PAN POLSKA AKADEMIA NAUK

JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

ITP-PIB

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2025.155306
2025, No. 66 (VII–IX): 98–105

Assessing the impact of flood on crop production in the Nabogo River basin, Ghana

Sumo Nula Mulbah*[1)], Abdul-Ganiyu Shaibu[1)], Musah S. Zango[2)]

[1)] University for Development Studies, West African Center for Water, Irrigation and Sustainable Agriculture, P.O. Box TL 1882, Tamale, Ghana

[2)] University for Development Studies, Department of Geology, P.O. Box TL 1350, Tamale, Ghana

* Corresponding author

RECEIVED 15.11.2024 ACCEPTED 27.03.2025 AVAILABLE ONLINE 14.08.2025

Abstract: The study examines the impact of floods on crop production in the Nabogo River basin, identifying flood risk and area affected. The flood extent in the research region was determined using Sentinel 1 images, global surface water, and a digital elevation model between July and October 2023. Flood analysis was carried out using Sentinel-2A and MODIS images, with cloud processing avoided and cloud and shadow masking techniques utilised. High-resolution data were used to map land use land cover (LULC) for affected and non-affected crops in the Nabogo River basin. The analyses were processed using Google Earth Engine. Heavy rainfall in the region, particularly upstream of the Nabogo River in northern of Ghana and Burkina Faso, causes severe flood damage every year, affecting farmers' crop production and social economics through surface runoff and riverine damage. The flood extent inundates a minimum of 50 ha in July, extending to 34,090 ha in August. The flood extent reached its peak of 60,900 ha in September during discharge of water at the Burkina Faso's Bagri Dam spillway through the White Volta in Ghana. Between July and October 2023, 24,223 ha of farm land were flooded, affecting 5,928 ha of crops. The impacted cropland experienced a 28-day flood with an average height of 1–3 m. Nevertheless, many farmers are forced to produce along the riverbank anyway due to land ownership and soil fertility benefits. To prevent ongoing losses, early-maturing crops are recommended.

Keywords: crop damage, flooding, food security, Google Earth Engine (GEE), remote sensing, river basin, Volta

INTRODUCTION

Floods are rapid inundations of water onto dry terrain, often caused by overflowing water bodies or intensive precipitation. They can result in loss of life and significant damage to property. The complexity of flooding depends on a variety of causes and their intensity, largely affected by atmospheric and hydrological processes. Climate change impacts all natural processes with different types and timing of floods (Whitfield, 2012). Broadly speaking, flood calamities can be divided into three primary categories: natural floods, altered natural floods, and entirely human-induced floods. The main causes of the flooding include extreme rainfall, debris accumulation, river overflow, coastal flooding, urbanisation, poor drainage, and issues related to land ownership.

In 2012, flooding caused economic losses exceeding $19 bln globally, necessitating integrated global flood risk assessment to prevent significant damage to infrastructure, croplands, and animals, and mitigate threats to food security (Reed *et al.*, 2022). The study predicts global average yield losses of 4% for soybeans, 3% for rice, 2% for wheat, and 1% for maize over longer return periods, resulting in a production loss of $5.5 billion (Kim, Caputo and Kilders, 2023).

In 2020, 720–811 mln people worldwide suffered from hunger, 161 mln more comparing to 2019, and 2.37 bln had inadequate access to food, largely due to high costs of healthy diets. Hunger-induced malnutrition can lead to disorders, while flood-related disasters affect victims' mental health, socio-economic status, and food security (Soulibouth, Hwang and Shin, 2021).

Flooding, a global issue in recent years, has hindered economic and social progress, causing loss of life and extensive damage in countries like Ghana. In 2015, Accra, the capital of Ghana, experienced a devastating flood that claimed over 150 lives. It is crucial to consider innovative solutions to integrate into current infrastructure to address this issue (Asumadu-Sarkodie, Owusu and Rufangura, 2017). The country's economy is based mostly on agriculture, generating 50% of the country's GDP. Ghana's agricultural production focuses in rural areas, where the majority of households make their living by growing crops and raising a small number of animals. Implementing flood control and regulation policies is vital in mitigating economic risks, preserving human life, and maintaining environmental sustainability (Manzoor *et al.*, 2022).

In 2007, severe floods in Northern Ghana caused significant damage, resulting in 20 deaths and destroying vital infrastructure, livestock, and disrupting food supplies. The floods occurred during the lean farming season, causing food insecurity. The disaster was exacerbated by an extended dry period, heavy rainfall, resulting in the discharge of water from the Bagre Dam in Burkina Faso, affecting the already vulnerable systems (Armah *et al.*, 2010).

The hunger surge in the Nabogo River basin is primarily due to climate change, which threatens food security and livelihoods (Chen *et al.*, 2019). Climate-related shocks jeopardise people's capacity to feed themselves and ruin lives, farms, and livelihoods (Chen *et al.*, 2019). The region's main employment source is agriculture, with a significant portion of the population engaged in crop production and animal raising, primarily relying on rain as the primary resource for food production (Armah *et al.*, 2010). According to Derbile *et al.* (2016). Thus, flood disasters significantly affect the region's food crops, including cereals, tubers, and legumes like maize, millet, and sorghum. These crops can be destroyed or damaged due to flooding, damp weather, and mould growth. Additionally, discharges from the dam cause floods affecting people, crops, and animals (Tankpa *et al.*, 2021). The basin, a flat area vulnerable to floods with few hilly sites in the southern section, is primarily drained by the White Volta and its tributaries, with the Nabogo River traversing the area (Barry *et al.*, 2005).

Sulemana *et al.* (2023) claim that changes in water level also disturb aquatic ecosystems, impacting biodiversity and fish populations, both of which are vital to the food and economic well-being of riverine communities. Therefore, having a backup source of income during such difficulties can be quite challenging for many farmers. According to FAO (2020), if action is not taken swiftly to address climate change, hunger would extend beyond control.

This study focuses on using remote sensing, Google Earth Engine, and GIS to determine the extent of flood hazards in agricultural areas, assess flood damage, and map flood hazards, highlighting the benefits of model integration in decision-making and the potential for disaster risk mitigation. These technologies can serve as a safeguard to help farmers choose the best time, location, and variety of crops to grow in a given area. Overall, this study can be applied to reduce crop loss and can be replicated in other areas.

MATERIALS AND METHODS

GEOGRAPHICAL LOCATION OF THE STUDY AREA

The Nabogo, a downstream basin in Savelugu, Nanton, Gushegu and Karenga districts in Northern Ghana, is severely affected by flooding due to discharges from the Burkina Faso dam and seasonal rainfall.

The Nabogo River basin is located near Tamale within the Northern Region of Ghana. Positioned between the latitudes of 9° 32'N and 10°01'N and longitudes of 0°59'W and 0°15'W (Fig. 1),

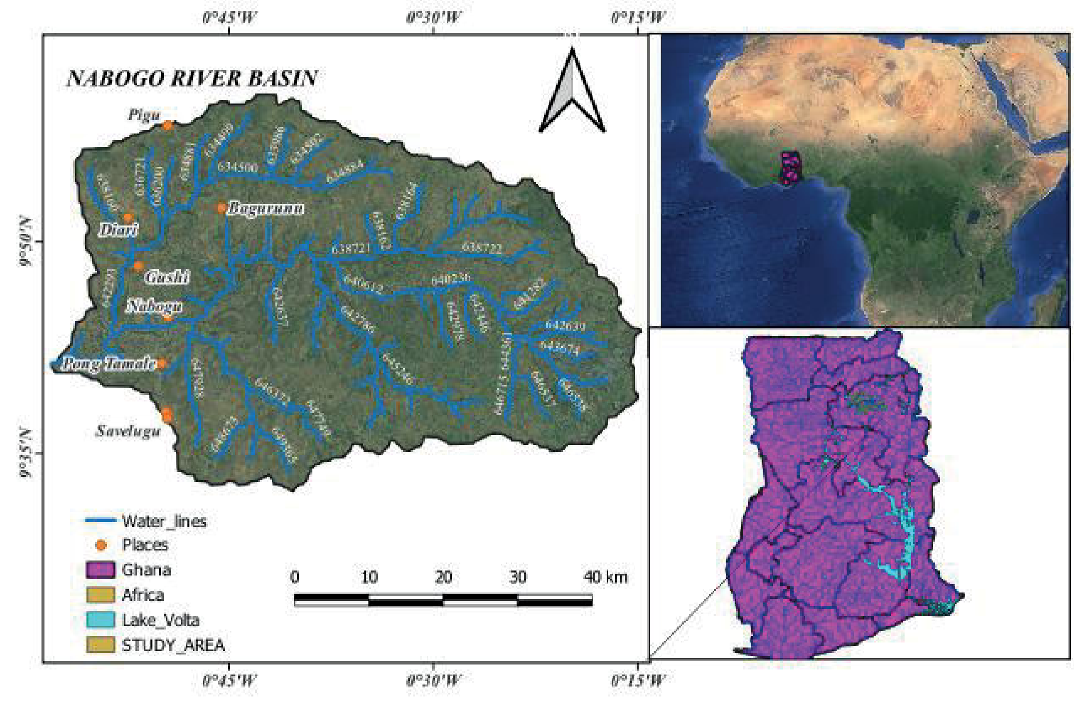

Fig. 1. Geographical location of the study area (Nabogo River basin); source: own elaboration

this region is known for its unique geographical features. The Nabogo basin, a sub-basin of the White Volta basin, spans 2,900 km^2 and has elevations ranging from 106 to 269 m a.s.l. It experiences a unimodal precipitation pattern from April to October, with an average annual rainfall of 1,094 mm. Temperature differences range from 22.9 to 34.5°C, with significant rainfall occurring between May and October (Apogba *et al.*, 2024).

DATA COLLECTION

This study used both primary and secondary data. Meanwhile, secondary data was obtained from published works and the gauge station of the Nabogo River. To assess potential flood extend in cropping areas and assess flood damage, the study used Sentinel1 and 2 and MODIS data, while the digital elevation model, hydro SHEDS, global surface water, stream flow data and climate data were utilised as additional sources of supporting information. The Sentinel-1 Ground Range Detected (GRD) scenes in Google Earth Engine (GEE) are processed using the Sentinel-1 Toolbox to produce an ortho-corrected, calibrated result. The GEE is used for flood extent analysis, particularly when using remote sensing data. Pre-processing and processing techniques include decibel conversion, noise elimination, and adjustments to terrain before and after floods. Techniques include the application of a digital elevation model, correcting geometric distortions, and using a 50 m smoothing radius speckle filter (Kumar *et al.*, 2022).

METHODS

The approach involves two steps: estimating the extent of flooding in cropping areas, and assessing the damage to crops caused by flooding. The flowchart of the methods used in this investigation is displayed in Figure 2.

SENTINEL-1

The research area experienced a flood from July to October 2023, calculated using Sentinel images, global surface water, and a digital elevation model. Sentinel-1A and Sentinel-1B formed a satellite constellation near the Arctic Circle, providing radar imaging coverage. The GRD product of Sentinel-1A satellite was used to extract the flooded area, with data from 10 m pixels resolution (Pandey, Awasthi and Jain, 2024).

Every day, all Sentinel 1-A and 1-B GRD image products taken in ascending orbits are added to the collection. Inter-

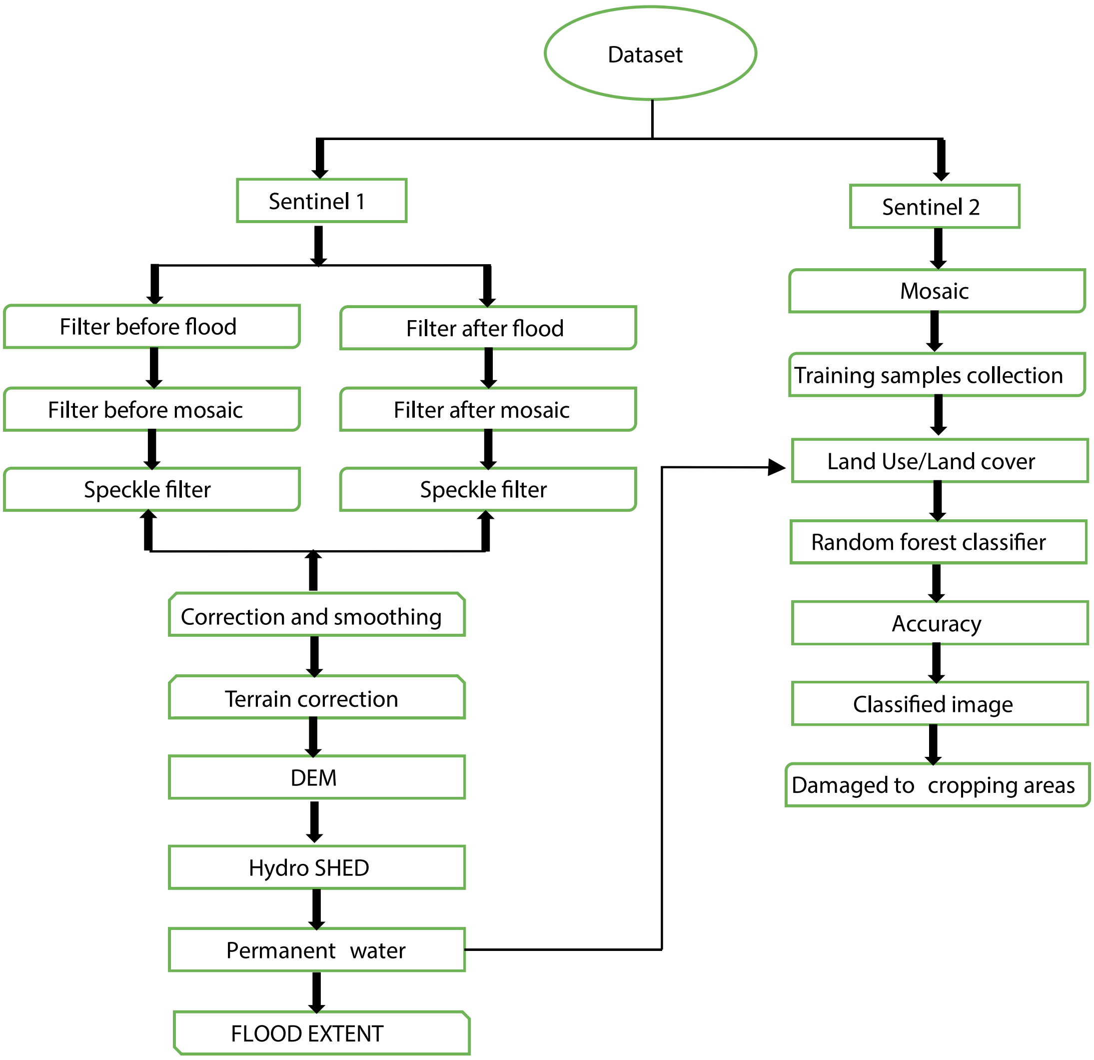

Fig. 2. Flowchart of research methods; source: own elaboration

ferometry wide swath mode is used to acquire the GRD images used in this framework. The pre-processing for SAR backscatter includes thermal removal, radiometric calibration, speckle filter, and terrain correction. The Sentinel-1 GRD product includes a calibration vector for image intensity conversion. A linear unified transformation (LUT) is used to generate Sigma-naught values varying with angles, wavelengths, polarisation, and scattering surfaces (Wang, Liu and Chen, 2022).

To lessen the impact of the granular noise, a 50 m smoothing radius speckle filter was applied during processing using the GEE platform. To adjust for the geometric distortions, present in SAR images, terrain correction was employed. Using a threshold of 1.25, before- and during-flood mosaics were separated to assess the alterations caused by floods. The resulting graphic analysis shows that the darker (lower values) pixels are less variable than the brighter (higher values) ones. Next, with a threshold value of 1.25, a binary raster layer is formed, designating 0 for all values below 1.25 (non-flood pixels) and 1 for all values over 1.25 (flood pixels) (Khan *et al.*, 2024).

The study used "VH" polarisation for flood mapping to account for the overestimation of "VV" polarisation results. The "VH" polarisation had more dark and black tones, making it suitable for identifying flood-affected areas. Post-processing refined the processed data for specific applications, including classification, change detection, time-series analysis, data fusion, and visualisation. This process helps identify flood-affected areas and improves the accuracy of flood mapping (Pandey, Awasthi and Jain, 2024).

LAND USE LAND COVER

The GEE platform used Sentinel-2A and MODIS images for flood analysis, avoiding cloud processing due to MODIS's composite dataset. Cloud and shadow masking techniques were used to eliminate gaps in data. Multi-temporal observations were combined for a seamless median composite imaging for 2023.

Sentinel 2 and MODIS produced Land Use Land Cover (LULC) that was used for high resolution mapping of the land cover for both affected and non-affected crops in the Nabogo River basin. Next, based on 231 sample points the flood extent (55), water-body (56), affected croplands (60), and unaffected cropping areas (60) of the basin – as well as the kappa coefficient – which is also used to determine the interrater reliability – the map of land use and land cover was utilised to calculate the overall producer and user accuracy.

The LULC raster data was converted to a vector format, cropping areas blended, and croplands extracted. A clipping tool was used to remove pixels overlapping with flood inundation extent.

RESULTS AND DISCUSSION

EXTENT OF FLOOD HAZARDS IN THE CROPPING AREAS

Sentinel 1 satellite imagery and ground data, such as hydrological and climatic data, were aggregated to analyse flood extent.

Data presented in Table 1 and Figure 3 indicate the minimum flood extent of 50 ha in the middle of July. The flood extended to 34,090 ha in the middle of August, which marked the second peak, resulting from heavy seasonal rain. The flood had its next peak of 60,900 ha in September, when the Bagre reservoir at the dam in Burkina Faso had overflown during the extreme rainy season. The Nabogo River basin experiences frequent flooding, submerging cropping areas for a month or longer.

Table 1. Monthly flood extent in the cropping areas in the Nabogo River basin

Month	Year	Maximum flood extent (ha)
July	2023	50
August	2023	34,090
September	2023	60,900
October	2023	1,210

Source: own study.

Ghosh, Karmakar and Ghosh (2022) noted that a range of climatic and non-climatic elements, such as rainfall, dam overflows, soil type, slope, and antecedent soil moisture, have impact on processes leading to flooding. The research results obtained from the Nabogo River basin strongly align with the assessment described in previously mentioned literature. The majority of the study area is flat, with a few gently sloping areas. With the exception of a few mountainous features in Ghana's southern region, which are normally located between 122 and 244 m a.s.l., the region lacks high mountains; the northern region is also flat (Barry *et al.*, 2005). According to opinion leaders and focus groups, land ownership is yet another factor having influence on flooding. Direct drivers of land use change affecting the land surface, but indirect drivers – caused by direct anthropogenic impacts – are also important factors in the process (Kleemann *et al.*, 2017). Consequently, many communities have been unable to install drainage systems to reduce floods and secure building and farming land to residents or farmers who live near waterways.

Because of the White Volta and the Nabogo River's proximity, Ada, Palung, Tindan, Nabogo, Yapaise, and Gushie were more severely impacted. Moreover, Pong Tamale were also impacted as the area is flat and located at lower elevation. Thus, a near flood event inundated 60,900 ha, or 20%, of the Nabogo River basin.

Floods have caused significant damage, particularly in vulnerable communities. However, this pattern is not uniformly observed across all highly vulnerable countries. In many low- and middle-income countries, flood hazards are associated with vulnerability and poverty (Rentschler, Salhab and Jafino, 2022). The top food producing communities in the Nabogo River watershed sell their produce on the local market. The basin is essential to the Northern region's continued leadership as Ghana's primary agricultural producer and food basket.

In 2023, severe flood affected the east and northwest of the basin in Northern Ghana. Satellite-1, global surface water, and GEE analysis helped pinpoint high-flood communities. The "VH" polarisation was chosen for flood mapping due to its sensitivity to vertical structures and land surface changes. This information may contribute to establishing effective mitigation guidelines (Ghosh, Karmakar and Ghosh, 2022).

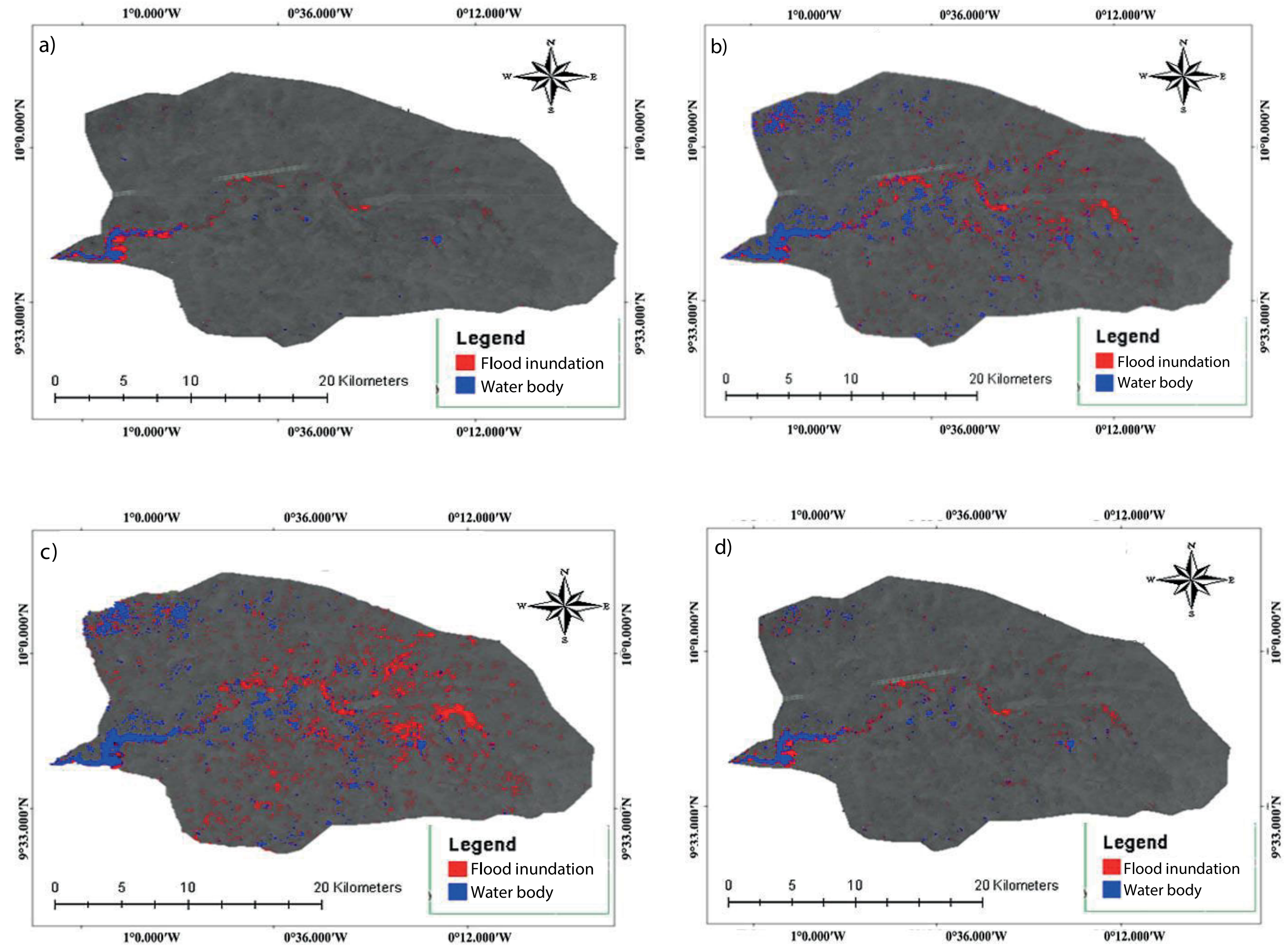

Fig. 3. Maximum flood in the Nabogo River basin: a) July 2023, b) August 2023, c) September 2023, d) October 2023; source: own study

FLOOD DAMAGE ASSESSMENT IN CROPPING AREAS

The research proposed a technique framework for mapping flood damage to agricultural regions in the Nabogo River basin. A straightforward and efficient technique was developed and utilised to assess the crop damage impacts related to the extreme flooding events in the Nabogo River basins from July to October 2023. Moreover, field data was used, combining SAR and optical images by Sentinel-2 and MODIS. The cropping area in the Nabogo River basin damaged in 2023 is shown in Figure 4.

INUNDATION DEPTH

As much as 2,300 ha of sown areas were totally submerged by flood in September 2023. Respiration in submerged plant tissues was adversely affected by oxygen depletion in the flooded

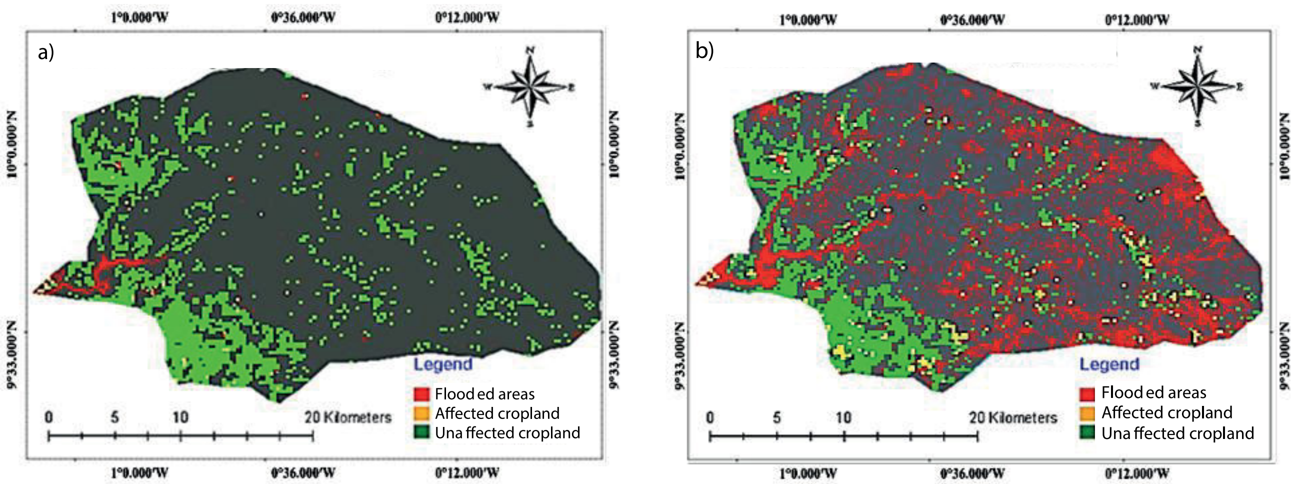

Fig. 4. Cropping area in the Nabogo River basin damaged in 2023: a) minimum, b) maximum; source: own study

sediments. Prolonged submergence for 28 days further reduced oxygen availability and significantly inhibited photosynthesis.

According to Table 2, 2,022 ha were nearly discarded when the flood receded. Plots that were closer to the river were filled with sand and gravel from the river. The cropping land in the lower areas upstream was covered with debris. Although the lower areas sensed the increased nutrients deposited from the upstream, it was difficult to clear the debris and immediately start planting. Additionally, in certain areas higher flood water velocity removed top soil and transported it to the valley or lower points in the basin.

Table 2. Inundation depth in sown area

Inundation depth (m)	Inundation on sown area (ha)
≤0.5	14,500
(0.5; 1.0>	2,862
<1.0; 2.0)	859
≥2.0	2,002
Total area	**20,223**

Source: own study.

Table 2 showed that 14,500 of the 20,223 ha were below 0.5 m, giving farmers the chance to harvest their plots. Of the 2,862 ha, more than 70% were also harvested, while a small number of plots were lost to insects and birds between 0.5 and 1.0 m. The farmers lacked resources to scare birds and apply pesticide at the time, and the high flood depth and velocity virtually destroyed 2,002 ha over 2.0 m and 859 ha between 1.0 and 2.0 m remained submerged for several days.

According to this analysis, 24,223 ha of farm lands were flooded between July and October of 2023. The total affected cropping areas were 5,928 ha, and the 18,295 ha of cropping areas were not affected (Tab. 3). The impacted cropland experienced a 28-day flood with an average height of one to three meters. The height and duration of the flood were particularly unfavourable for several crops, including rice, maize, cowpeas, onions, and some other vegetables. Long periods of total submersion made cowpea, onion, and several other vegetable crops to break and lose their roots. Several of them were also completely deprived of oxygen and were unable to perform photosynthesis.

The total 2,022 ha were identified in a separate analysis. Of this area, 491 ha were classified as having poor soil quality due to flooding, 520 ha were covered with silt, and 1,011 ha of cropland were filled with debris. As many as 24,223 ha of farmland were inundated between July and October of 2023, based on the study shown in Table 3. There were 5,928 ha of agricultural fields in total that were impacted; the remaining 18,295 ha were unaffected. A 28-day flood, with an average water height of one to three meters, affected crop areas. According to Table 2d, the total sown area was 2,223 ha. Of this, 2,861 ha were completely destroyed, while 17,362 ha were successfully harvested.

In addition, floods can reduce yields and oxygen levels in the soil, disrupting essential life-sustaining processes including respiration and water absorption (Butzen, 2007). Water-logging also leads to the accumulation of harmful substances such as CO_2, which inhibits plant development and causes significant damage. Furthermore, nutrients are rapidly washed away by fast moving flood waters, particularly from upstream areas into adjacent water bodies or valleys. As a result farmers are often left with nutrient depleted and infertile soils (Asiamah, 2008). The topsoil surrounding the crops is also removed, leaving the roots exposed and vulnerable to disease and damage. These preliminary study findings align with other studies conducted in the Nabogo River basin. Once the flood subsided, many agricultural plants that had recovered from a protracted period of flooding were unable to offer higher yields. Moreover, some of the plant stems exhibited signs of rot. Flooding often results in large areas of cropland being left unfertilised. This situation is particularly critical for resource-poor farmers who lack the financial means apply fertilisers.

The basin is one of the leading producers of food crops in Northern Ghana, including soybeans, rice, millets, yam, maize, and other vegetable crops (Carrier *et al.*, 2008). However, the production is disrupted by extremely destructive floods, endangering further operation of the "breadbasket of Ghana". Although there are generally fewer people living in rural areas of northern Ghana due to poorer economic conditions in the region (Tankpa *et al.*, 2021), the lack of food may affect not only them but also the entire population in other regions that rely on them for local food supplies.

In the Yangtze River Basin and Henan Province, flood effect evaluation has been greatly enhanced by satellite images and geospatial data, allowing for precise mapping and damage assessment (Monteleone *et al.*, 2023). Interviews with residents revealed that floods caused significant crop losses, with many people reporting that crops like as rice, yams, and maize were either rotting or swept away by the excessive wetness. Additionally, flooding was frequently associated with controlled spills from the Bagre Dam. Crops such as rice and maize, already weakened

Table 3. Monthly flood-affected sown cropping area

Month	Total monthly flood extents	Affected cropping areas	Unaffected cropping areas	Affected others areas (built-up, roads etc.)
	ha			
July	50	15	8,002	–
August	34,090	1,144	5,092	25,854
September	60,900	4,671	1,101	53,128
October	1,210	98	4,100	6,988

Source: own study.

by excess water, became highly vulnerable to damage from insects and birds, which often destroy the remaining harvest.

High-resolution land use/land cover (LULC) datasets are crucial for crop classification accuracy, and a 10-m resolution dataset was created using Sentinel-2 data. Global surface water and hydrological models help identify floodwater depth and permanent surface water (Pandey, Awasthi and Jain, 2022). To map flood inundation at the Nabogo River basin from July to October 2023, Google Earth Engine is a potent platform for SAR data. With kappa 0.86 statistics and the confusion matrix, the study's overall classification accuracy is 92%. Therefore, mapping potential flood areas and providing information to decision-makers, the public, and crisis managers are essential for flood mitigation strategies and basin risk assessment. A technique used in Khuzestan, Iran, enabled to map agricultural areas damaged by flooding using Sentinel-1 and Sentinel-2 data. With a kappa coefficient of 0.8003 and accuracy of 96.30%, the final map demonstrated its effectiveness and shows potential for rapid generalisation to other regions (Dodangeh and Shah-Hosseini, 2023).

CONCLUSIONS

Flood forecasting can be useful for hazard mapping, crop production, and timely evacuation of animals and people in case of severe flooding. The method's consistent formula allows for similar studies in other regions.

The flood peaks in September, which began in late July and ended in early to mid-October, affected 20% of the Nabogo River basin (60,900 ha). The flood reached its second peak in mid-August at 34,090 ha due to high seasonal rains. Burkina Faso experienced a large discharge of water in September.

Riverine floods caused by low elevation damaged 24,223 ha of cropping areas over 28 days. Vegetable crops such as onion, cowpea, and soybeans lost roots and oxygen, and capability of photosynthesis. Damage to corn can be worse than to soybean, as corn grows taller. Rice, on the other hand, can withstand water exposure without losing its flavour. A pixel-level validation was conducted to compare SAR data with *NDVI* in Google Earth Engine.

Over 85% of Northern Ghana's population relies on farming despite the region's challenging topography and severe water scarcity during the dry season. This has led to food insecurity and socioeconomic issues. Farmers often travel to other parts of the country to provide for their families during the drought. Rain-fed farming techniques are also problematic due to riverine floods and Burkina Faso's Volta discharge.

ACKNOWLEDGEMENT

This publication was made possible through the support provided by the West African Center for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, Ghana and the author's supervisors.

CONFLICT OF INTEREST

All authors declare that they have no conflict of interests.

REFERENCES

Apogba, J.N. *et al.* (2024) "Application of machine learning techniques to predict groundwater quality in the Nabogo Basin, Northern Ghana," *Heliyon*, 10(7), e28527. Available at: https://doi.org/10.1016/j.heliyon.2024.e28527.

Armah, F.A. *et al.* (2010) "Impact of floods on livelihoods and vulnerability of natural resource dependent communities in Northern Ghana," *Water*, 2(2), pp. 120–139. Available at: https://doi.org/10.3390/w2020120.

Asiamah, R.D. (2008) "Soil resources in Ghana," in A. Bationo *et al.* (eds.) (2008) *Synthesis of soil, water and nutrient management research in the Volta Basin.* Nairobi: Ecomedia Ltd., pp. 25–41. Available at: https://cgspace.cgiar.org/server/api/core/bitstreams/51bccdca-4d1e-46b0-98e0-da46ee805c5c/content (Accessed: October 10, 2024).

Asumadu-Sarkodie, S., Owusu, P.A. and Rufangura, P. (2017) "Impact analysis of flood in Accra, Ghana," *Advances in Applied Science Research*, 6(9), pp. 53–78. Available at: https://doi.org/10.5281/zenodo.812994.

Barry, B. *et al.* (2005) *The Volta River basin. Comprehensive assessment of water management in agriculture. Comparative study of river basin development and management.* Colombo, Sri Lanka: IWMI, CAWMA. Available at: https://archive.iwmi.org/assessment/files_new/research_projects/river_basin_development_and_management/VoltaRiverBasin_Boubacar.pdf (Accessed: October 10, 2024).

Butzen, P.F. (2007) *Leakage current modeling in Sub-micrometer CMOS complex gates.* MSc Thesis. Porto Alegre: Universidade Federal do Rio Grande do Sul Instituto de Informática. Available at: https://www.inf.ufrgs.br/logics/docman/work_msc_butzen.pdf (Accessed: October 10, 2024).

Carrier, M.A. *et al.* (2011) *Hydrogeological assessment project of the northern regions of Ghana: Final technical report: Hydrogeological Assessment of the Northern Regions of Ghana (HAP).* Québec City: INRS.

Chen, X.S. *et al.* (2019) "Differential strategies to tolerate flooding in *Polygonum hydropiper* plants originating from low-and high-elevation habitats," *Frontiers in Plant Science*, 9, 1970. Available at: https://doi.org/10.3389/fpls.2018.01970.

Dodangeh, P. and Shah-Hosseini, R. (2023) "Extraction of flood-affected agricultural lands in the Google Earth Engine; case study of Khuzestan, Iran," *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, X-4/W1-2022, pp. 123–128. Available at: https://doi.org/10.5194/isprs-annals-x-4-w1-2022-123-2023.

FAO (2020) *The state of food security and agriculture in Ghana. Overcoming water challenges in agriculture*. Rome: Food and Agriculture Organization of the United Nations. Available at: https://openknowledge.fao.org/server/api/core/bitstreams/6e2d2772-5976-4671-9e2a-0b2ad87cb646/content (Accessed: October 11, 2024).

Ghosh, M., Karmakar, S. and Ghosh, S. (2022) "Flood modelling for an urban Indian catchment: Challenges and way forward," in S. Kolathayar, A. Mondal and S.C. Chian (eds.) *Climate change and water security: Select Proceedings of VCDRR 2021.* Singapore: Springer, pp. 51–62.

Khan, N.S. *et al.* (2024) "Empowering real-time flood impact assessment through the integration of machine learning and Google Earth Engine: A comprehensive approach," *Environmental Science and Pollution Research*, 31, pp. 53877–53892. Available at: https://doi.org/10.1007/s11356-024-33090-7.

Kim, D., Caputo, V. and Kilders, V. (2023) "Consumer preferences and demand for conventional seafood and seafood alternatives: Do ingredient information and processing stage matter?," *Food Quality and Preference*, 108, 104872. Available at: https://doi.org/10.1016/j.foodqual.2023.104872.

Kleemann, J. *et al*. (2017) "Assessing driving forces of land use and land cover change by a mixed-method approach in north-eastern Ghana, West Africa," *Journal of Environmental Management*, 196, pp. 411–442. Available at: https://doi.org/10.1016/j.jenvman.2017.01.053.

Kumar, P. *et al.* (2022) *Machine-learning groundwork and cluster analysis for vortex detection. ARL-TR-9425*. Adelphi, MD: DEVCOM Army Research Laboratory. Available at: https://apps.dtic.mil/sti/trecms/pdf/AD1165710.pdf (Accessed: October 12, 2024).

Manzoor, Z. *et al*. (2022) "Floods and flood management and its socio-economic impact on Pakistan: A review of the empirical literature," *Frontiers in Environmental Science*, 10, 1021862. Available at: https://doi.org/10.3389/fenvs.2022.1021862.

Monteleone, B. *et al*. (2023) "Estimations of crop losses due to flood using multiple sources of information and models: The case study of the Panaro River," *Water*, 15(11), 1980. Available at: https://doi.org/10.3390/w15111980.

Pandey, A., Awasthi, S. and Jain, K. (2024) "Development of a modeling approach for agriculture crop type classification aiming at large-scale precision agriculture by synergistic utilization of fused Sentinel-1 and Sentinel-2 datasets with UAV datasets," in S. Gupta *et al*. (eds.) *Agri-tech approaches for nutrients and irrigation water management*. Boca Raton: CRC Press, pp. 24–47.

Reed, C. *et al*. (2022) "The impact of flooding on food security across Africa," *Proceedings of the National Academy of Sciences*, 119(43), e2119399119. Available at: https://doi.org/10.1073/pnas.2119399119.

Rentschler, J., Salhab, M. and Jafino, B.A. (2022) "Flood exposure and poverty in 188 countries," *Nature Communications*, 13(1), 3527. Available at: https://doi.org/10.1038/s41467-022-30727-4.

Soulibouth, L., Hwang, H.S. and Shin, D.H. (2021) "The impact of flood damage on farmers, agricultural sector and food security in Laos: A regional case study of Champhone District, Savannaket Province," *Journal of International Development Cooperation*, 16(2), pp. 151–170. Available at: https://doi.org/10.34225/jidc.2021.16.2.151.

Suleman, A.R. *et al*. (2023) "Flood mitigation of Bila River in Sidrap Regency Indonesia based on eco-drainage retention pond," *Water Practice & Technology*, 18(5), pp. 1184–1195. Available at: https://doi.org/10.2166/wpt.2023.051.

Tankpa, V. *et al*. (2021) "Modeling the effects of historical and future land use/land cover change dynamics on the hydrological response of Ashi watershed, northeastern China," *Environment, Development and Sustainability*, 23, pp. 7883–7912. Available at: https://doi.org/10.1007/s10668-020-00952-2.

Wang, X., Liu, Z. and Chen, H. (2022) "Investigating flood impact on crop production under a comprehensive and spatially explicit risk evaluation framework," *Agriculture*, 12(4), 484. Available at: https://doi.org/10.3390/agriculture12040484.

Whitfield, P.H. (2012) "Floods in future climates: A review," *Journal of Flood Risk Management*, 5(4), pp. 336–365. Available at: https://doi.org/10.1111/j.1753-318X.2012.01150.x.