

APPLICATION OF GIS TECHNIQUES IN FLOOD EXTENT MAPPING AND MANAGEMENT ON MATEBELE FLOOD PLAIN IN SHANGOMBO DISTRICT, ZAMBIA

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ABSTRACT

Floods are among the world's most devastating hazards, adversely affecting both ecological (provisional and regulatory services) and socioeconomic systems (loss of life, property, and financial costs). The application of GIS techniques in flood mapping is increasingly significant for establishing the extent and effects of floods. This study focused on establishing the spatial extents and trends in the flooding events on the Matebele Plain in the Shangombo District of Zambia using GIS techniques. Primary data was collected via structured interviews with 160 respondents and 13 key informant interviews. Synthetic Aperture Radar (SAR) images in C-band (C-SAR), integrated with supporting satellite data, were used. Interview data were analysed thematically with descriptive statistics, while satellite images were processed using ArcGIS 10.3 software and Sentinel Application Platform (SNAP). Results indicated that the maximum flood coverage was recorded in 2018, covering 16,441 km², representing 78% of the total area. A regression analysis of the trends yielded an r^2 of 0.70, indicating significant geospatial variation in the aerial coverage of floods from 2008 to 2018 ($p=0.001$). A thematic analysis of responses on the effects of floods on land-use activities yielded a positive response rate of 97%. The study concludes that flooding on the Matabele Plain exhibits geospatial variation to an extent. Further research into the impacts of floods on specific land uses is highly recommended.

Keywords: *Floods, GIS, flood extent mapping, Synthetic Aperture Radar, Land Use/Land Cover.*

INTRODUCTION

Floods are among the world's most alarming natural disasters. They are probably the most recurrent, widespread, and frequent natural hazards (DMSG, 2001). A flood is a relatively high flow of water that overtops the natural and artificial banks of a stream. When banks are overtopped, water spreads over floodplains and generally causes problems for inhabitants, crops, and vegetation (Wang et al., 2002). To achieve effective flood management and risk control during extreme flood events, it is important to determine the extent of flooding (Wang et al., 2002). Updated details of floodplain inundation extents serve as a rich and valuable source for mitigating, managing, and avoiding severe social and economic losses from floods. Accurate, up-to-date floodplain inundation and extent information also improves public safety and aids flood disaster mitigation and management. Furthermore, identifying and assessing flood-prone properties during emergencies allows public safety institutions to establish warning and evacuation priorities. Providing well-researched and documented information can aid disaster response institutions in better planning for emergencies before they occur (Chapman and Canaan, 2001).

Flood monitoring using remote sensing is an effective method for obtaining a quick and precise overview of flooded areas. Flood extent mapping is crucial for calibrating and validating hydraulic and hydro-morphological assessment models (Horritt, 2006). Earth-based satellite observations can provide valuable and timely information when spatial and temporal flood data are required. In this study, a timely and detailed analysis was carried out using remote sensing (RS) and geospatial techniques to aid the identification of flood-affected areas, coupled with land-use/land-cover assessments. According to Shamsi (2002), Geographic Information Systems (GIS) play a vital role in flood management by providing flood assessment and monitoring tools and information for planning and management. Recent technological advancements in GIS and Remote Sensing are largely contributing to flood monitoring and management while reducing the time required to provide the much-needed information. Through modelling, floods can be predicted and vulnerable areas identified.

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The operation of the Sentinel 1 mission, deployed on two polar-orbiting satellites, is relevant for mapping surface and flood water at 10 m spatial resolution. Several SAR satellite missions (ALOS-2, RADARSAT-2 and Terra SAR-X) now provide satellite data to support environmental needs, including flood mapping (Arnesen et al., 2013). Flood extents, derived from SAR images, utilise histogram-based approaches and backscatter thresholding to differentiate between water and non-water classes (Di Baldassarre et al., 2011). GIS techniques are effective for real-time flood monitoring, management and the development of flood maps (Thilavagathi, 2011). Satellite-based RS is effective for mapping flood inundation extents (Deutsch, 1973). Tiger (2008) used satellite data to monitor the relationship between flooding and vegetation changes on the Kafue Flats. Aduah (2012) applied RS to map wetland floods in the Kafue Flats. Zimba (2017) assessed trends in the extent of inundation on the Barotse Floodplain. In these studies, gaps remain in the application of Synthetic Aperture Radar (SAR) imagery for flood mapping and in mainstreaming flood impacts on land-use activities using GIS and remote sensing techniques.

Over the years, the number of settlements and livestock, as well as land use and land cover changes on the Matebele flood plain, have been affected by changes in the inundation of the flood plains. According to the Rapid Flood Impact Assessment Report of March 2007, floods posed a high risk of water contamination and flooded shallow wells for communities living around the Matebele Plain of Shangombo District. In 2009, four pupils from two schools were swept away and died due to floods in the area (Lusaka Times, 2009). Additionally, the flooding of the plain submerged many roads in the area, and Shangombo District was reported to be worst hit in that year. In the same year, reporting on the floods on the same plain and the whole district of Shangombo, the Disaster Management and Mitigation Unit (DMMU) stated that infrastructure such as roads and bridges were damaged, submerged and/or washed away. Mud houses collapsed, displacing 460 people (76 households). Further, water points and toilets in the affected communities had been submerged, and some had collapsed. In addition, during the same period, three schools were closed after classrooms were submerged, along with teachers' houses and toilets. Furthermore, water points (boreholes with hand pumps), mainly located near schools, were submerged by the floods, posing a risk of contamination in some areas. Furthermore, most crop fields and settlement areas were flooded (Zambia Vulnerability Assessment Committee, 2009). Despite numerous studies assessing the impacts of flooding events in Zambia, very few have established the extent of flooding in areas such as the Matebele Plain using geospatial techniques, owing to the vastness of the area and the challenges of ground-based monitoring.

According to the Vulnerability Assessment and Analysis Survey for Zambia conducted in 2007, the Matebele floodplain has recorded chronic heavy flooding for decades, with the impacts of these events being disastrous. Recent annual heavy rains have resulted in recurrent flash floods and waterlogging in valleys and floodplains, causing varying impacts on several sectors, namely infrastructure, agriculture, education, health, water and sanitation, and habitation.

The continued occurrence of floods on the Matebele plain has negatively affected human activities, livelihood, settlements, food production, the provision of social services and progress on developmental projects. Effects of the floods on the plain include submerging crop fields and grazing land, loss of life, biodiversity, collapse of houses, washing away crossing points, livestock deaths and diseases, and loss of agricultural produce, social infrastructure, and slowing infrastructural development and reduction in socio-economic activities. Traditional methods of monitoring and predicting the floods, such as ground surveys and media reports, have not proven adequate to support the identification of the extent of the floods and mitigation of the effects. The gaps in information about the flooding events on the floodplain have resulted in uncertainties during selection of suitable sites for new schools, clinics and other infrastructural projects.

Additionally, there is little information available on the trends and extents of the flood plain and the common flood-prone areas, which often results in difficulties in issuing early warnings to affected communities. As a result, this has negatively affected flood management of the area and implementation of developmental activities in the communities living on the plain. Without detailed information on the extent and changes in flooding on the plain, communities living on the plain, government agencies, and other actors will continue to find it challenging to plan and implement relevant programs in the area. This study applied modern scientific techniques, including satellite-based information and participatory ground-based data collection and analysis, to establish the extent of flooding events on the Matebele Plain. The study conducted a comprehensive geospatial analysis of flooding on the plain, establishing the maximum aerial extent, spatial variations, and affected land-use/land-cover types for the purpose of developing an effective flood information system.

MATERIALS AND METHODS

Study Area

The Matebele flood plain is an extension of the Barotse Flood Plain located in the Southwestern part and subject to seasonal flooding by flash floods from Cuandu River in Angola. The Flood Plain is geographically situated between 16° and 17° South and 22° and 23° East, mainly in Shangombo District (Figure 1).

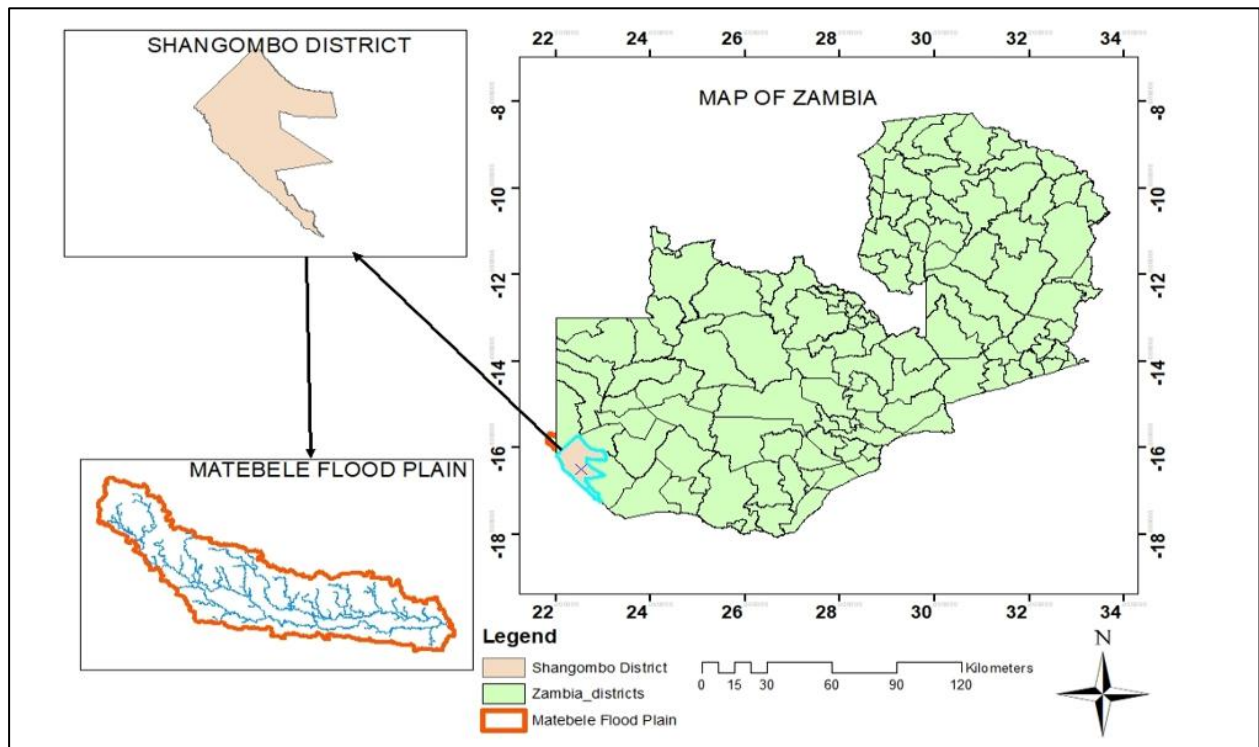


Figure 1: Study Area Map of Matebele Flood Plain

It covers an area of about 21,078 Km². It is in the Southwest of the Zambezi floodplain and extends marginally into Angola.

The materials used included the Global Positioning System (GPS), topographic maps of the study area to support participatory GIS, satellite images covering the period 2008 to 2018, ArcGIS 10.3, and the Sentinel Application Platform (SNAP) software. To determine the flood extent, satellite images were acquired and processed using suitable software. Data from respondents was collected using questionnaires. Data from key informants were collected using interview guides.

Satellite Data Acquisition

Synthetic Aperture Radar (SAR) is an active remote sensing system that emits a radar pulse and measures the backscattered signal (Gibson, 2000). SAR satellite data are preferred for flood mapping due to their ability to capture images day and night (Martinis et al., 2015). Satellite images for the study period were sampled and downloaded from Copernicus' Sentinel 1A, RADARSAT SAR images in the C-band frequency with HH polarisation, and USGS. The terrain characteristics of the plain were extracted using a Digital Elevation Model (DEM) downloaded from USGS.

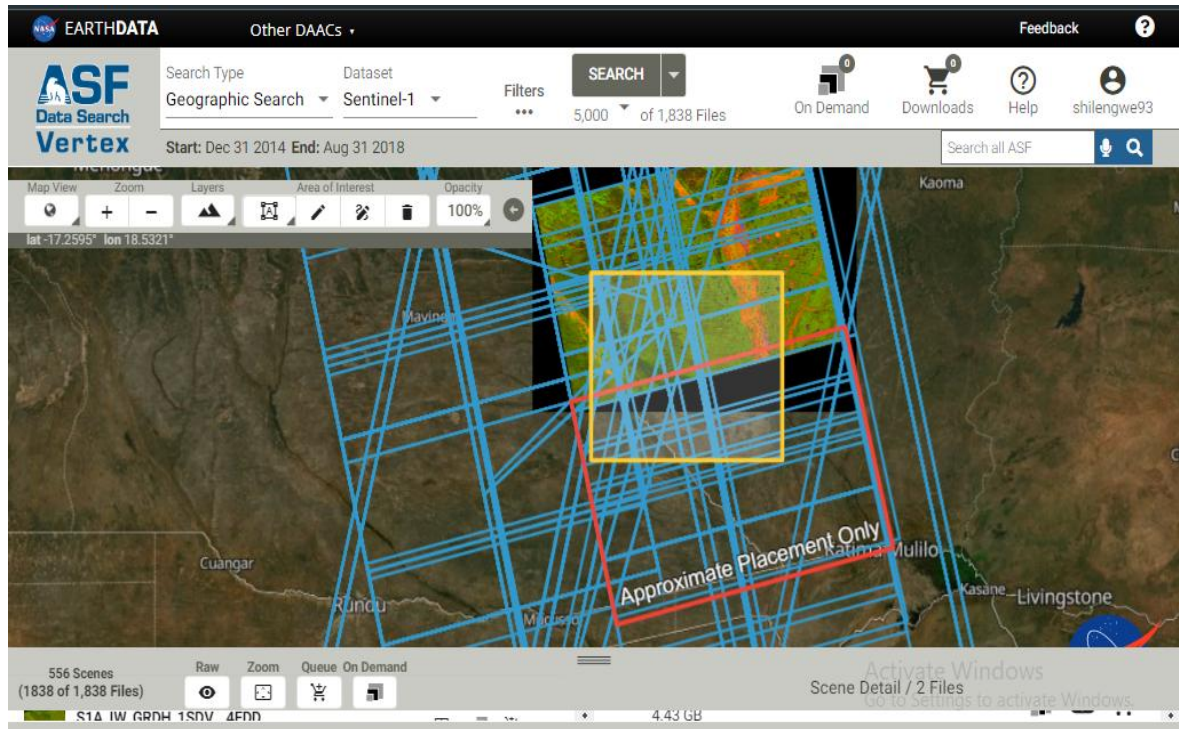


Figure 2. Extent of the tiles for SAR Data used for the study

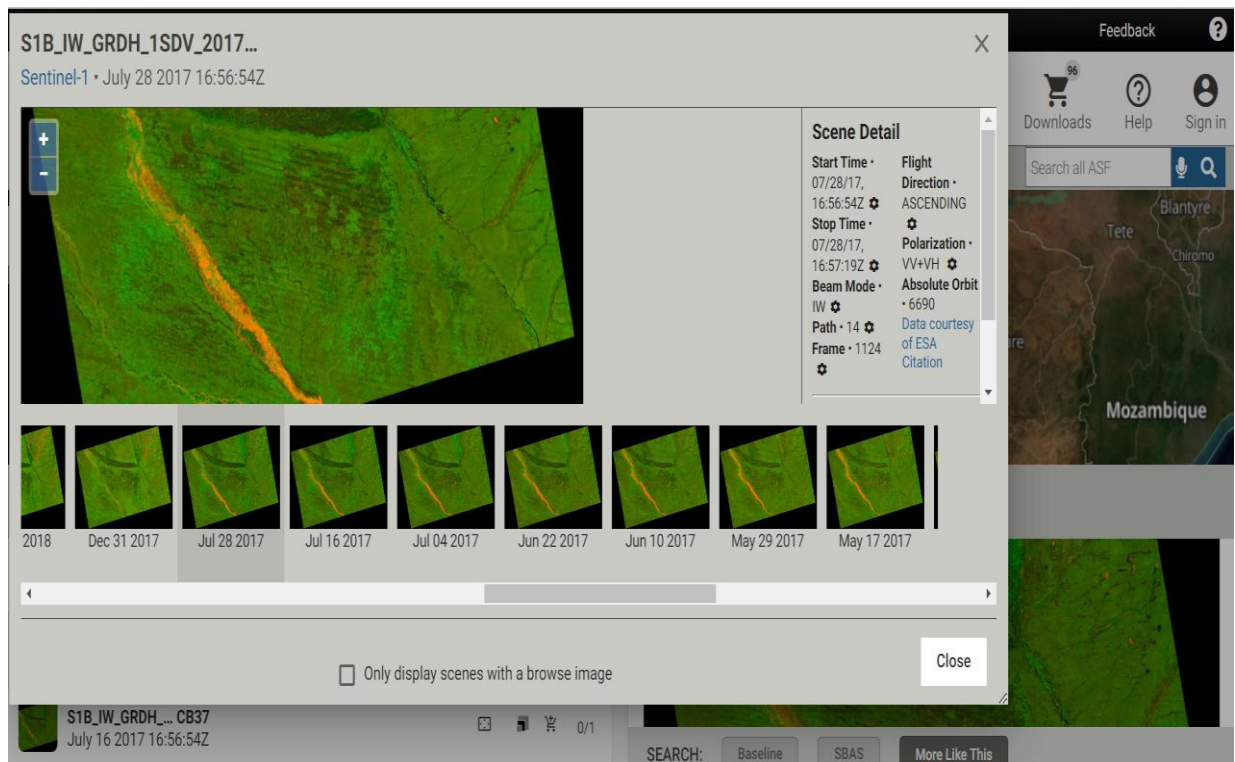


Figure 3: Acquisition of Satellite Images

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Table 1: Sampled Satellite Images used for the study

S/N	Acquisition Date	Images Details	Acquisition Model
01	01/09/2008	R1_63585_ST2_F858-L0_F858	VH + HH- Pol
02	02/02/2008	R1_63928_ST2_F858-_L0_F858	VH + HH- Pol
03	18/06/2009	LC08_L2SP_17507_202009-02_	Dual Pol
04	23/05/2010	ALPSRP227966850-H2.2_	VH + HH
06	11/08/2011	IW_GRDH_1SDV_20110814T165703_2011121	VH + HH
07	16/04/2015	S1A_IW_GRDH_1SDV	VH + HH - Pol
08	19/09/2012	S1A_IW_GRDH_1SDV	VH + HH - Pol
09	24/12/2016	S1B_IW_GRDH_1SDV	High-Res Dual-Pol (GRD-HD)
10	17/01/2017	S1B_IW_GRDH_1SDV	High-Res Dual-Pol (GRD-HD)

Hydro-Meteorological Data

Climatic data, based on rainfall as the primary parameter in this study, were collected online at the site <https://power.larc.nasa.gov/data-access-viewer>. The web platform provides climate information on humidity, temperature, wind and other weather parameters

Field Observations

Field observations played a critical role in the collection of both qualitative and quantitative data. Marshall (1989) defines observations as the systematic description of the events, behaviours, and artefacts of a social setting. Field observations were conducted in areas that flood, as well as in land-use activities affected. This method enabled the observation of shifts in land-use activities due to changing flood events in the plain. Participatory observation with key informants provided additional data and detailed explanations of visible surface activities that were not readily identifiable to the researcher.

Interviews

Semi-structured interviews were adopted for their flexibility during data collection and to enable the researcher to introduce auxiliary questions that elicited detailed information from participants. This method enabled the researcher to gain a deeper understanding of the area of the plain that regularly floods, the land-use activities affected, and the relationship between changing flood regimes and land-use activities. Key informants included planners, agricultural and veterinary experts, and schoolteachers living on the floodplain. They provided valuable data on flood-prone areas. The data collected using this method supported the determination of flood-prone areas on the plain, assisting in delineation and validation with satellite images.

Data Analysis

Qualitative data analysis was conducted using thematic analysis, which focused on analysing the content as it was collected in the field. Coding and interpretation techniques of the transcribed data from interviews and field notes were the initial step in the analysis of this type of data. Quantitative data analysis began with exploratory data analysis to summarise the main characteristics of the data and to provide a framework for selecting statistical analyses. Statistics involving the mean, standard deviation and frequencies were computed on all quantitative data. Association analyses were conducted to establish relationships among variables, such as flood extent and the area covered, and change in extent and the land uses affected.

Analysis of satellite imagery

Processing of the SAR images collected before, during, and after the flood in each flood season began with calibration, geometric correction, and filtering. A threshold method was applied to extract inundated areas from the images using pixel estimates (Figure 4). Superimposing and analysing the flood maps for each flood cycle will then be undertaken to determine the spatial variations in the extent of flooding across the floodplain. On the other hand, digital elevation models (DEMs) were used to generate GIS models representing potential wetness and potential flood inundation. The results were presented through maps delineating the boundaries and extents of flooding in the study area and establishing possible management measures. The SAR images were georeferenced, and suitable image enhancements were applied to facilitate the delineation of flood areas and the interpretation of various thematic information. To enhance interpretation, visual and digital interpretation methods were used to derive information from satellite images and topographic maps. ArcGIS 10.3 software was used for processing and analysis of the images for easy availability and familiarity. The results are provided in Figures 5 and 6.

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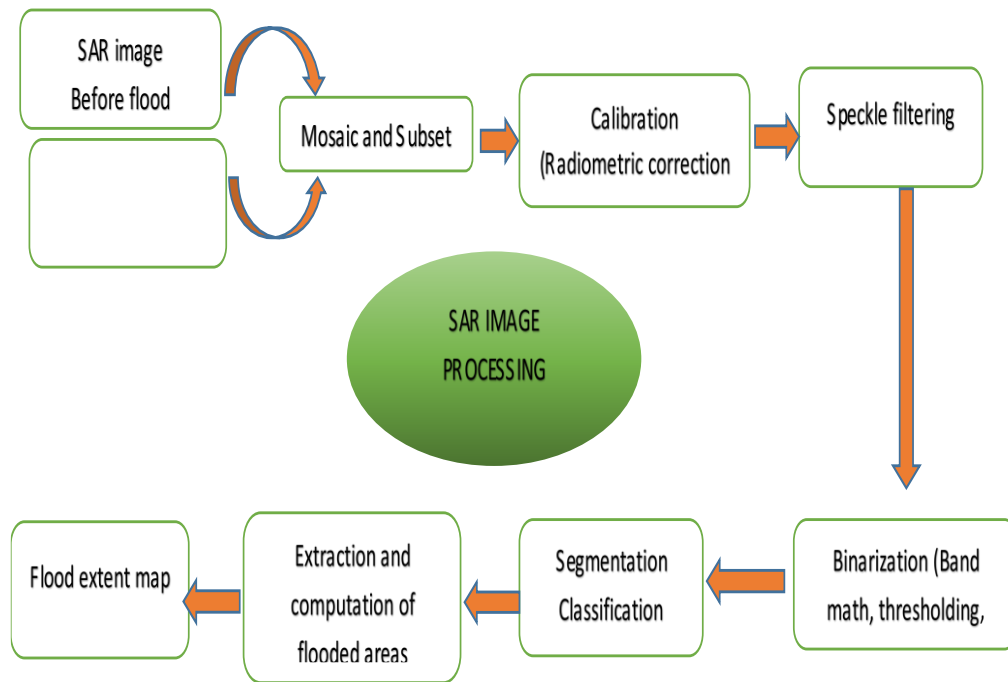


Figure 4: Image Analysis Procedure

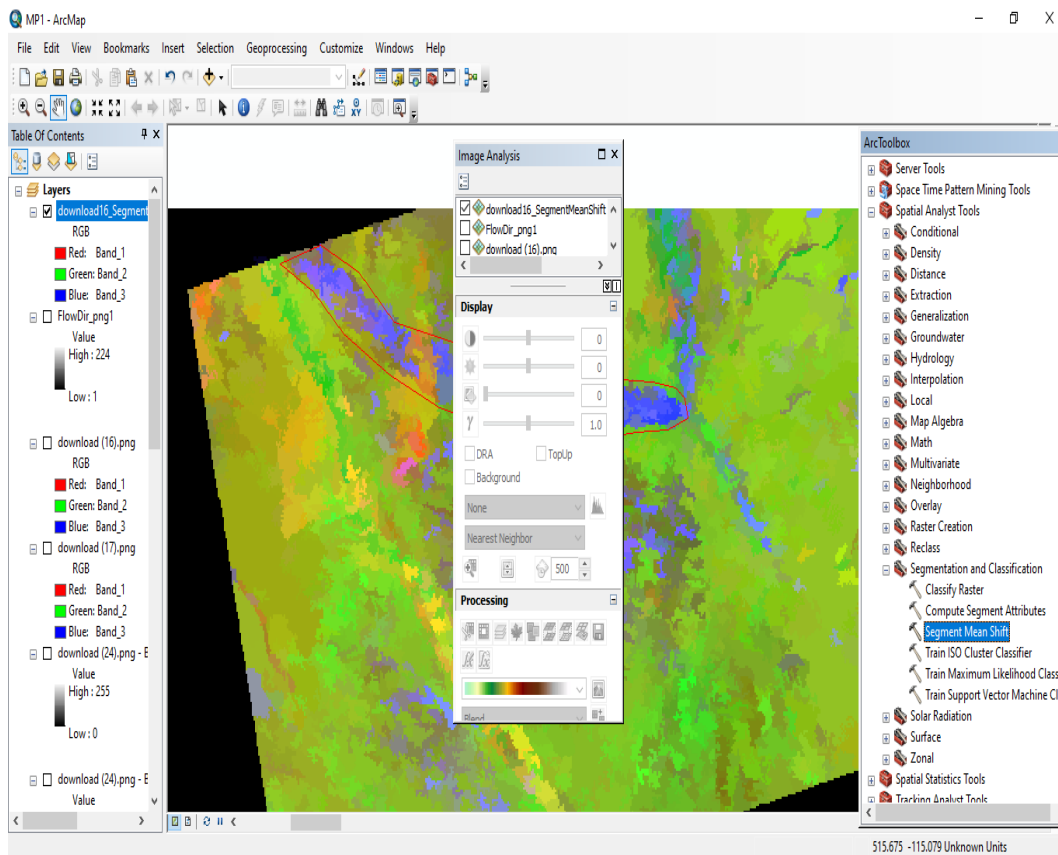


Figure 5: Image processing algorithm in Arcmap

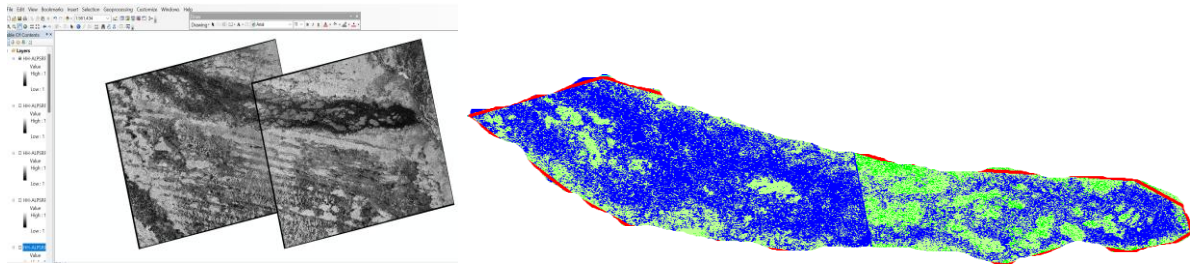


Figure 6: Image processing and results

RESULTS

Maximum Aerial coverage of floods on Matebele Floodplain

Overall, the peak flood (maximum flood extent) on the floodplain was recorded during the 2017/2018 flood season. Based on the radiometric threshold applied to the sampled SAR flood image for March 2018, the blue band covered an area of 16,441 km², corresponding to the highest threshold in the histogram analysis of the pixels (Figure 7). Compared with the lowest extent in 2012 (9559.9 km²), the maximum flood extent differs by 6881.1 km² from the lowest extent and by 5094 km² above the mean, respectively. However, the results showed a slight difference in aerial coverage in 2009, when the area experienced coverage close to the maximum in 2018 (Figures 7 and 8).

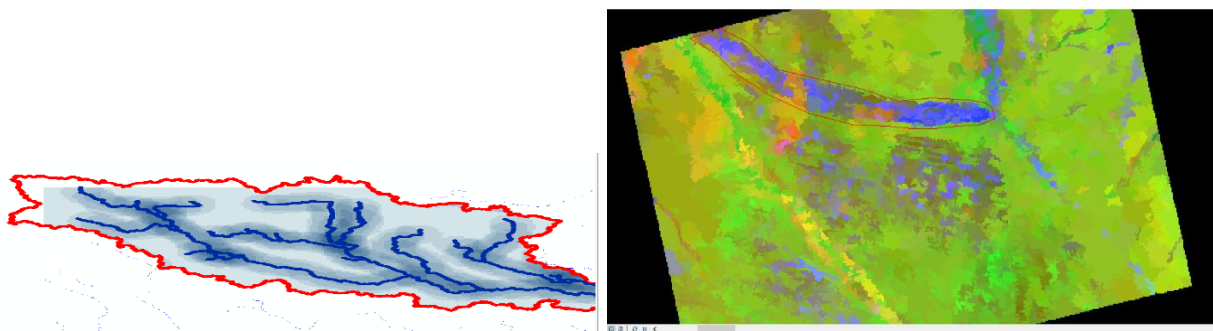


Figure 7: Flood coverage and distribution in the study area

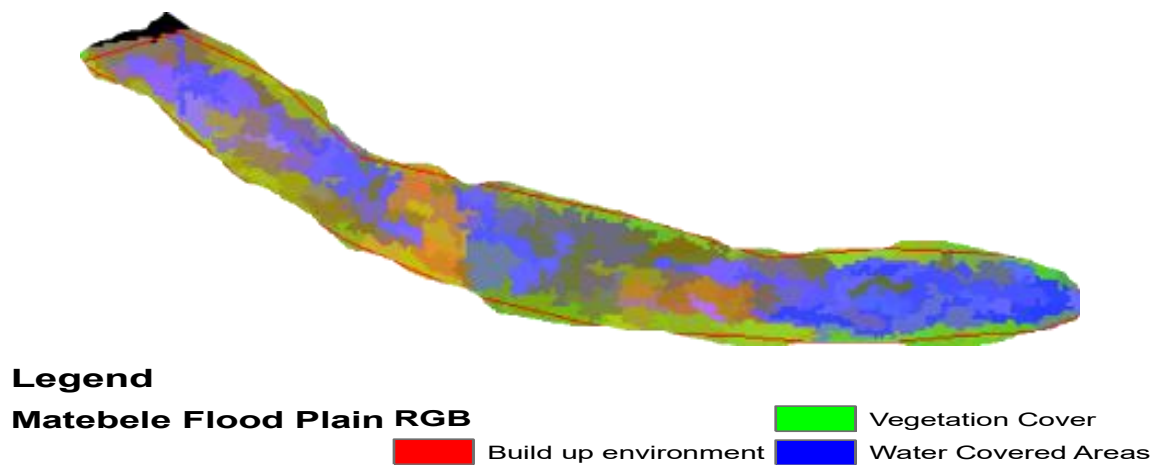


Figure 8: Processed image giving an overview of pixel distribution in the study area

Table 2. Computed estimates of flood extents from 2008 to 2018 on the Matebele Flood Plain based on sampled images with the highest flood coverage.

Image Date	Pixels Count	Pixel Size	Area Coverage (Km ²)
16.07.2008	37724	0.25	9431
12.06.2009	59744	0.25	14936
07.07.2010	45280	0.25	11320
04.08.2011	26284	0.25	6571
29.07.2012	20376	0.25	5094
21.05.2013	24084	0.25	6021
18.07.2014	22932	0.25	5733
14.08.2015	30168	0.25	7542
22.06.2016	37700	0.25	9425
09.07.2017	50645	0.25	12645
14.04.2018	65764	0.25	16441

Spatial Variations in Flooding Events on Matebele Plain 208-2018

There are significant variations in the spatial coverage of flooding events on the Matebele Plain. The distribution of the blue pixels in the resulting images indicates that, in each particular year, there is either an increase or a reduction in the coverage of floods (Figures 9 and 10).

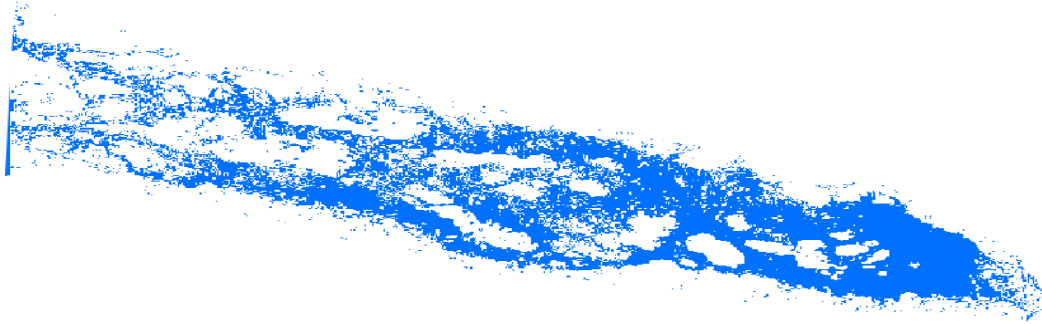


Figure 9: Results of water coverage from the June 2010 Image

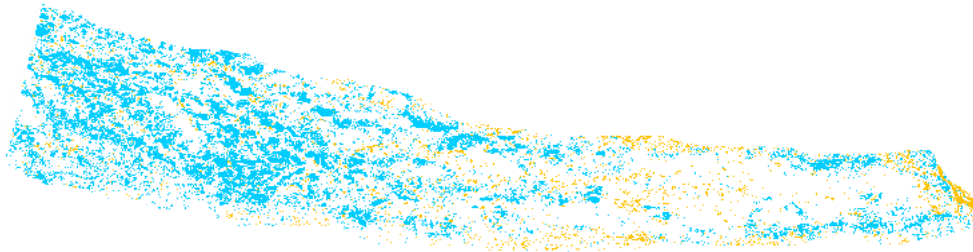


Figure 10: Results of water coverage from the July 2012 image

The variations in the maximum area covered by flooding extents are detailed in Table 3, with a plot in Figure 11. A four-year cycle of reduction and increase was observed through the plotting of the coverage areas.

Table 3: Spatial Coverage of flood extents from 2008 to 2018

S/N	Year	Maximum Area covered by floods (km ²)
1	2008	9431
2	2009	14936
3	2010	11320
4	2011	6571
5	2012	5094
6	2013	6021
7	2014	5733
8	2015	7542
9	2016	9425
10	2017	12645
11	2018	16441

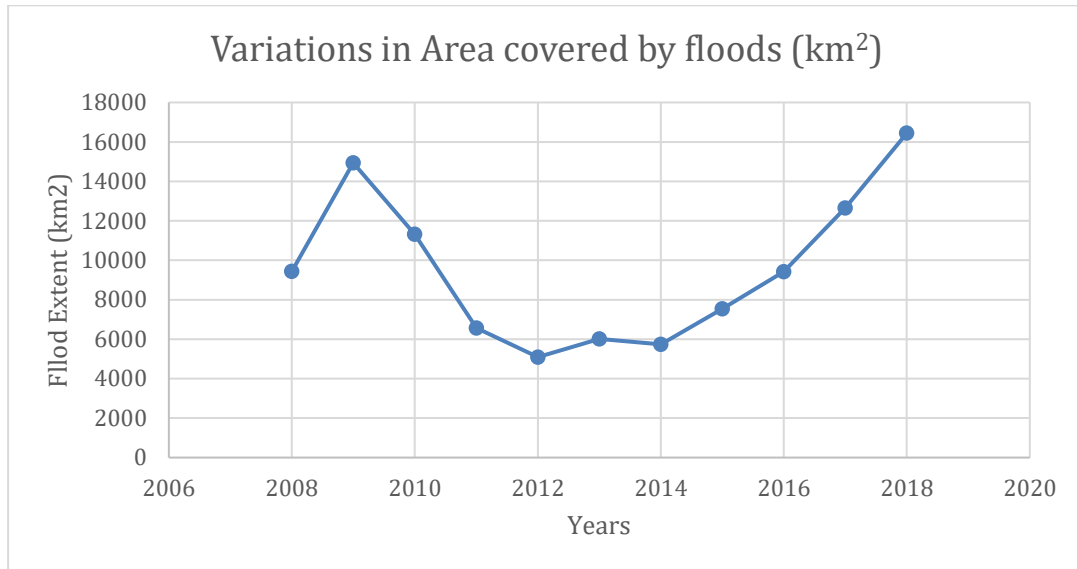


Figure 11: A plot of the annual variations in the distribution of flooding extents

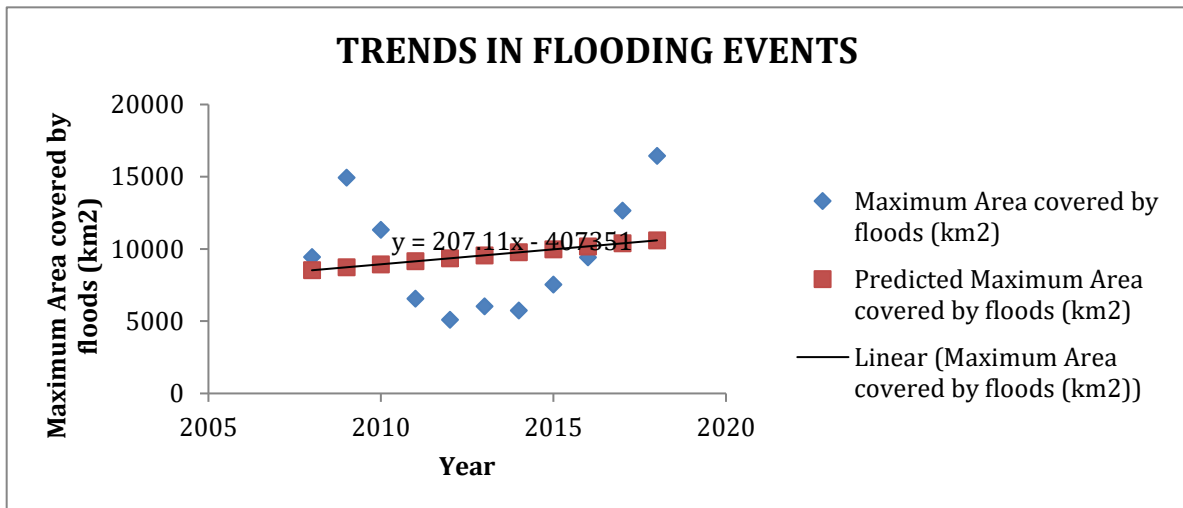


Figure 12: Regression analysis of the variations in flooding Extents on Matebele Plain

Identification of affected land use/land cover types

The study area was covered by various land use activities. These ranged from agricultural to other related human activities such as settlements. Thus, the area is covered by agricultural farmlands, settlements such as villages, schools, health centers, and development projects under implementation. Figure 13 indicates the variations in the effects of the flooding events on the plain with loss of lives being the most common and water-related illnesses being the least common.

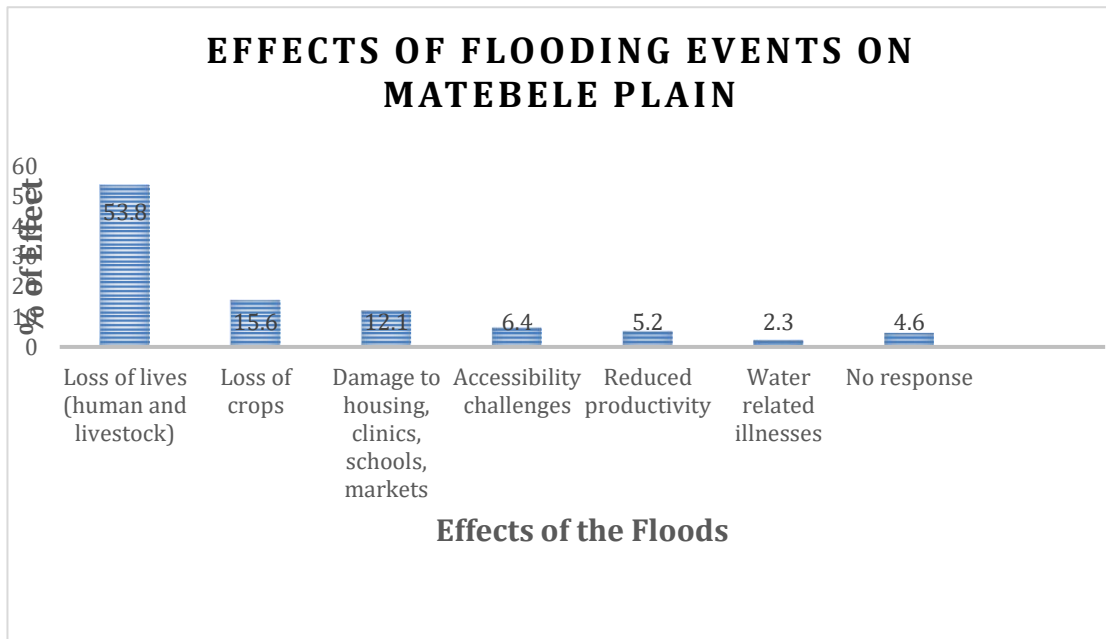


Figure 13: Effects of flooding on Land use/Land Cover types on Matebele Flood Plain

Table 7 presents the land uses and response strategies to flooding events. The main response strategies are draining of the flood waters from the affected areas through canals and relocation to upper land.

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Table 7. Effects of flooding events on various land cover/uses on Matebele Plain

Identified use/land cover	land	Flood effect	Severity score of effect	Possible mitigation measures
Settlements (Villages)		Submerging settlement areas	High	Opening up canals to divert flood water from reaching the settlements, use of water-resistant materials for buildings.
Farmlands		Submerging of the crops in the fields,	High	Digging canals around fields to divert the flood water, planting early before floods affect crop fields, relocating the fields to areas that are not highly flooded.
Grazing lands		Submerging grazing areas	High	Opening up canal on the plain to control the flows and reducing on flooding.
Water Points		Contamination, eroding shallow wells, blocking access to the wells	High	Opening up canal on the plain to control the flows and reducing on flooding.
Social Infrastructure		Damaging buildings, washing away building made of pole and mud, damaging bridges	High	Diverting the waters from the building through construction of canals and use of water-resistant materials for construction.
Access routes		Blocked and flooded	High	Opening up canal on the plain to control the flows and reducing on flooding.
Wildlife habitats		Flooded and displace wildlife	Moderate	Opening up canal on the plain to control the flows and reducing on flooding.

Management on Matebele Plains

The communities have devised several mechanisms (Table 8) to mitigate the effects of floods on their livelihoods. Among them are determining the areas which get heavily flooded on the plain to locate their fields strategically. Other farmers try to build canals around their crop fields to divert water away from their fields.

Table 8: Flood Management Mechanisms in Matebele Flood Plain

Effect of Flood on Livelihoods	Severity of the effects	Flood Mechanism	Management	Effectiveness rating
Increased health hazards and health costs.	High	Evacuation of families from flooded areas.		1
Increased cost of farming	High	Relocation of farms to upland areas, building canals		1
Low returns from animal husbandry	High	Relocation of livestock to uplands to increase returns.		1
Loss of natural source-based livelihoods	High	Developing mechanisms to harvest natural resources in flooded areas. For example, canoes and diverting waters from the sources.		3
Increased transport costs	High	Use of water transport, such as the use of canoes.		3
Reduced crop production	High	Introduction of crops, such as rice farming, and relocation of other crop fields to uplands.		2
Collapsing of Houses	High	Construction of houses using flood resilient materials, and relocating settlements to upland areas.		1

Rating: 1 =Very Effective, 2= Effective, 3= Average

DISCUSSION

The study demonstrates that integrating C-band Synthetic Aperture Radar (SAR) with GIS techniques is a superior approach for monitoring vast, often inaccessible floodplains such as the

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Matebele, which are difficult to survey on the ground. The identification of a peak flood extent of 16,441 km² in 2018, representing 78% of the study area, confirms the capacity of SAR imagery (specifically Sentinel-1 and RADARSAT) to penetrate logistical barriers that hinder traditional monitoring. This finding aligns with previous research indicating that satellite-derived data provides the timely, broad-scale coverage necessary for decision-making, which ground surveys cannot consistently provide because of cost and time constraints. (Phiri, 2021; Dhanabalan, 2021; Baghdadi, 2001).

A critical contribution of this research is the identification of significant temporal heterogeneity in flood events. The analysis reveals a distinct four-year cycle of flood reduction and increase, as evidenced by the sharp contrast between the lowest extent in 2012 (5,094 km²) and the peak in 2018. This geospatial variation ($r^2 = 0.70$) shows that static, one-off assessments are insufficient for accurate hazard profiling. Instead, the observed fluctuations suggest that infrastructure planning in the Shangombo District must account for dynamic flood regimes rather than average conditions, as reliance on low-flood years for zoning could lead to catastrophic exposure during peak cycles.

The study confirms a strong correlation between the mapped flood extents and disruptions to land-use activities. The thematic analysis yielded a 97% positive response rate on flood impacts, with high severity scores for the submergence of settlements, farmlands, and social infrastructure, including schools. This directly links the physical hazard (extent) to community vulnerability. For instance, the destruction of pole-and-mud housing and the submersion of boreholes near schools are not random events but are spatially correlated with the high-risk zones identified in the 2018 imagery. These findings highlight a gap in current development planning, where critical infrastructure continues to be sited in areas prone to recurrent inundation.

Regionally, these findings align with trends observed across the broader Barotse Floodplain system, where inundation extent is highly variable. However, this study advances discourse by applying thresholding methods to C-band SAR data, thereby overcoming the limitations of optical imagery during cloud-prone flood seasons. The success of this approach provides a scalable template for the Zambia Vulnerability Assessment Committee and other agencies to operationalise real-time flood monitoring, moving beyond reactive, rapid assessments to proactive, data-driven spatial planning.

While the study utilises high-resolution SAR imagery, it relies on sampled images from specific acquisition dates (e.g., one or two images per flood season). This sampling strategy may not capture the absolute peak of flash floods if they occurred between satellite pass times. Additionally, while the study assesses the extent of flooding, the specific depth and velocity of the water, critical factors in structural damage, were not modeled in this specific analysis. A key strength of this research is its mixed-methods approach, which triangulates quantitative SAR satellite data with qualitative participatory GIS and ground-truth interviews. This integration ensures that the technical mapping of flood extents is ground-truthed against the lived experiences of local communities. Furthermore, the longitudinal analysis

spanning 2008 to 2018 allows for the identification of temporal trends and cycles that a single-year study would miss.

CONCLUSION

This study concludes that the Matebele Plain is subject to significant and variable flooding, with aerial extents fluctuating markedly over the investigated decade. This validates scientific research indicating that geospatial technologies coupled with remote sensing provide a quick and reliable source of information for mapping large areas affected by flooding events. The results indicate that the Matebele Plain experienced a high extent of flooding between 2008 and 2018. Communities and their socio-economic activities on the floodplain were highly affected by these flooding events. The findings have critical implications for disaster management and infrastructure planning in the Shangombo District. The generated flood maps provide a scientific basis for zoning, allowing stakeholders to identify safe locations for schools, clinics, and new settlements, thereby reducing future infrastructure damage. Additionally, establishing the specific trends and extents of flooding facilitates the creation of targeted early warning systems, which are currently lacking but essential for community safety. For local, regional, and national governments, flood mapping using satellite-based observations is a reliable source of information and a quicker way to provide the required data for planning, disaster mitigation, and management.

Future research should model flood depth and velocity alongside extent to provide a more comprehensive hazard profile. Additionally, further studies should investigate the correlation between these flood cycles and broader climate change indicators to predict future regimes. Disaster management agencies should operationalise the use of SAR and GIS techniques for real-time monitoring rather than relying solely on post-event assessments. This includes using the identified flood-prone zones to prioritise the construction of drainage canals and flood-resilient infrastructure. Government entities must integrate these geospatial flood maps into the formal district development plans for Shangombo. Policies should be enacted to restrict the construction of critical social infrastructure, such as schools and health centers, within the high-risk zones identified in the 2018 maximum extent data.

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