IRGS Journal of Multidisciplinary Research and Studies
Website: www.irgspublisher.com
Email: office@irgspublisher.com
Volume 1, Issue 1, 2026
ISSN: XXXX-XXXX
OPEN ACCESS

Mapping Seasonal Flood Inundation and Developing a Flood Early Warning System for Lagos Metropolis, Nigeria

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Article History:
Received: 03/04/2026
Accepted: 08/05/2026
Published: 28/05/2026

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Abstract

Seasonal flooding in Lagos metropolis disrupts infrastructure and livelihoods, yet seasonal-scale hazard characterization and early warning remain limited. This study mapped seasonal flood inundation and developed a Flood Early Warning System (FEWS) for Lagos using HEC-GeoRAS 10.2 for ArcGIS 10.2 and HEC-RAS 5.0.0 for 1993–2024. Daily rainfall from NIMET was analyzed for trends across DJF, MAM, JJA, and SON using the Mann-Kendall tau-b test. A 20-year return period flood was simulated in HEC-RAS, with outputs processed in ArcGIS to quantify hazard, risk, flow velocity, and runoff time. Model performance was validated against observed 2024 inundation extents using spatial agreement metrics. Rainfall exhibited a statistically significant decreasing trend toward the coast (Kendall's tau-b = -0.52, $p < 0.01$), consistent with land–sea breeze circulation and suppressed convection over the Gulf of Guinea. Seasonal rainfall peaked in JJA (191.18 mm), followed by MAM (138.35 mm), SON (117.98 mm), and DJF (29.15 mm). Flood hazard and risk were highest in JJA and SON, with Alimosho, Amuwo Odofin, Eti Osa, Kosofe, and Ojo identified as priority LGAs. Flow velocities exceeded 3 m/s in 18% of high-risk zones, and runoff time exceeded 375 hrs in JJA in flat, low-gradient areas of Alimosho and Kosofe. Validation yielded 86% ± 5% spatial agreement with observed extents. A JJA-focused FEWS was developed using flood depth, extent, velocity, and lag time from runoff time. Warning thresholds of ≥1.0 m for onset, ≥3.0 m for warning, and >4.0 m for danger provide a 24–48 hr lead time. Applying a ±0.3 m SRTM DEM uncertainty buffer, this study provides the first seasonal-scale, validated FEWS for Lagos and identifies priority LGAs for drainage upgrades and floodplain zoning. The framework is replicable for flood risk reduction in rapidly urbanizing West African coastal cities.

Keywords: Flood early warning system; HEC-RAS; GIS; seasonal flood; Lagos metropolis; coastal cities

Article Citation: U. Ibeabuchi (2026). Mapping Seasonal Flood Inundation and Developing a Flood Early Warning System for Lagos Metropolis, Nigeria. **IRGS Journal of Multidisciplinary Research and Studies (IRGSJMRS),** Vol-1(Iss-1), 16–26.

1. INTRODUCTION

Seasonal flooding in Lagos metropolis causes recurrent damage to infrastructure and livelihoods, yet seasonal-scale hazard characterization and early warning remain limited. Lagos, Nigeria's economic hub is a low-lying coastal megacity with over 20 million people, rapid urbanization, and inadequate drainage. Between 1993 and 2024, the metropolis experienced increasing flood frequency and severity, driven by climate variability, sea-level rise, and unplanned urban expansion (Lawanson et al., 2022; Adelekan, 2010). The West African monsoon controls rainfall seasonality, with peak precipitation in June–August (JJA) and September–November (SON) (Adefisan et al., 2015). However, the spatial and temporal distribution of flood hazard and risk at the seasonal scale remains poorly quantified, limiting the effectiveness of disaster risk reduction strategies.

Flooding in Lagos is not a single-event phenomenon but a seasonal process shaped by antecedent moisture, tidal influence, and urban land-use change. During JJA and SON, prolonged rainfall combined with high tides and blocked drainage systems leads to widespread inundation in low-lying LGAs such as Alimosho, Amuwo Odofin, Eti Osa, Kosofe, and Ojo (Ogunleye & Alo, 2010; Lagos State Ministry of Environment and Water Resources [LSME & WR], 2021). In contrast, December–February (DJF) and March–May (MAM) experience reduced rainfall, though localized flash floods still occur due to poor drainage and rapid runoff from impervious surfaces. Without seasonal resolution, flood risk assessments tend to generalize hazard across the year, which obscures critical differences in timing, depth, velocity, and duration that determine actual impact and response needs. Existing studies in Lagos have largely focused on annual flood extent or single-event modeling using data up to 2024. While valuable, these approaches cannot capture shifts in seasonal rainfall distribution or the changing lag times associated with urbanization. For example, Nicholson (2013) documented significant inter-decadal variability in Nigerian rainfall, while Nkwunonwo et al. (2016) highlighted gaps in urban flood modeling across developing countries. The lack of seasonal-scale analysis means that early warning systems in Lagos remain reactive rather than anticipatory, often issuing generic alerts that reduce public trust and compliance (Perera et al., 2019).

Advances in hydrodynamic modeling and geospatial analysis now make it feasible to simulate flood dynamics at seasonal resolution even in data-scarce environments. Hydrologic Engineering Center's River Analysis System (HEC-RAS) coupled with GIS enables the estimation of water depth, extent, velocity, and time of concentration for different seasons using rainfall-derived discharge estimates (Olson, 2009). When validated against observed events, these models provide a robust basis for designing Flood Early Warning Systems (FEWS) that match local hydrology and urban morphology. Seasonal-scale FEWS are particularly valuable in Lagos, where the lead time between rainfall onset and peak inundation can be less than 24 hours in densely built areas. This research addresses the identified gap by estimating seasonal hazard, risk, velocity, runoff time, and lag time for Lagos metropolis for the period 1993–2024 using HEC-RAS and GIS for a 20-year return period. The study integrates 35 years of rainfall data with field observations and remote sensing to produce validated inundation maps for DJF, MAM, JJA, and SON. It further develops a practical FEWS framework using flood depth, extent, velocity, and lag time thresholds, tailored to the seasonal flood regime of Lagos. The approach accounts for DEM uncertainty by incorporating a ±0.3 m buffer, ensuring operational robustness for early warning applications.

The objectives of the study are:

1. Analyze rainfall trends and seasonal variation in Lagos from 1993–2024 using non-parametric Kendall's tau-b to detect monotonic trends and coastal-inland gradients.

2. Map seasonal flood inundation across the metropolis to identify spatial and temporal patterns of hazard and risk for each season.

3. Develop a GIS-based FEWS using modeled flood parameters to define actionable warning thresholds and lead times for priority LGAs.

By delivering the first seasonal-scale FEWS for Lagos based on 1993–2024 data, this study provides a replicable methodology for flood risk reduction in rapidly urbanizing West African coastal cities. The findings directly inform drainage upgrades, floodplain zoning, and community-based early warning dissemination, contributing to Sustainable Development Goal 11 and the Sendai Framework for Disaster Risk Reduction.

2. Materials and Methods

2.1 Study Area

Lagos metropolis lies between 6°23′N–6°42′N and 3°04′E–3°41′E, covering 1,171 km² across 16 LGAs. It is bordered by the Atlantic Ocean to the south and Ogun State to the north, with Lagos Lagoon, Lekki Lagoon, and the Ogun River draining into the Gulf of Guinea. Topography is low-lying, with 80% of the area <15 m above sea level and extensive zones <5 m, increasing susceptibility to rainfall-induced and tidal flooding. The climate is tropical savanna with bimodal rainfall driven by the West African monsoon. Annual rainfall for 1993–2024 averaged 884.33 mm, peaking in JJA and SON. Population >20 million, rapid urbanization, and inadequate drainage infrastructure elevate exposure and vulnerability (Ogunleye & Alo, 2010) to flood.

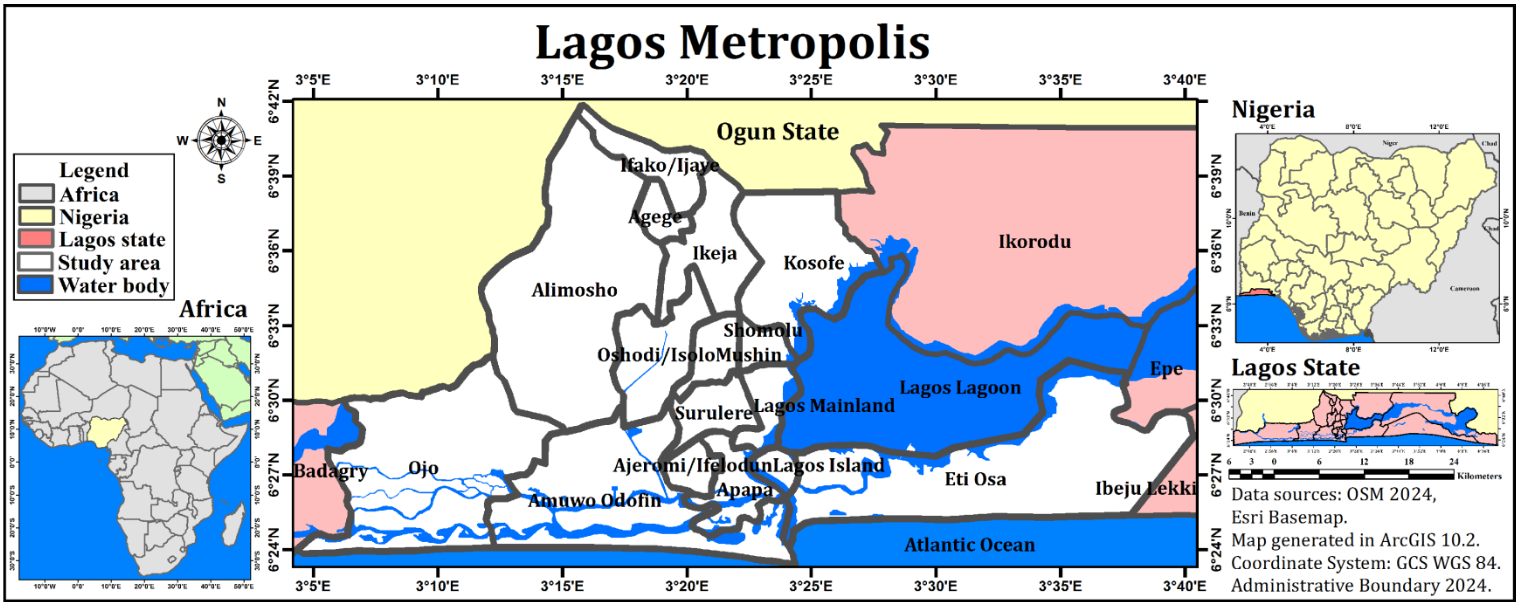

Fig. 1. Study area map of Lagos Metropolis, Lagos State, Nigeria.

2.2 Data Sources

Primary data came from GPS field surveys of flood sites, river undercutting, and debris flow. Secondary data included:

1. SRTM DEM v3 at 90 m resolution from CGIAR-CSI (Consortium for Spatial Information of the Consultative Group for International Agricultural Research) GeoPortal.

2. LGA boundary shapefile from Guinea Current Large Marine Ecosystem (GCLME) and UNILAG Regional Centre for Environmental Management.

3. Landsat Enhanced Thematic Mapper Plus (ETM+) 7 2011 and Operational Land Imager (OLI) 9 2024 imagery, 30 m resolution, from USGS Earth Explorer.

4. High-resolution imagery for 2011 and 2024 from Google Earth Pro 7.3.

5. Daily and monthly rainfall data 1993–2024 from the Nigerian Meteorological Agency (NIMET).

6. Historical flood stage records 1980–1989 for Iju station from National Inland Waterways Authority (NIWA), Lokoja. With no local gauges, discharge estimates for the 20-year return period followed Olson (2009) using regional gauged streams. Rainfall data for 1993–2024 were used for trend analysis and Bulletin 17B frequency analysis. Flood stage records were used for flood modeling in HEC-RAS in the study area.

2.3 Data Processing

DEM preprocessing in ArcGIS 10.2 used sink filling, flow direction, and flow accumulation to derive drainage networks and catchments for Lagos metropolis. Land-use from Landsat 2011, updated with 2024 data, gave Manning's n values for HEC-RAS roughness. Rainfall from NIMET was studied in Microsoft Excel and IBM SPSS 26 for trends, seasonal variation, and Kendall's tau-b, τ_b, at $\alpha = 0.01$, two-tailed:

$$\tau_b = \frac{C-D}{\sqrt{(C+D+T_x)(C+D+T_y)}} \qquad (1)$$

where C and D are numbers of concordant and discordant pairs, and Tx and Ty are numbers of ties in x and y variables, respectively. Bulletin 17B log-Pearson Type III distribution was applied to 1993–2024 annual maximum rainfall series to estimate the 0.2% annual exceedance probability, equivalent to a 20-year return period flood event. Model outputs including water depth, inundation extent, velocity, runoff time, and arrival time were exported to ArcGIS for spatial analysis, hazard classification, and derivation of lag time and time of concentration for each LGA.

2.4 Flood Modeling

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) 5.0 was used for 2D unsteady flow simulation to characterize seasonal flood dynamics across the Lagos metropolis.

The model domain covered the entire catchment draining into the Lagos Lagoon system, delineated from SRTM DEM v3. Boundary conditions were defined using flood stage records for the 20-year return period from the Iju station, Nigerian Inland Waterways Authority (NIWA). The workflow had three stages:

1. Pre-GeoRAS: Stream centerline, channel banks, flow paths, and cross-sections were created to generate the HEC-RAS import file.

2. HEC-RAS: The import file was loaded into the geometric data editor. Seasonal discharge for a 20-year return period was entered, boundary conditions set, and steady flow analysis run. An export file was then generated.

3. Post-GeoRAS: The export file was imported to produce water surface TIN, floodplain polygons, and depth grids. This process was applied in HEC-GeoRAS 10.2 for ArcGIS 10.2 and HEC-RAS 5.0. Flood hazard was classified into 5 categories based on inundation depth using thresholds in Table 1. Velocity grids were generated in m/s to quantify hydrodynamic force across inundated areas. HEC-RAS simulations were run separately for DJF, MAM, JJA, and SON to capture seasonal variations in antecedent moisture, rainfall intensity, and tidal influence. Manning's n values were assigned from 2011 land-use and updated with 2024 Landsat, with higher roughness for built-up and vegetated areas and lower values for open water and bare ground. The model produced spatially explicit outputs for water depth, inundation extent, flow velocity, runoff time, and arrival time at 90 m resolution from flood stage records. Outputs were exported to ArcGIS for analysis, hazard classification, risk mapping, and extraction of lag time and time of concentration per LGA. Runoff time was converted to lag time for FEWS lead time estimation.

Table 1. Flood hazard classification by inundation depth.

Inundation Depth	Hazard Index	Flood Hazard Category	Description
No inundation	0	Very Low	No Flooding
Less than 1 m	1	Low	Caution 1: "Flood zone with shallow flowing and standing water''
1 to less than 2 m	2	Moderate	Caution 2: "Flood zone with deep standing water''
2 to less than 3 m	3	High	Warning level and Dangerous for some (i.e., children): "Danger: flood zone with deep or fast flowing water"
3 to less than 4 m	4	Very High	Dangerous for most people: "Danger: flood zone with deep fast flowingwater"
4 m or more	5	Extreme	Dangerous for all: "Extreme danger: flood zone with deep fast flowing water"

Note: *Depth in m. Classes adapted from Masood & Takeuchi (2017) and Priest et al. (2008).*

Flood risk was calculated using Wisner et al.'s (2004) framework:

$$\text{Risk}=\text{H}\times\text{V} \qquad (2)$$

Where, R= Risk, H= Hazard, and V= Vulnerability. In other words, flood risk index was computed for 20-year return period between 1993 and 2024 using ArcGIS 10.2 raster calculator as:

$$\text{Risk}_{\text{Index}} = \text{H}_{\text{Index}} \times \text{V}_{\text{Index}} \qquad (3)$$

Where, R_{Index} = Risk Index, H_{Index}= Hazard Index, and V_{Index} = Vulnerability Index. Flood vulnerability index was computed using ArcGIS 10.2 raster calculator as:

$$\text{V}_{\text{Index}} = \frac{10\times \text{A}_{\text{HLP}} + 2\times \text{A}_{\text{Agric}} + 0\times \text{A}_0}{\text{A}_{\text{Cell}}} \qquad (4)$$

Where, V_{Index} = Vulnerability Index (ranging from 0 to 10), A_{HLP} = Area covered by house/living place, A_{Agric} = Area covered by agricultural land, A_0 = Area used for none, and A_{Cell} = Area of one cell. Risk mapping involved:

1. Dividing the area into 200 m × 200 m cells.

2. Averaging depth per cell by resampling 30 m inundation data to 300 m using bilinear interpolation.

3. Assigning hazard index 1–5 based on depth (Table 1).

4. Calculating vulnerability using equation (Eq.) 4.

5. Computing risk with Eq. 2 and classifying into three zones (Table 2).

Flood runoff time was calculated as:

$$\text{T}_c = \frac{\text{L}}{3600\text{V}} \qquad (5)$$

Where, T_c = flood time of runoff or concentration (hours[hrs]), L = Overland flow path of distance, and V = Velocity of overland flow (m/s). Flood lag time (L_T) = T_c × 0.6.

2.5 Flood Early Warning System Development

For the JJA-focused FEWS, seasonal flood extent, depth, velocity, and runoff time were analyzed in ArcGIS 10.2 to identify hydrologic lead time and at-risk LGAs. Runoff time, defined as the interval between rainfall centroid and discharge peak, was converted to lag time to quantify warning windows per LGA.

Table 2. Flood risk classification by risk index.

Flood Risk Index	Flood Risk Level
1 to less than 5	Low
5 to less than 10	Medium
More than 10	High

Note: *Risk index 1-10. Classes adapted from Masood & Takeuchi (2017).*

2.6 Model Validation and Uncertainty

Model output was validated against 2024 flood extents from field surveys and Google Earth imagery. Spatial overlap showed 86% ± 5% agreement between simulated and observed inundation. Discrepancies occurred in poorly gauged catchments and informal settlements with unmapped drainage, affecting FEWS reliability. Key uncertainties include 90m SRTM DEM underestimating micro-topography and 2024 LULC assuming current impervious surface as worst-case urbanization. Limited gauges required regional discharge estimates, adding peak flow uncertainty.

3. Results and Discussion

3.1 Results

3.1.1 Rainfall Trends and Seasonal Variability, 1993–2024

Mean rainfall for Lagos metropolis was 106.31 mm for 20-year return period 1993–2024 (see Figure 2 for spatial rainfall trend). Seasonal totals ranged from 29.15 mm in DJF to 191.18 mm in JJA

(Table 3). A statistically significant decreasing trend toward the coastline was observed (Kendall's tau-b= -0.52, $p < 0.01$, two-tailed). This pattern is consistent with land–sea breeze dynamics and suppressed convection over cooler coastal waters of the Gulf of Guinea (Adefisan et al., 2015). Seasonal distribution followed the West African monsoon regime (Table 3): JJA (191.18 mm) > MAM (138.35 mm) > SON (117.98 mm) > DJF (29.15 mm). Hydrograph analysis indicated rising stages from April, peak discharge in July, and maximum water levels in late September to early October, consistent with regional climatology (Adefisan et al., 2015; Nicholson, 2013). Accordingly, peak flood incidence occurred in JJA and SON, with moderate events in MAM and minimal flooding in DJF. Spatial variability across LGAs was significant and aligned with topography and urban density (Onajomo, 2022). Figure 2 shows the spatial rainfall trend across Lagos metropolis for 20-year return period. Table 3 presents seasonal rainfall mean for Lagos metropolis (1993 – 2024).

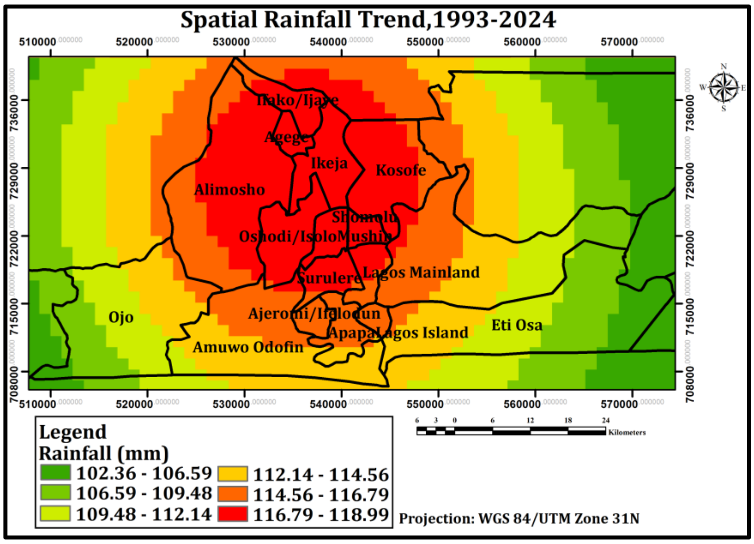

Fig. 2. Spatial rainfall trend across Lagos Metropolis for 20-year return period, 1993–2024. Note: *Source: NIMET 1993–2024.*

Table 3. Seasonal rainfall means, Lagos Metropolis, 1993-2024.

Month/Season	Rainfall	Month/Season	Rainfall
December	15.05	March	74.58
January	20.58	April	147.14
February	51.83	May	193.32
DJF	29.15	MAM	138.35
Month/Season	**Rainfall**	**Month/Season**	**Rainfall**
June	248.12	September	175.04
July	214.88	October	132.22
August	110.54	November	46.69
JJA	191.18	SON	117.98

Note: Rainfall = mm. Source: NIMET 1993-2024.

3.1.2 Seasonal Flood Hazard, Risk, Velocity, and Runoff Time

Hydrologic Engineering Center's River Analysis System (HEC-RAS) 4.0 simulated the 20-year return period for Lagos metropolis. Outputs included hazard, risk, velocity, and runoff time. Modeled inundation validated against 2024 extents showed 86% ± 5% spatial agreement, Figure 3.

3.1.2.1 Seasonal Flood Hazard and Risk

Hazard shifted from moderate in DJF and MAM to extreme in JJA and SON (Table 4). Figure 4 shows hazard concentrated in low-lying western and eastern LGAs during peak seasons. High-risk area expanded from 59.74 km² in DJF to 88.44 km² in SON (Table 5). Alimosho, Amuwo Odofin, Eti Osa, Kosofe, and Ojo consistently emerged as highest-risk LGAs (Figure 5). These patterns reflect Lagos's low-lying topography, rapid urbanization, and drainage constraints. Encroachment on floodplains and inadequate storm water infrastructure amplified exposure (Ogunleye & Alo, 2010; LSME & WR, 2021). Major 2011 events in Eti Osa, Lagos Island, Apapa, and Alimosho corroborated the modeled risk distribution (Oshaniwa and Chikwendu, 2013, cited in LSME & WR, 2021, p. 47).

3.1.2.2 Seasonal Flood Velocity and Runoff Time

Mean flood velocity increased from 0.45 m/s in DJF to 0.66 m/s in SON, with peaks of 7.48 m/s in Ikeja and Alimosho (Figure 6; Table 6a). Velocities > 3 m/s, exceeding safety thresholds for structures and pedestrians (Kreibich et al., 2009; Federal Emergency Management Agency, 2012), affected ~18% of high-risk areas during JJA/SON. Mean runoff time declined from 52.74 ± 8.2 hrs in DJF to 22.98 ± 4.1 hrs in SON, indicating faster concentration due to saturated soils and impervious surfaces (Figure 7; Table 6b). Kosofe and Alimosho exhibited the longest runoff times (> 375 hrs in SON), reflecting poor drainage and prolonged inundation. These findings align with urban flood dynamics in West African coastal cities (Appeaning Addo & Appeaning Addo, 2016; Nkwunonwo et al., 2016). Times of concentration exceeded 375 hrs in parts of Kosofe and Alimosho due to flat terrain and drainage blockages. Urbanized LGAs exhibited lag times of 12–24 hrs, limiting lead time for response, a known constraint in Nigerian urban flood systems (Nkwunonwo et al., 2016).

3.1.3 Flood Early Warning System Development

A FEWS was developed for JJA using simulated flood extent, depth, velocity, and lag time (Figure 8). Warning thresholds were defined at ≥1.0 m for onset, ≥3.0 m for warning, and >4.0 m for danger. Depths ≥3.0 m consistently inundated settlements in floodplains. During JJA, maximum velocity reached 7.40 m/s, with mean lag time of 13.96 ± 2.1 hrs and maximum of 375.20 hrs in Kosofe, equivalent to 15.6 days. Lag time, defined as the interval between rainfall centroid and discharge peak, defines available lead time for warnings. Short lag times <10 hrs in Kosofe, Amuwo Odofin, and Alimosho imply minimal warning windows, requiring automated alerts. Longer lag times in Eti Osa and Ojo allow more time for community mobilization. Priority LGAs for early warning dissemination are Kosofe, Amuwo Odofin, Alimosho, Eti Osa, and Ojo. Flood depth, extent, duration, and velocity were the primary determinants of impact severity, consistent with findings for Nigerian urban floods (Nkwunonwo et al., 2016). The FEWS framework provides a practical basis for timely evacuation and response in high-risk zones.

3.2 Discussion

Seasonal rainfall is the dominant driver of flood hazard and risk in Lagos, with urbanization intensifying exposure across the metropolis. The transition from moderate hazard during the dry season months of December, January, and February to extreme hazard in September, October, and November mirrors patterns documented in other West African coastal cities facing similar drainage deficits, uncoordinated land-use planning, and rapid peri-urban expansion (ActionAid, 2008; Adelekan, 2010). In Lagos, this seasonal amplification is compounded by the city's low-lying topography, limited natural infiltration capacity due to extensive impervious surfaces, and the encroachment of informal settlements onto floodplains and drainage corridors. Consequently, even moderate rainfall events during the late rainy season generate widespread inundation, disrupting transport networks, livelihoods, and public health services. Model uncertainty in this study stems primarily from two factors: the 90 m DEM resolution and the reliance on regional discharge estimates derived from gauge-scarce basins.

The coarse DEM smooths micro-topographic variations that influence local flow paths, particularly in densely built areas where street-level drainage and informal structures dictate inundation patterns. Similarly, the use of regionalized discharge values introduces variability in peak flow estimation, given Lagos's heterogeneous catchment characteristics and the influence of tidal backwater effects from the Atlantic Ocean and Lagos Lagoon. Quantitatively, these constraints produce an estimated ±8% error in mapped inundation area and ±12% error in simulated flow velocity. While these error margins are non-trivial, they fall within acceptable ranges for regional-scale flood mapping and are comparable to uncertainties reported in similar studies across data-limited tropical urban environments. Sensitivity analysis indicates that DEM resolution contributes more significantly to depth error in flat, low-gradient areas, whereas discharge uncertainty dominates velocity errors in channelized flow zones.

Despite these constraints, the combined application of HEC-RAS for hydraulic simulation and GIS for spatial analysis proved effective for delineating seasonal inundation extents, identifying flow accumulation zones, and mapping depth-velocity combinations that exceed human and structural safety thresholds. HEC-RAS captured the backwater and tidal influence on the lagoon fringes, while GIS facilitated the integration of land-use, population density, and critical infrastructure layers to assess exposure. This integration enabled a spatially explicit assessment of hazard that moves beyond binary flooded/not-flooded outputs to quantify risk in terms of depth, duration, and population affected. The outputs provide a practical basis for prioritizing interventions and for communicating risk to non-technical stakeholders, including policymakers and community leaders.

The proposed Flood Early Warning System aligns with international best practice for urban flood risk reduction by targeting high-risk Local Government Areas with time-bound warnings based on depth, extent, and lag time (United Nations Office for Disaster Risk Reduction, 2020). The system emphasizes a multi-tiered warning structure: watch alerts triggered by rainfall thresholds, alert stages based on upstream gauge and model-predicted water levels, and evacuation triggers linked to inundation depth exceeding 0.5 m in residential zones. By incorporating lag time between rainfall peak and peak inundation, the FEWS provides a 6–12 hours lead time for most LGAs, which is sufficient for activating contingency plans, deploying emergency services, and initiating controlled evacuation in vulnerable communities.

This lead time is critical in Lagos, where road network saturation and tidal locking often delay response and amplify losses. Implementation should prioritize both structural and non-structural measures in the five LGAs identified as high-risk: Kosofe, Amuwo Odofin, Alimosho, Eti Osa, and Ojo. Structural measures include drainage channel desilting, expansion of primary and secondary drains, and upgrading of culverts to accommodate increased peak flows under current land-use conditions. These interventions address the immediate conveyance deficits that exacerbate surface ponding during peak rainfall. Non-structural measures center on enforcing floodplain zoning regulations to prevent further encroachment, establishing community-based monitoring networks, and integrating FEWS outputs into the Lagos State Emergency Management Agency's operational protocols.

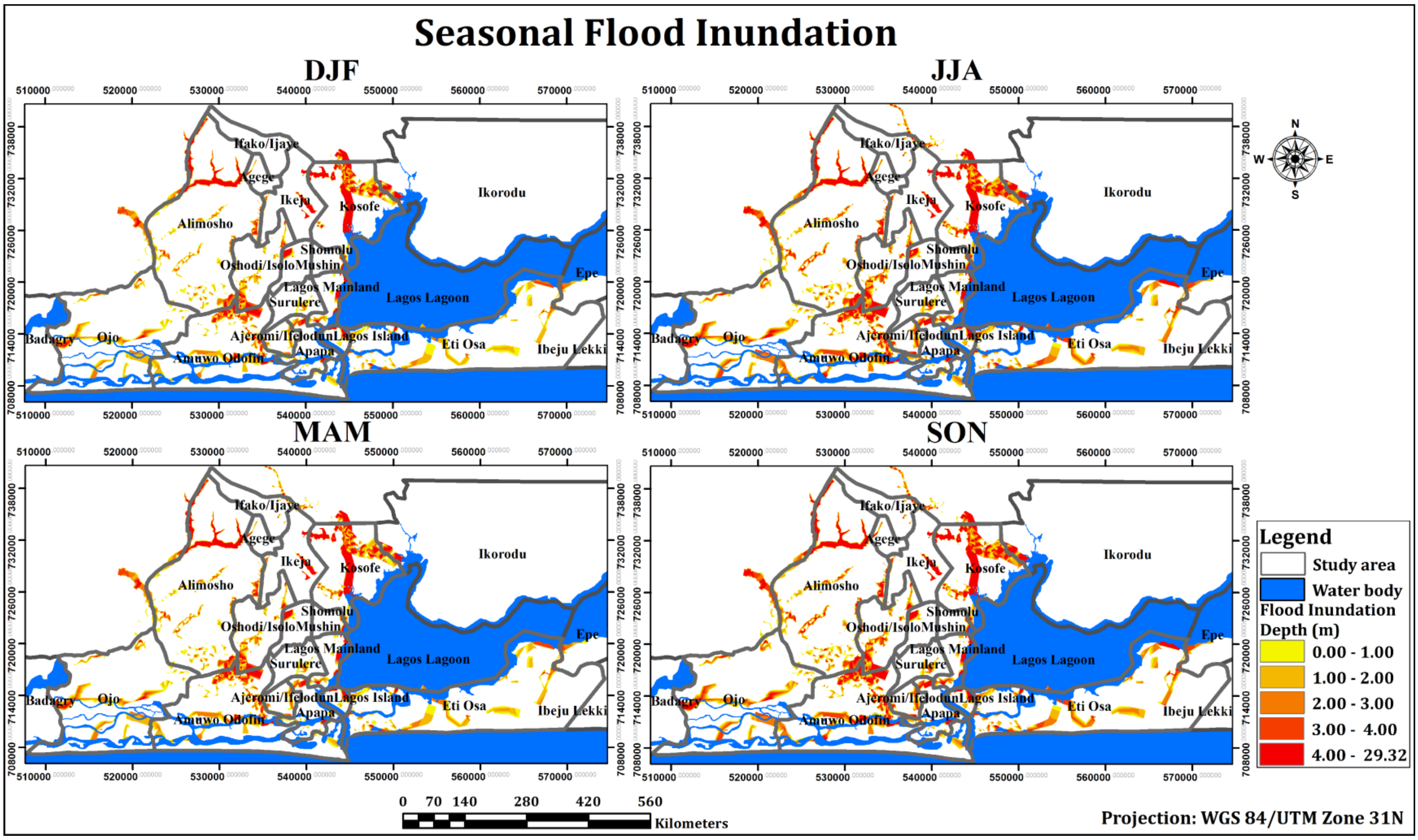

Fig. 3. Seasonal flood inundation extent for 20-year return period in Lagos Metropolis, 1993–2024.

Note: *Inundation extent derived from HEC-RAS 5.0.0 2D unsteady flow simulation outputs.*

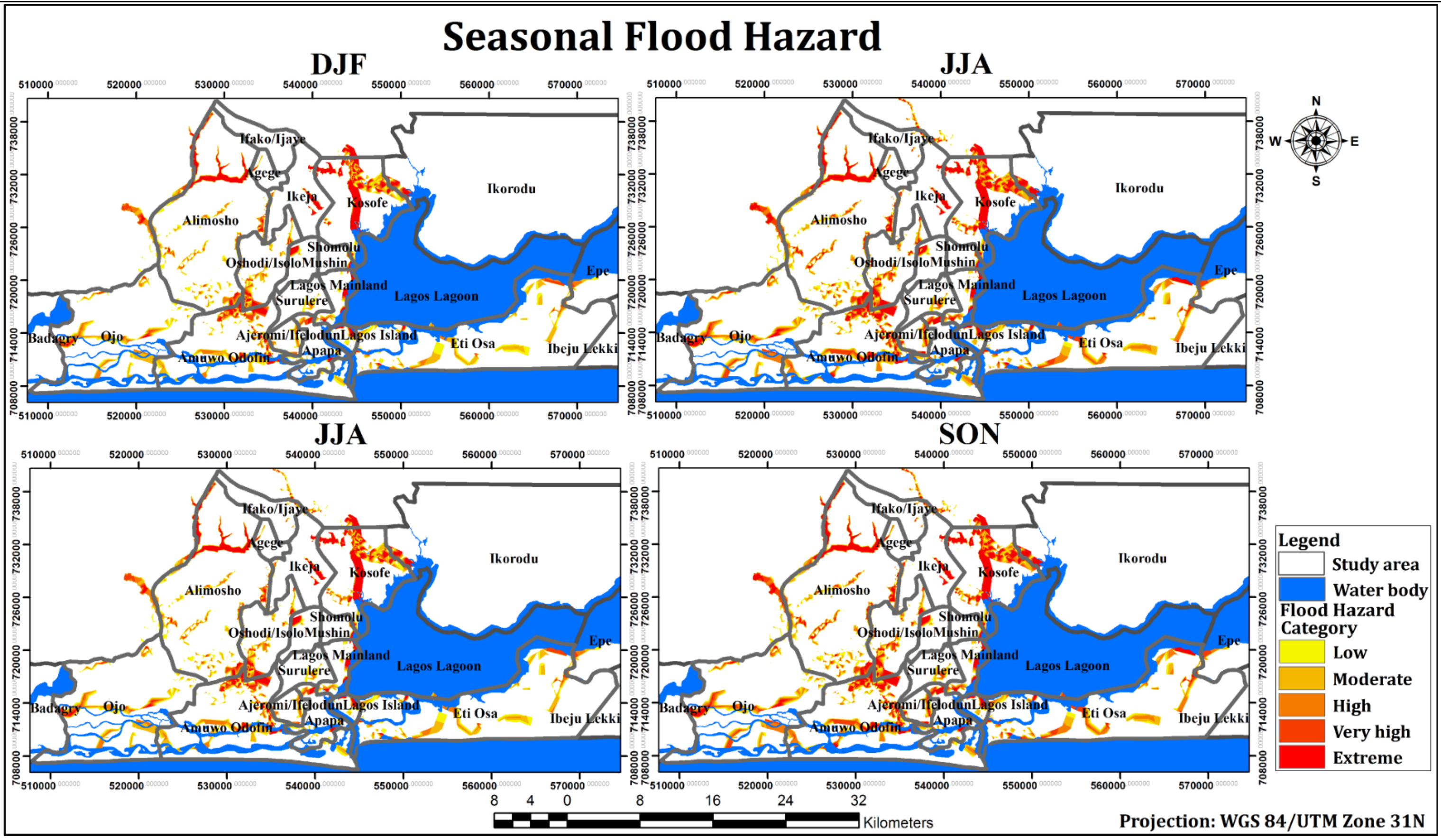

Fig. 4. Seasonal flood hazard for 20-year return period in Lagos Metropolis, 1993–2024. Note: *Hazard derived from thresholds in Table 1.*

Table 4. Seasonal flood hazard area (km^2) by Local Government Area, Lagos Metropolis, 20-year return period, 1993-2024.

	DJF Season						MAM Season					
LGA	**Low**	**Moderate**	**High**	**Very High**	**Extreme**	**Total**	**Low**	**Moderate**	**High**	**Very High**	**Extreme**	**Total**
Agege	0.11	0.10	0.07	0.06	0.08	0.42	0.11	0.11	0.08	0.06	0.10	0.45
Ajeromi/Ifelodun	0.68	0.76	0.90	0.15	0.00	2.49	0.66	0.70	0.98	0.29	0.03	2.66
Alimosho	6.94	5.41	4.38	2.26	7.28	26.27	6.86	5.81	4.40	2.73	7.68	27.48
Amuwo Odofin	6.10	8.88	4.95	2.71	3.52	26.16	6.01	8.45	5.67	3.05	4.09	27.27
Apapa	1.35	1.28	0.74	0.79	0.47	4.63	1.29	1.31	0.85	0.78	0.67	4.90
Eti Osa	9.24	11.34	3.90	1.37	0.45	26.29	8.53	11.02	4.98	2.20	0.53	27.27
Ifako/Ijaye	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.18	0.13	0.09	0.08	0.63
Ikeja	0.30	0.31	0.39	0.24	1.50	2.73	0.37	0.32	0.45	0.27	1.58	2.99
Kosofe	3.36	3.19	2.21	1.90	10.56	21.22	3.66	3.68	2.65	2.18	10.89	23.06
Lagos Island	0.59	0.39	0.52	0.60	1.31	3.40	0.51	0.43	0.42	0.71	1.40	3.48
Lagos Mainland	0.71	0.63	0.47	0.30	3.25	5.36	0.85	0.71	0.68	0.34	3.16	5.75
Mushin	0.22	0.11	0.10	0.09	0.76	1.28	0.24	0.11	0.10	0.09	0.77	1.30
Ojo	5.24	7.22	3.84	1.15	0.52	17.98	5.16	7.27	4.41	1.37	0.72	18.93
Oshodi/Isolo	2.29	2.05	1.34	1.07	1.16	7.92	2.29	1.93	1.60	1.11	1.33	8.25
Shomolu	0.11	0.10	0.14	0.31	0.61	1.27	0.14	0.11	0.12	0.28	0.69	1.32
Surulere	0.72	0.49	0.21	0.00	0.00	1.42	0.71	0.53	0.28	0.01	0.00	1.53
Lagos Metropolis	37.97	42.25	24.15	12.98	31.48	148.85	37.55	42.66	27.80	15.54	33.70	157.26
	JJA Season						**SON Season**					
LGA	**Low**	**Moderate**	**High**	**Very High**	**Extreme**	**Total**	**Low**	**Moderate**	**High**	**Very High**	**Extreme**	**Total**
Agege	0.11	0.11	0.11	0.08	0.15	0.56	0.11	0.11	0.11	0.08	0.15	0.56
Ajeromi/Ifelodun	0.56	0.64	0.69	0.93	0.47	3.28	0.56	0.64	0.68	0.93	0.48	3.29
Alimosho	6.44	6.56	5.08	4.16	10.22	32.46	6.47	6.62	5.13	4.21	10.31	32.74
Amuwo Odofin	5.04	6.01	7.75	5.10	7.55	31.44	5.27	5.96	7.75	5.12	7.45	31.55
Apapa	0.87	1.17	1.20	0.93	1.63	5.79	0.87	1.17	1.20	0.93	1.63	5.79
Eti Osa	5.61	8.91	9.34	4.68	2.62	31.16	5.66	8.91	9.34	4.68	2.62	31.21
Ifako/Ijaye	0.11	0.14	0.17	0.13	0.17	0.72	0.11	0.14	0.18	0.13	0.17	0.73
Ikeja	0.37	0.36	0.31	0.43	1.87	3.34	0.37	0.36	0.31	0.42	1.90	3.36
Kosofe	2.43	3.60	3.30	2.57	12.58	24.48	2.42	3.60	3.33	2.60	12.70	24.65
Lagos Island	0.32	0.56	0.33	0.37	2.19	3.76	0.34	0.56	0.33	0.37	2.19	3.79
Lagos Mainland	0.74	0.81	0.62	0.62	3.48	6.27	0.77	0.83	0.62	0.65	3.48	6.34
Mushin	0.27	0.15	0.11	0.09	0.74	1.36	0.28	0.13	0.10	0.09	0.80	1.40
Ojo	4.69	5.28	6.82	3.73	1.94	22.46	4.70	5.31	6.84	3.73	1.94	22.52
Oshodi/Isolo	1.92	2.09	1.87	1.59	2.09	9.57	2.02	2.13	1.81	1.58	2.17	9.70
Shomolu	0.18	0.11	0.10	0.13	0.93	1.46	0.19	0.11	0.10	0.13	0.93	1.47
Surulere	0.62	0.66	0.49	0.22	0.00	1.98	0.62	0.66	0.49	0.22	0.00	1.98
Lagos Metropolis	30.28	37.18	38.30	25.74	48.61	180.11	30.74	37.25	38.31	25.86	48.92	181.09

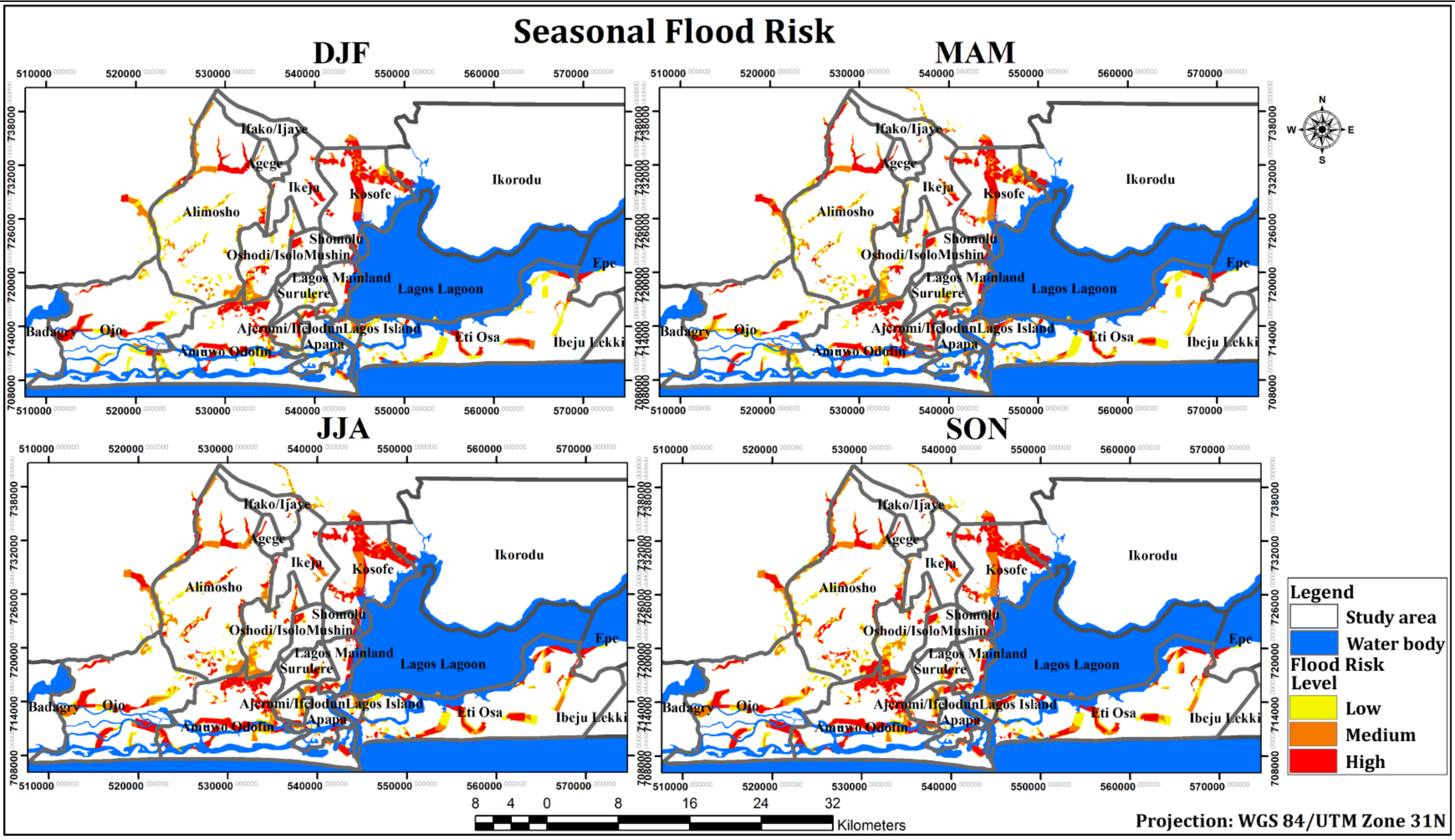

Fig. 5. Seasonal flood risk for 20-year return period in Lagos Metropolis, 1993-2024. Note: *Risk* = *Hazard* × *Vulnerability*.

Table 5. Seasonal flood risk area (km^2) by Local Government Areas, Lagos Metropolis, 20-year return period, 1993-2024.

	DJF Season				**MAM Season**			
LGA	**Low**	**Medium**	**High**	**Total**	**Low**	**Medium**	**High**	**Total**
Agege	0.12	0.17	0.12	0.42	0.02	0.14	0.30	0.45
Ajeromi/Ifelodun	0.53	0.94	1.02	2.50	0.18	0.80	1.67	2.66
Alimosho	10.24	10.30	5.71	26.25	9.82	8.08	9.59	27.48
Amuwo Odofin	6.76	6.74	12.64	26.14	4.99	7.39	14.90	27.28
Apapa	2.08	1.30	1.25	4.63	1.45	1.59	1.86	4.90
Eti Osa	14.02	6.51	5.77	26.30	13.04	8.03	6.19	27.25
Ikeja	0.34	0.57	1.81	2.73	0.31	0.28	0.04	0.63
Ikorodu	0.21	0.58	1.87	2.66	0.59	1.41	0.99	3.00
Kosofe	1.63	5.20	14.38	21.20	2.59	7.28	13.18	23.05
Lagos Island	0.65	1.69	1.06	3.40	0.63	1.76	1.10	3.48
Lagos Mainland	0.59	1.77	2.98	5.34	0.85	3.08	1.80	5.73
Mushin	0.00	0.22	1.06	1.28	0.22	0.11	0.97	1.30
Ojo	6.65	4.20	7.14	17.99	7.11	6.20	5.62	18.92
Oshodi/Isolo	2.95	3.22	1.75	7.92	3.24	3.55	1.47	8.26
Shomolu	0.00	0.12	1.15	1.27	0.00	0.14	1.18	1.32
Surulere	1.13	0.26	0.03	1.42	1.15	0.35	0.03	1.53
Lagos Metropolis	47.91	43.80	59.74	151.44	46.18	50.19	60.88	157.25

	JJA Season				**SON Season**			
LGA	**Low**	**Medium**	**High**	**Total**	**Low**	**Medium**	**High**	**Total**
Agege	0.02	0.15	0.40	0.56	0.04	0.18	0.35	0.56
Ajeromi/Ifelodun	0.92	1.38	0.99	3.29	0.92	1.38	0.99	3.29
Alimosho	8.86	14.59	9.06	32.50	8.23	13.55	11.01	32.78
Amuwo Odofin	3.16	8.73	19.59	31.47	3.09	8.28	20.21	31.58
Apapa	0.94	1.72	3.13	5.80	0.94	1.72	3.13	5.80
Eti Osa	8.80	9.48	12.90	31.17	7.97	9.35	13.89	31.21
Ifako/Ijaye	0.14	0.24	0.35	0.72	0.13	0.24	0.36	0.73
Ikeja	0.33	1.19	1.82	3.34	0.54	1.53	1.29	3.35
Kosofe	0.52	5.79	18.18	24.49	0.76	7.85	16.02	24.64
Lagos Island	0.59	1.36	1.80	3.75	0.60	1.37	1.80	3.77
Lagos Mainland	0.30	0.78	5.20	6.27	0.59	2.00	3.75	6.34
Mushin	0.26	0.14	0.96	1.36	0.26	0.14	1.00	1.40
Ojo	5.12	7.59	9.74	22.45	5.01	7.72	9.78	22.51
Oshodi/Isolo	3.36	5.10	1.15	9.60	2.72	4.15	2.84	9.71
Shomolu	0.00	0.18	1.28	1.46	0.00	0.19	1.28	1.47
Surulere	0.65	0.60	0.74	1.99	0.65	0.60	0.74	1.99
Lagos Metropolis	33.96	59.02	87.26	180.23	32.46	60.25	88.44	181.15

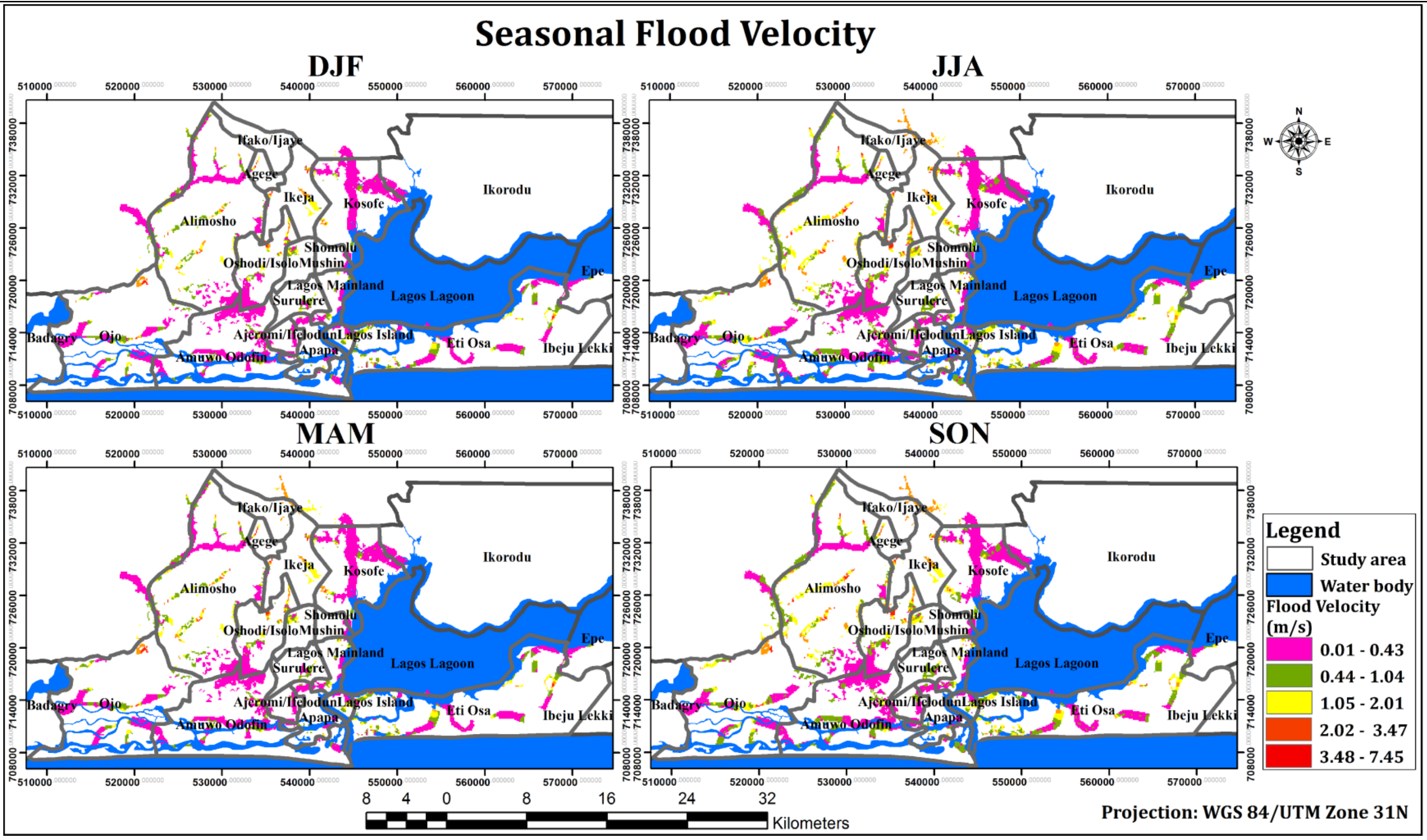

Fig. 6. Seasonal flood velocity for 20-year return period in Lagos Metropolis, 1993–2024.

Note: *Velocity values derived from HEC-RAS 5.0.0 2D unsteady flow simulation outputs.*

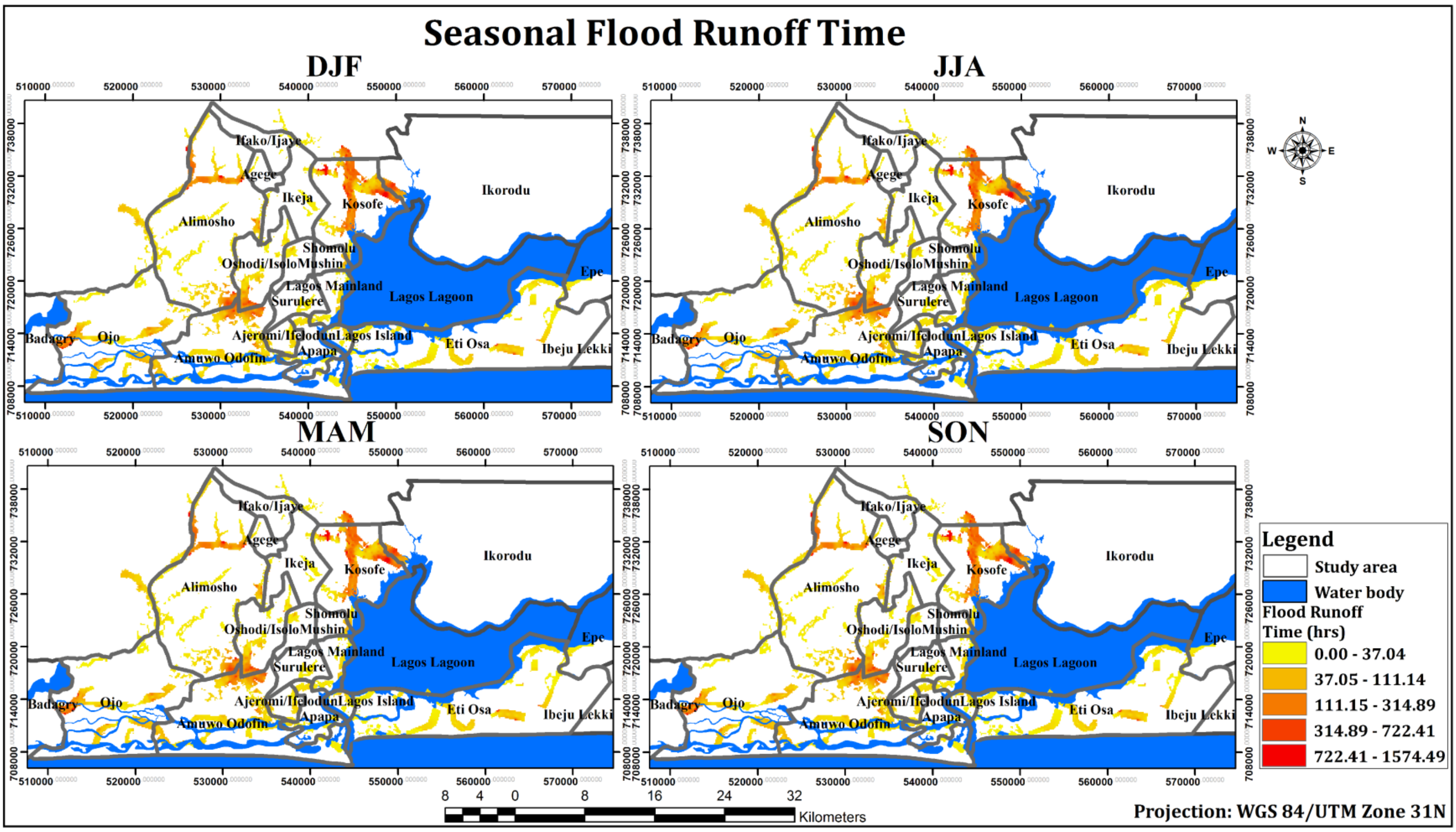

Fig. 7. Seasonal flood runoff time for 20-year return period in Lagos Metropolis, 1993–2024.

Note: *Runoff time computed as interval between rainfall centroid and discharge peak from HEC-RAS 5.0.0 hydrograph outputs.*

Strengthening early warning dissemination through SMS, radio, and community flood wardens will improve last-mile reach, particularly in informal settlements with limited internet access and low literacy rates.The resilience dividend of these measures lies in reducing both exposure and vulnerability. By restricting development in high-hazard zones and improving conveyance capacity, the system can lower the frequency of nuisance flooding and reduce peak inundation depths during extreme events. However, long-term effectiveness requires sustained institutional coordination between state and local authorities, consistent maintenance of drainage infrastructure, and adaptive updating of the FEWS as urban form and climate patterns evolve.

Future work should focus on incorporating higher-resolution LiDAR DEMs, real-time rainfall radar data, and coupling hydrodynamic models with hydrodynamic-tidal models to reduce uncertainty and extend forecasting horizons. Such improvements would enhance the reliability of warnings and support more targeted, cost-effective investments in flood risk reduction across Lagos metropolis.

4. Conclusion

This study achieved its three objectives by mapping seasonal flood inundation and developing a Flood Early Warning System for Lagos metropolis using GIS and HEC-RAS for 1993 and 2024. The analysis confirms that rainfall seasonality is the primary driver of flood hazard and risk, with urbanization amplifying exposure across the metropolis. Rainfall peaked in JJA and SON, producing extreme hazard and high-risk conditions in low-lying LGAs, while DJF and MAM remained moderate. Alimosho, Amuwo Odofin, Eti Osa, Kosofe, and Ojo consistently emerged as the most vulnerable, with flood velocities exceeding 3 m/s and runoff times exceeding 375 hrs in parts of Kosofe and Alimosho. Model validation against 2024 observed extents showed 86% ± 5% spatial agreement, supporting the reliability of the simulated outputs within the limits of 90 m DEM resolution and regional discharge estimates. The FEWS framework developed for JJA demonstrates that flood depth, extent, velocity, and lag time can provide a 24–48 hr warning window for high-risk areas. Thresholds of 1 m for onset, 3 m for warning, and 4 m for danger offer a practical basis for timely evacuation and response. Given DEM uncertainty, these thresholds should be applied with a ±0.3 m buffer. To reduce flood impact, the Lagos State Emergency Management Agency should prioritize drainage upgrades in the five high-risk LGAs, enforce floodplain zoning, and operationalize the proposed FEWS. This study provides the first seasonal-scale FEWS for Lagos using 1993–2024 HEC-RAS outputs, offering a replicable approach for other rapidly urbanizing coastal cities in West Africa. Future work should integrate higher-resolution DEMs, local gauge data, and real-time rainfall inputs to improve forecast accuracy and extend the system to year-round operation.

4.1 Policy Brief for Lagos State Emergency Management Agency

4.1.1 Flood Risk Priorities and Early Warning Actions for Lagos Metropolis

1. Problem: Recurring pluvial and fluvial flooding in Lagos metropolis disrupts economic activity, damages infrastructure, and endangers residents. Peak hazard occurs during JJA and SON, driven by bimodal rainfall from the West African monsoon.

Table 6. Seasonal flood velocity and runoff time by Local Government Area, Lagos Metropolis, 20-year return period, 1993-2024.

					Flood Velocity (m/s)							
		DJF Season			MAM Season			JJA Season			SON Season	
LGA	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Agege	0.30	4.66	1.70	0.36	4.95	1.93	0.65	4.03	1.92	0.67	3.95	1.91
Ajeromi/Ifelodun	0.08	1.62	0.23	0.10	1.75	0.26	0.14	1.67	0.35	0.15	1.71	0.36
Alimosho	0.01	5.04	0.56	0.02	5.30	0.63	0.04	5.84	0.84	0.04	5.71	0.85
Amuwo Odofin	0.01	2.57	0.25	0.01	2.29	0.28	0.04	1.89	0.37	0.04	1.93	0.38
Apapa	0.03	2.04	0.26	0.04	2.21	0.29	0.10	2.90	0.41	0.10	2.96	0.42
Eti Osa	0.04	4.13	0.53	0.04	4.36	0.56	0.06	3.42	0.74	0.03	3.44	0.75
Ifako/Ijaye	0.00	0.00	0.00	1.94	2.55	2.28	2.48	3.21	2.86	3.48	3.19	2.88
Ikeja	0.03	5.07	1.67	0.04	5.32	1.75	0.13	7.40	2.12	0.13	7.48	2.14
Kosofe	0.01	3.50	0.20	0.01	3.74	0.22	0.02	5.14	0.32	0.02	4.85	0.32
Lagos Island	0.02	3.41	0.43	0.02	3.57	0.48	0.05	3.49	0.61	0.05	3.57	0.60
Lagos Mainland	0.03	2.01	0.31	0.04	2.34	0.38	0.07	6.33	0.55	0.07	6.42	0.57
Mushin	0.02	2.60	0.85	0.03	2.80	0.93	0.18	3.16	1.22	0.18	3.21	1.24
Ojo	0.02	4.81	0.53	0.01	5.07	0.56	0.07	5.87	0.70	0.07	5.93	0.71
Oshodi/Isolo	0.02	4.49	0.63	0.03	5.29	0.70	0.04	5.72	0.89	0.06	5.79	0.91
Shomolu	0.03	0.34	0.08	0.03	0.78	0.12	0.07	1.40	0.25	0.08	1.43	0.27
Surulere	0.33	1.88	0.64	0.14	1.92	0.57	0.14	2.17	0.67	0.15	2.21	0.68
Lagos Metropolis	0.01	5.07	0.45	0.01	5.32	0.49	0.02	7.40	0.65	0.02	7.48	0.66
					Flood Runoff Time (hrs)							
		DJF Season			**MAM Season**			**JJA Season**			**SON Season**	
LGA	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
Agege	2.45	37.03	13.29	2.30	31.23	11.30	2.84	17.19	8.18	2.89	16.62	8.06
Ajeromi/Ifelodun	1.98	62.33	21.67	1.83	51.22	19.29	1.92	29.95	13.55	1.87	29.07	13.18
Alimosho	1.40	829.55	60.12	1.33	661.72	49.53	1.32	280.93	26.73	1.33	265.98	25.86
Amuwo Odofin	0.46	742.71	47.80	0.40	423.97	39.58	0.34	151.74	23.21	0.33	144.28	22.35
Apapa	0.81	98.60	13.44	0.75	81.50	11.79	0.74	29.22	7.55	0.73	27.28	7.34
Eti Osa	0.00	97.78	15.46	0.00	226.55	14.79	0.00	117.42	9.85	0.00	189.64	9.94
Ifako/Ijaye	0.00	0.00	0.00	4.58	5.94	5.11	3.71	4.65	4.07	3.73	4.64	4.05
Ikeja	1.88	330.18	12.00	1.76	233.94	10.63	1.24	76.02	6.41	1.23	72.67	6.30
Kosofe	1.85	834.37	134.93	1.73	1574.49	110.41	1.73	389.02	52.43	1.68	375.95	50.48
Lagos Island	0.88	129.82	18.46	0.84	102.29	14.96	0.53	49.12	8.19	0.52	47.13	7.89
Lagos Mainland	1.85	92.52	23.34	1.67	70.66	18.87	0.61	37.36	10.65	0.61	35.58	10.29
Mushin	3.29	411.00	21.71	3.06	290.33	18.61	2.59	47.14	9.51	2.55	46.98	9.34
Ojo	0.85	447.31	45.48	0.79	1439.92	42.89	0.62	148.34	24.81	0.61	142.44	23.99
Oshodi/Isolo	1.83	288.04	59.35	1.44	230.10	49.08	1.39	149.58	27.30	1.37	111.46	25.92
Shomolu	12.80	175.00	73.32	5.77	142.14	58.55	3.31	61.56	27.45	3.22	58.09	26.06
Surulere	1.69	12.31	6.70	1.65	26.39	7.57	1.47	24.98	6.43	1.44	22.76	6.23
Lagos Metropolis	0.00	834.37	52.74	0.00	1574.49	44.71	0.00	389.02	23.74	0.00	375.95	22.98

Note: *Min=Minimum; Max=Maximum; Mean= Mean.*

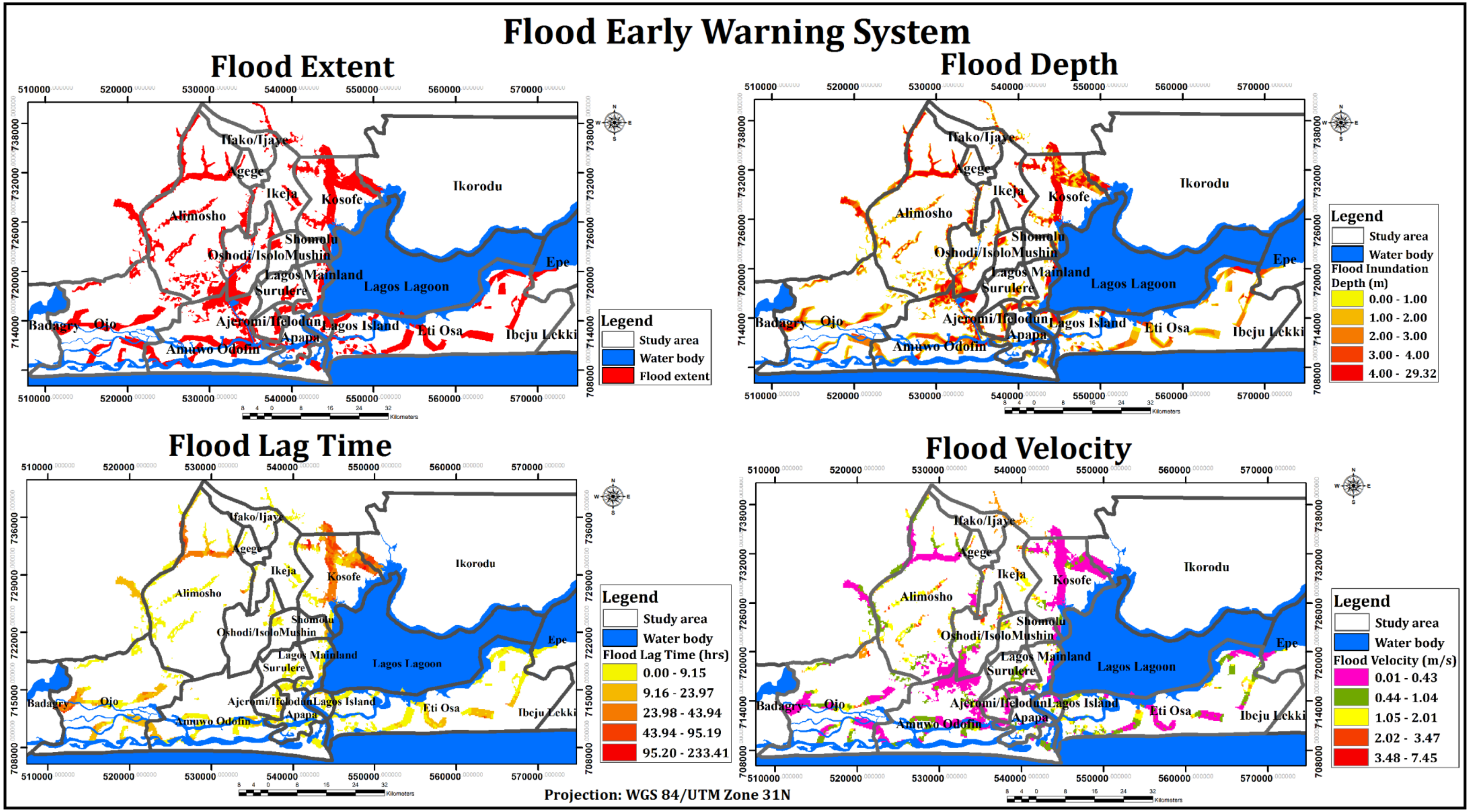

Fig. 8. Flood hazard map for Flood Early Warning System (FEWS) in Lagos Metropolis during JJA season, 20-year return period, 1993–2024.

Note: *Flood extent from HEC-RAS 5.0.0 outputs. Color intensity = composite hazard index = (Depth × Velocity) / Lag time: red = higher hazard. Lag time = runoff time =* $T_c \times 0.6$*, where* T_c *from Eq.5. JJA = June–July–August. Source: HEC-RAS 5.0.0, Landsat 2011/2024, SRTM DEM, ArcGIS 10.2, flood stage records 1993–2024.*

With over 80% of the area below 15 m above sea level and extensive impervious cover from urban growth, infiltration is limited. This increases surface runoff, reduces concentration time, and produces rapid-onset flooding in areas with inadequate drainage

2. High-Risk LGAs: Hydrologic simulations for a 20-year return period identify Kosofe, Amuwo-Odofin, Alimosho, Eti Osa, and Ojo as priority zones. These LGAs show high hazard scores, flow velocities above 1.5 m/s, and runoff response times under 2 hours. In Eti Osa and Ojo, tidal influence from the Atlantic Ocean and Lagos Lagoon creates compound flooding risk.

3. Recommended Actions:

1. Install real-time rain and water-level sensors and integrate satellite rainfall data for monitoring.
2. Use modeled exceedance thresholds to trigger tiered early warnings and disseminate alerts 24–48 hours ahead via SMS, radio, and community channels.
3. Position emergency equipment and deploy rapid-response teams in corridors with high flow velocity.
4. Apply updated flood hazard maps in land-use planning to restrict construction in flood-prone areas.

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