of the existing stations are located downstream, characterized by the presence of riverine flood plains and coastal sand dunes. In contrast, there are few stations in the upstream, where the terrain is mountains and hills, precipitation is high, and the rise and fall of floods are quick. These rain gauges and HM stations operate manually under the management of the Mid-Central Hydro-Meteorological Centre. Thanks to the additional installation of 20 meteorological stations and five hydrological stations, we have contributed to increasing the density of the HM observation network on VGTB basin, especially in hard-to-reach areas upstream. The automatic monitoring method allows these stations to monitor the change of weather and stream flow round-the-clock with data recording frequency easily customized by the users according to their requirements. On the other hand, according to the master plan for national natural

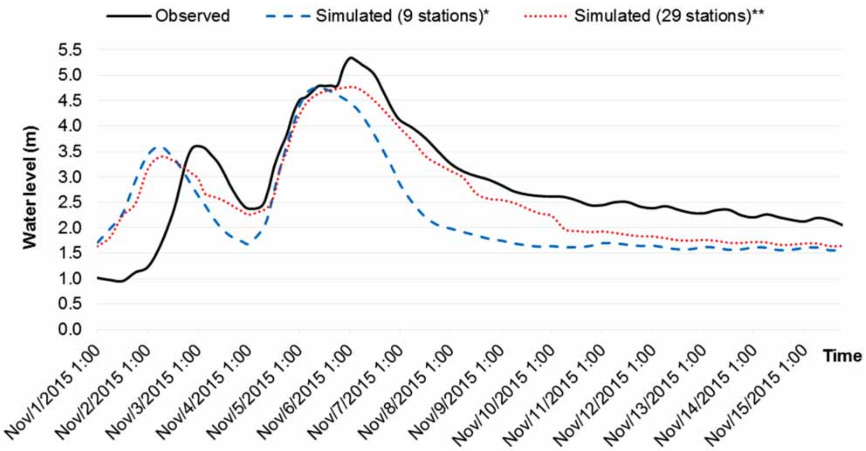

Figure 14 | Comparisons between observed and simulated water levels on hourly timestep at Giao Thuy stream gauge during flood events in November 2015. (*nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre; **nine rain gauges, HM stations operated by Mid-Central Hydro-Meteorological Centre plus 20 automatic weather stations).

Table 2 | Evaluation results in terms of NSE for simulated water level using various weather data

		Weather data case	
Flood event	**Stream gauge**	**Nine stations**	**29 stations**
September 14–21, 2015	Ai Nghia	0.24	0.75
	Giao Thuy	0.44	0.74
November 1–15, 2015	Ai Nghia	0.65	0.81
	Giao Thuy	0.28	0.72

resources and environment monitoring networks for 2016–2025, with a vision to 2030 (Vietnamese Government 2016), there will be six new surface meteorological stations installed on VGTB river basin. At that time, if the Mid-Central Hydro-Meteorological Centre's observation network and our automatic monitoring stations are integrated, it will create a large amount of HM data which contributes to improving the accuracy of flood forecasting in the basin.

Compared to previous studies, the novelty of our study lies in an interdisciplinary approach integrating coefficient of variation, spatial interpolation, spatial analysis, Vietnamese Standards and WMO regulations to optimally design an automatic HM observation network in order to improve the availability and continuity of weather and stream flow data in VGTB river basin. This allows the detection of significant differences in the local climate between upstream and downstream as well as providing detailed HM data for inundation simulation in the basin.

The limitation of our automatic HM observation network is the high system maintenance cost. Validation/calibration of measuring equipment needs to be carried out every six months to ensure full and accurate HM monitoring data. Automatic HM stations also need to be maintained in order to maintain normal system operating conditions. Further research should utilize the constantly increasing volume of the HM database for specific applications such as climate change assessment, drought forecasting and water balance calculations.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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