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Satellite Based Estimation of Methane from Selected Dumpsites in Benin City

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ABSTRACT **Original research paper**

Urban solid waste is a significant source of methane (CH_4), a potent greenhouse gas with serious implications for climate change and public health. This study presents a multi-source estimation of methane emissions from two active dumpsites in Benin City, Nigeria. The dumpsites are Otofure Waste Disposal Site (Oluku, Benin Bypass) and the Jubilant Citizen Resources Limited dumpsite (Omo-Imasuen Street, Avbiama). The research adopted satellite-based remote sensing data covering the period from November 2024 to August 2025. Results revealed distinct temporal variations in methane emissions across the two sites, with significant peaks corresponding to seasonal waste generation patterns and meteorological conditions. CH_4 buildup was generally higher in the dry season months compared to levels observed in the rainy season months. Results also revealed a substantial drop in methane buildup between June–July (~1,820–1,821ppbv) and which can be liked to the dominant role of atmospheric sinks and transport, essentially the hydroxyl radicals (OH) and the effects of the West African monsoon which encourages deep boundary-layer development and vigorous convection, enhancing vertical mixing and dilution of methane columns. Findings show that tropospeheric methane concentration value around Otofure Waste Disposal Site located near Oluku, Benin Bypass stood at 1,831.16 - 1,831.52ppbv (176.3km²) whereas that of Jubilant Citizen Resources Limited dumpsite situated in Omo Imasuen Street, Avbiama range from 1,830.41 - 1,830.77ppbv (194.9km²). the differences in methane level between the sampled dumpsites suggest the effects of population density coupled with socio-economic variables such as household income level, urban lifestyle expanding commercial land use on total waste generation and hence methane production in Benin City. Since methane emission from dumpsites is proportional to organic waste there is need polices and practices aimed to support food waste prevention, organic waste diversion through composting, dumpsite rehabilitation, optimize the capture of landfill gas through biogas technologies etc.

Keywords: Methane Emissions, Urban Solid Waste, Remote Sensing, Benin City, Waste Management Policy, Spatio-Temporal Analysis, Greenhouse Gases.

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1. Introduction

One of the growing sources of atmospheric methane (CH_4) is solid waste disposal sites in many urban canters globally. In global warming and climate change debates, methane has been widely acknowledged as a lethal greenhouse gas (GHG) warming potential exceeding that of carbon dioxide (CO_2) over the short term. It is well documented that remote sensing technology through the deployment of space-borne satellite sensors have the capability of observing and detecting methane emissions from waste dumpsites which frequently act as super-emitters. Over African including areas with little or no well-structured and formal waste management infrastructure, Aminu & Binietoglou (2024) reported that dumpsitesemits up to several thousand kilograms of methane hourly.

Nevertheless, the use of satellite technology in the observation and measurement of methane has key limitation based on its inability to record diffuse emissions from open dumps (Zhang et al., 2023; Aminu & Binietoglou, 2024). This therefore underscores the need for a multi-source observational framework that integrates satellite remote sensing and ground-level measurements to support policy. Globally, urban methane emissions have been shown to be systematically underestimated by emission inventories (by factors of 3 to 4) based on top-down analytical framework using the European Space Agency (ESA) operated Tropospheric Monitoring Instrument (TROPOMI) satellite data over major cities, including landfills as a primary emission source (de Foy et al., 2023). Recent inversion-based satellite models in Denmark also revealed up to 66% underestimation in official inventories, signaling the need for more granular local-level measurement and model corroboration (Zhang et al., 2023).

Schuit et al (2023) also undertook automated assessment of methane super-emitters globally with TROPOMI, to identify the sources down to facilities, including municipal landfills in Africa and South Africa. The study demonstrated a practical multi-sensor workflow with broad satellite screening in addition to targeted high-resolution confirmation. They were able to quantify and locate waste-sector plumes for follow-up on the ground. Cusworth et al (2024) surveyed hundreds of landfills in the United States with approximately 20% of them being open sites using airborne imaging spectrometers (AVIRIS-NG/PRISM) and compared observations with bottom-up inventories. They found widespread, persistent “super-emitting” plumes and systematic under-reporting in traditional inventories. Media briefings reported emission level of approximately 40% higher than the US Environmental Protection Agency (EPA) estimates, with about 60% of large emitters persistent (American Association for the Advancement of Science, 2024;Volcovici, 2024). Cusworth et al (2024) study showed the value of combining repeated airborne measurements with facility reports to pinpoint working faces, cover failures, and gas-system leaks for mitigation.

In the United Kingdom (UK), Rees-White et al (2019) used the tracer-gas dispersion method (mobile downwind transects with acetylene as a co-released tracer) to quantify the entire dumpsite emissions over multiple days at a landfill. The plumes were partitioned to estimate non-combusted engine exhaust emissions which were about 14–22 kg CH_4 h^{-1}. The overall emissions varied substantially on a day-to-day basis which was attributed to operations and meteorology. They also emphasized the drawback of deploying single-method spot checks in omitting true annual loads while integrating mobile measurements with in-situ operations remarkably improved estimates.

Also, Niu et al (2023) compared seven parameter sets for the Intergovernmental Panel on Climate Change (IPCC) first-order-decay (FOD) model against real measurements from five Chinese landfills. The finding showed misfit of local conditions when compared with default/global parameters. But when the finding was calibrated using Chinese waste characteristics/management practices, it improved the agreement, thus, underscoring the need to integrate local empirical data with inventory models for credible city-scale estimates. In South Africa, Njoku et al (2023) instrumented the Thohoyandou landfill with boundary gas probes in a two-year study and correlated CH_4/CO_2 levels with meteorology along with site activity. Subsurface CH_4 spanned about 0.24–2.56% v/v (with higher values near active cells), and temperature/pressure shifted modulated concentrations. This clearly indicates that integrating continuous in-situ monitoring with weather/operations data is essential in the interpretation of variability and design mitigation.

Unfortunately, in Nigeria in general and Benin City in particular, empirical studies deploying satellite remote sensing for methane estimation are few and for Benin city such studies are lacking. Some of these studies are, Riman et al., (2022), who investigated seasonal methane emission from municipal solid waste disposal sites in

Lagos, Nigeria, Aboyade, (2004) ion the potential for climate change mitigation in the Nigerian Solid Waste Disposal Sector, using Lagos State as a case study. Balogun-Adeleye et al., (2019) developed a model for the accurate estimation of methane emission in landfills in Nigeria. Daura, (2014), estimated methane gas emission from solid waste disposal sites in Kano. Oladejo, et al., (2020), estimated Methane Emission Potentials in Landmark University Open Dump Site, Omu Aran, Kwara State Nigeria. Balogun-Adeleye et al., (2018) worked on estimation of methane emissions from waste disposal sites in Lagos. In another study Attah et al., (2024) assessed the spatio-temporal variation of methane gas emission from landfills in Kano metropolis, Nigeria. Other include Adeboye et al., (2022) on characterization and energy potential of municipal solid waste in Osogbo metropolis, Elemile, et al., (2019), on the determination of carbon emission Potentials in a solid waste management facility in Akure, Nigeria, Idehai and Akujieze (2015) on estimation of landfill gas and its renewable energy potential in Lagos, Nigeria, Faraday and Oluwabunmi, (2024) on Greenhouse gas levels (CH_4 and CO_2) in Lagos state and Oyo state, Nigeria, Okafor et al., (2022) on estimating emissions from open-burning of uncollected municipal solid waste in Nigeria, Ogbowuokara, et al. (2024), on the assessing the relative contribution of various anthropogenic sources to atmospheric methane in Rivers State, Nigeria using a multi-criteria decision analysis approach, Yusuf et al., (2019) on energy recovery from municipal solid waste in Nigeria and its economic and environmental implications etc. Findings from these studies suggest strong sensitivity of methane emissions to organic waste fraction and meteorological conditions. However, most of these insights derive from large-scale urban or national case studies. In Benin City however, existing MSW management studies have either focused on perception studies such as Adekola, et al., (2021), Agbebaku (2021), Okosun et al., (2023), or MSW disposal methods such as the works of Asikhia and Olaye (2011), Igbinomwanhia and Ideho, (2014), Onwuemele (2015), Imasuen and omorogieva (2015), Agbebaku (2019), Oriakhi and Okonofua (2022), Biose et al., (2023). Other studies on MWS management in Benin City have focused on the environmental impact of MSW such as Ikpe et al., (2020), Enerijiofi and Ekhaise, (2019), generation pattern such as Rawlings and Uzebu (2024), or characterization of waste such as Igbinomwanhia (2012) etc. None of these studies have addressed methane estimation from active dumpsites and its spatio-temporal patterns. This creates a gap for which the present study attempts to address. The present study focuses on two active dumpsites in Benin City namely Otofure Waste Disposal Site located near Oluku, Benin Bypass and the Jubilant Citizen Resources Limited dumpsite situated in Omo-Imasuen Street, Avbiama. These sites are the only operational solid waste disposal locations within the city. The broad objective therefore is to quantify spatio-temporal methane emission levels at Otofure and Jubilant Citizen dumpsites using ground-truth in-situ measurements and satellite-based methane concentration data.

2. Materials and Methods

2.1 The Study Area

This research was carried in Benin City as shown in Figure 1, which doubles as the capital city of Edo State and the traditional headquarter of the *Bini* people. It is a humid-tropical metropolis spanning across five local government areas (LGAs) including Egor, Ikpoba-Okha, Oredo, Orhionmwon and Uhunmwonde. Approximately, the primordial city is geographically located within the coordinates of latitude 6°11’N, 6°27’N (Southern andNorthern boundaries respectively) and longitude 5°31’E and 5°44’E (Western and Easternboundaries respectively) (Balogun & Orimoogunje, 2015). It covers an estimated land area of 850 square kilometres as at year 2019 (Fabolude & Aighewi, 2022). Benin City has vibrant socio-economic environment, and is expected that the range of socio-economic activities in the city could result in urbanenvironmental stressors, one of which is solid waste management.

In terms of the climate, Benin City have distinctive rainy (around March to October) and dry around November–March) seasons. The climatic condition is also marked by high humidity throughout the year, with relatively elevated precipitation ranging from about 2,000–2,500 mm, with local drainage by the Ikpoba and Ogba rivers (Cirella 2019;Iduseri et al., 2024). These physiographic and demographic conditions, together with inadequate urban services, underpin recurrent flooding and complicate solid-waste handling. Waste collection is irregular and open dumping/makeshift landfills persist across the urban fringe, with municipal solid waste generation reported at ~574 t day^{-1}—factors relevant to methane emissions from the solid-waste sector and to the need for spatially explicit, multi-source emissions estimation in this setting (Cirella et al., 2019; Adekola et al., 2021).

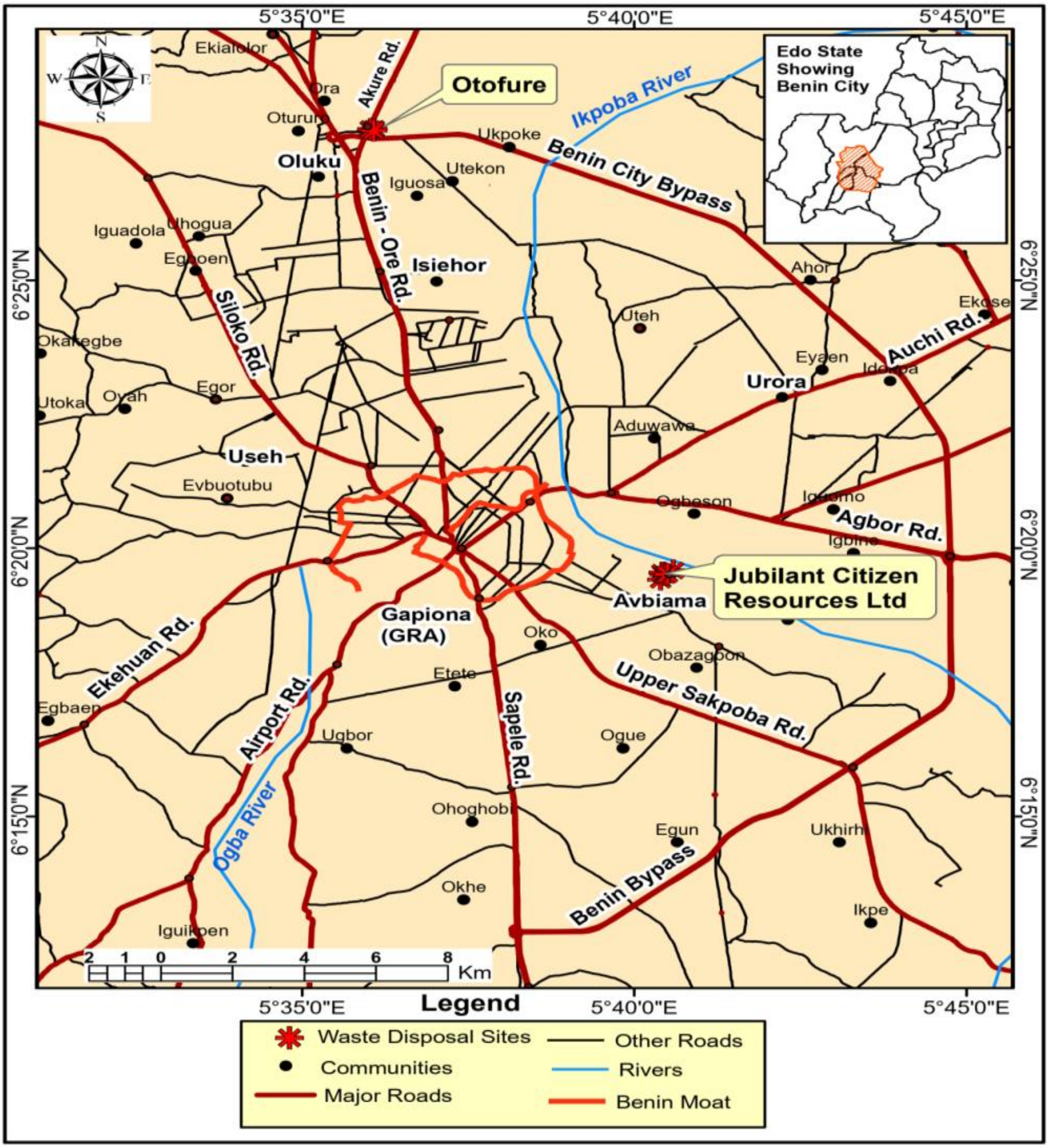

Figure 1: Benin City Showing Waste Disposal Sites
Source: Compiled using Open Street Map Database (2024)

2.2 Datasets and Sources

The main GHG used for this study was methane (CH_4) and was sourced from Giovanni web archive, established and serviced by the United States (US) National Aeronautics and Space Administration's (NASA) Goddard Earth Sciences Data and Information Services Center (GES DISC). This is a high-resolution gridded time-series dataset remotely sensed using the NASA's Atmospheric Infrared Sounder (AIRS) sensor onboard NASA's Aqua satellite launched in 2002 (AIRS Science Team & Joao Teixeira, 2013). The latest edition (Version 7.0) of Aqua/AIRS L3 Monthly methane data with Standard Physical Retrieval (AIRS-only) with enhanced spatial resolution of 1 degree x 1 degree measured at 1000hPa (ground-level pressure) was used. Comprehensive description of algorithms deployed in the satellite data retrieval, instrument calibration, corrections and consistency checks can be found in the works of AIRS project (2019), Tian et al (2020) and Thrastarson et al (2021) among others. Empirical studies deploying NASA GES DISC methane data include Rodionova (2022) in Tiksi Region of Russia, Zhou et al (2023) global assessment and Tao et al (2024) in Monsoon Asia to mention a few, hence it deployment in this paper.

2.3 Methods of Data Analysis

The retrieved methane data passed through several analytical processes to achieve the expected outcome for discussion given the fact that the remotely-sensed dataset is usually available in interoperable NetCDF format. Based on Ibanga et al (2023), Balogun et al (2024), Ogbomida et al (2024), Ibanga et al (2025), the monthly methane NetCDF layers were converted to NetCDF raster layers using make NetCDF raster layer algorithm in ArcGIS 10.8 Spatial Analyst Extension. *Extract-values-to-point* tool in ArcGIS 10.8 Spatial Analyst was also deployed in the extraction of numerical methane concentration values (in ppbv) from the resultant eight NetCDF raster layers with the aid of x, y coordinates of some locations in Benin City including the two solid waste dumpsites.

Another vital analytical procedure involved the deployment of *Geostatistical Kriging* algorithm in the interpolation of the created point methane layers. According to Environmental Systems Research Institute (ESRI, 2020), *Kriging* assumes that at least some of the spatial variation observed in natural phenomena can be modeled by random processes with spatial autocorrelation, and require that the spatial autocorrelation be explicitly modelled. *Kriging* frameworks are very useful in spatial patterns description and modelling, prediction of values at unsampled locations, as well as in uncertainty assessment especially when it is linked the prediction of values at the unmeasured locations. The framework gives smoothed surface of phenomenon for easy visualisation as seen in the works of Stadler et al (2023) Raissouni et al (2024) and Aldungarova et al (2024) among others.

In total, 10 new interpolated layers were created including those from November 2024 to August 2025 as well as the coalesced mean seasonal values. To map the seasonal distribution of methane concentration, monthly values in each season were merged followed by the determination of mean values and subsequent interpolation of the mean values. Specifically, mean methane values of dry season comprised of concentrations from November 2024 to March 2025 while wet (rainy) season mean values include coalesced values from April to August 2025. The final procedure involved the deployment of *Equal Interval Classification* framework in the segmentation of the interpolated layers for easy visualisation, interpretation and quantitative determination of areal coverage of each methane concentration level.

3. Results and Discussion

3.1. Seasonal Variation of Methane Concentration in Benin City

The results of coalesced mean values of tropospeheric methane concentration in dry season (Nov 2024 – Mar 2025) and rainy season (April – Aug 2025) in Benin City are presented in Figures 2 and 3 respectively. As it can be seen, the analysis reveals divergent contrasts between the dry season (Figure 2)and therainy season (Figure 3)in Benin City. Taking a look at the dry season mean, the concentration values ranged between 1,856.21–1,859.24ppbv, with corresponding areal coverage ranging between 165.5–220.2km². Spatially, higher concentration ranging from 1,858.63 - 1,859.24 with estimated areal coverage of 165.5km^2 clustered in the north-western flank of Benin City. Gradual decrement in methane concentration in a south-easterly pattern can also be noticed with lowest range of 1,856.21 - 1,856.81ppbv and estimated areal coverage of 194.8km^2.

Also, tropospeheric methane concentration value around Otofure Waste Disposal Site located near Oluku, Benin Bypass stood at 1,858.03 - 1,858.62ppbv (194.0km²) while that of Jubilant Citizen Resources Limited dumpsite situated in Omo-Imasuen Street, Avbiama range from 1,856.82- 1,857.41 (220.2km²). This obviously indicates relatively higher CH_4 buildup during the dry months. Apparently, the pronounced methane spike in January corresponds to the core of the dry period, characterized by shallow boundary layers**,** reduced convective mixing**,** and prevalent biomass burning and anthropogenic emissions which are all favorable conditions for methane accumulation. A decade-long observational study by Tiemoko et al (2021) at Lamto (Côte d'Ivoire) similarly identified methane maxima in January and minima in September, attributing this seasonality partly to fire-related emissions and reduced atmospheric dispersion early in the year

Regarding the rainy season mean, the concentration values were comparatively lower, ranging from 1,829.66–1,831.52ppbv, with subsequent slightly higher areal coverage in some classes (174.9–231.4 km²). Similarly, there is decrease in mean tropospeheric methane concentration in rainy season in a north-south pattern with higher concentration ranging from 1,831.16 - 1,831.52ppbv and estimated areal coverage of 176.3km^2 clustered in the northern part of Benin City. In contrast, lowest range of 1,829.66 - 1,830.03ppbv and estimated areal coverage of 174.9km^2 are seen in the southern part of the city. Interestingly, tropospeheric methane concentration value around Otofure Waste Disposal Site located near Oluku, Benin Bypass stood at 1,831.16 - 1,831.52ppbv (176.3km²) whereas that of Jubilant Citizen Resources Limited dumpsite situated in Omo-Imasuen Street, Avbiama range from 1,830.41 - 1,830.77ppbv (194.9km²). Again, this indicates that rainfall, enhanced atmospheric mixing, and stronger surface and other atmospheric interactions may have diluted or dispersed methane thus, reducing accumulation.

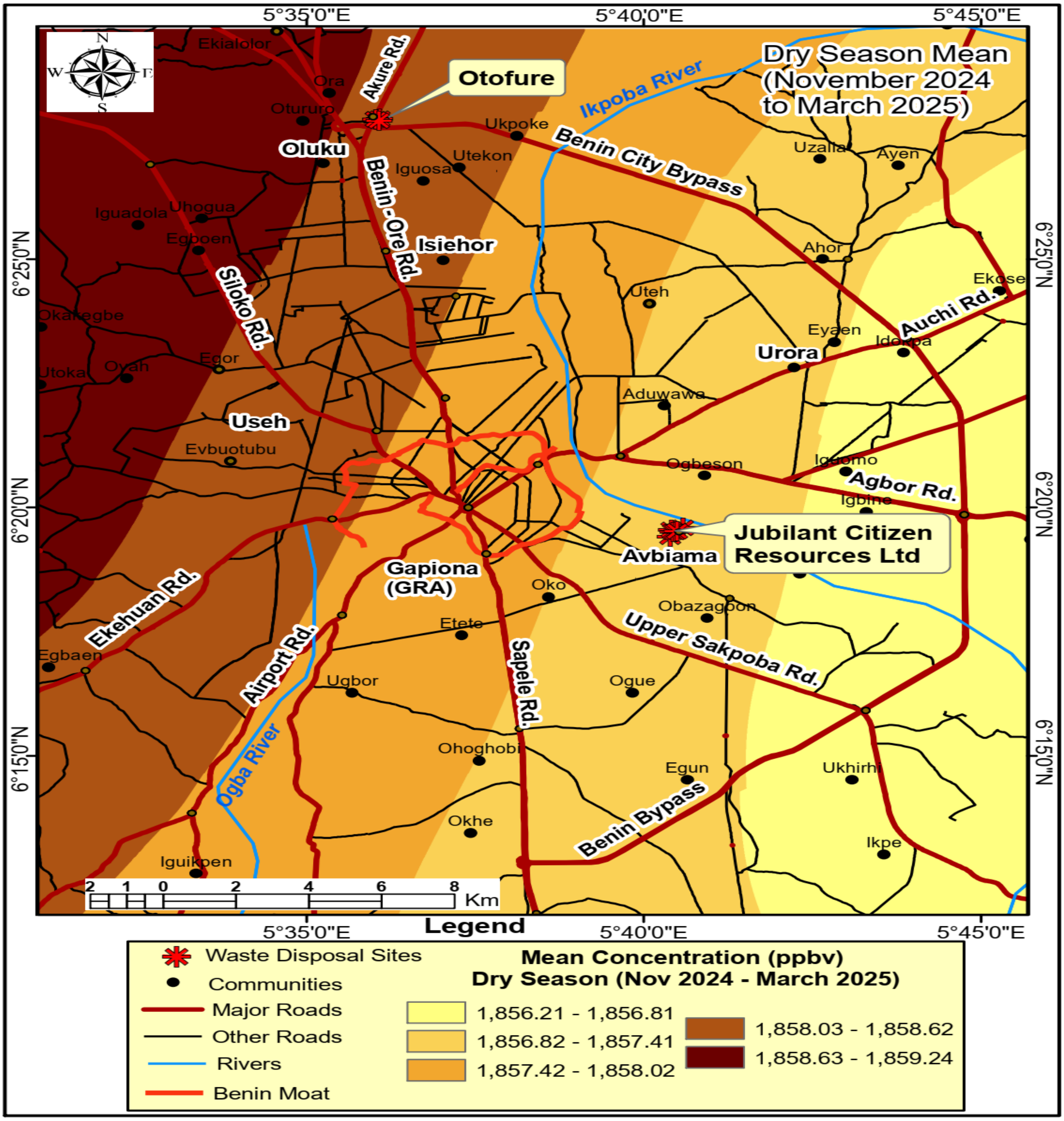

Figure 2: Spatial Distribution of Mean Dry Season Concentration of Methane in Benin City
Source: GIS Data Analysis by the Research (2025)

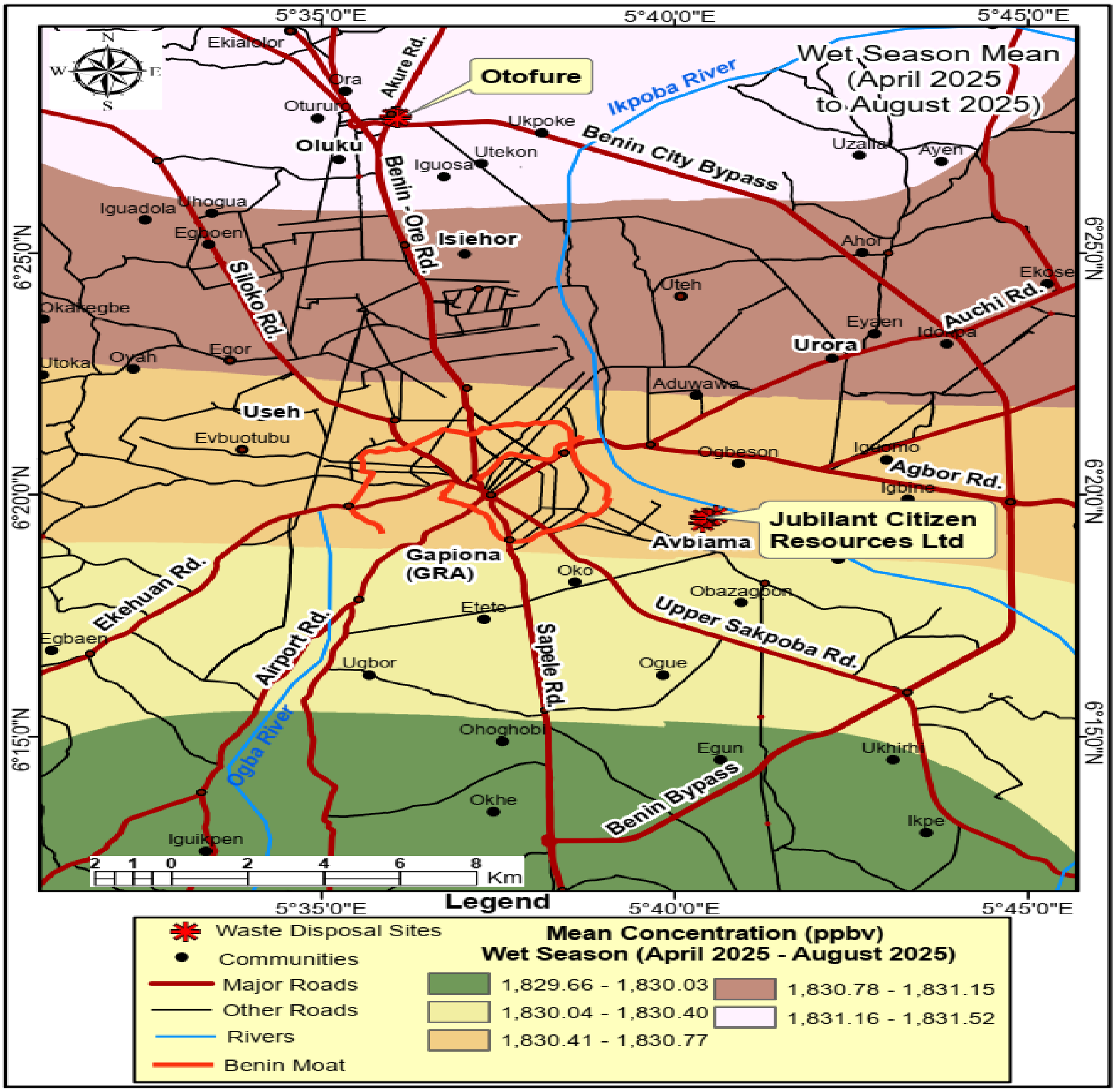

Figure 3: Spatial Distribution of Mean Rainy Season Concentration of Methane in Benin City
Source: GIS Data Analysis by the Research (2025)

Similarly, the substantial drop in methane during June–July (~1,820–1,821ppbv) underscores the dominant role of atmospheric sinks and transport, notably hydroxyl radicals (OH) and the West African monsoon as reported byDowd et al (2023). The authors stated that OH is the primary chemical sink for methane. Their findings showed that OH is known to exhibits diurnal and seasonal variation with peaks during the daytime in humid, sunlit conditions typical of monsoons. Enhanced OH during the rainy season therefore accelerates methane oxidation. Besides, Dowd et al (2023) also observed that the West African monsoon is known to encourage deep boundary-layer development and vigorous convection, enhancing vertical mixing and dilution of methane columns. This mechanism reduces surface methane even amid ongoing emissions. Together, these processes reconcile how rainy-season observation of lower methane can coexist with increased wetland activity.

3.2 Monthly Methane Variation in Benin City

The spatial distribution of monthly methane fluxes are also presented in Figures 4 to 13. As it can be seen, November 2024 (Figure 4) and December 2024 (Figure 5) showed methane concentrations exceeding 1,861ppbv, with substantial areal coverage (>200 km² in some bands). This indicates the onset of methane buildup coinciding with reduced precipitation and weaker dispersion. Similarly, January 2025 (Figure 6) recorded the highest dry season values, peaking at 1,869.95ppbv, with wide spatial coverage (>240 km²). This peak likely reflects enhanced emissions from biomass burning, waste decomposition, and stagnant atmospheric conditions common during the harmattan. Besides, February 2025 (Figure 7) and March 2025 (Figure 8) show a marked decline (down to 1,833.86–1,848.36ppbv), suggesting a transitional phase as rainfall gradually resumes and thus, improving methane dispersion.

Moreover, April 2025 (Figure 9) and May 2025 (Figure 10) recorded moderately high CH_4 levels (1,832–1,839 ppbv) with areal coverage of ~220–248 km². This indicates that at the onset of the rains, methane is still elevated, likely due to soil and landfill emissions enhanced by early wetting. Also, June 2025 (Figure 11) and July 2025 (Figure 12) showed the lowest concentrations (1,819–1,821ppbv) with wide spatial distribution (~210–255 km²). This reflects maximum dilution from heavy rains, higher humidity and increased vertical mixing. In addition, August 2025 (Figure 13) revealed a rebound in methane levels (1,836–1,839ppbv) with areal coverage up to 228.9 km². This late-rainy season increase may be linked to intensified organic matter decomposition in saturated soils and dumpsites.

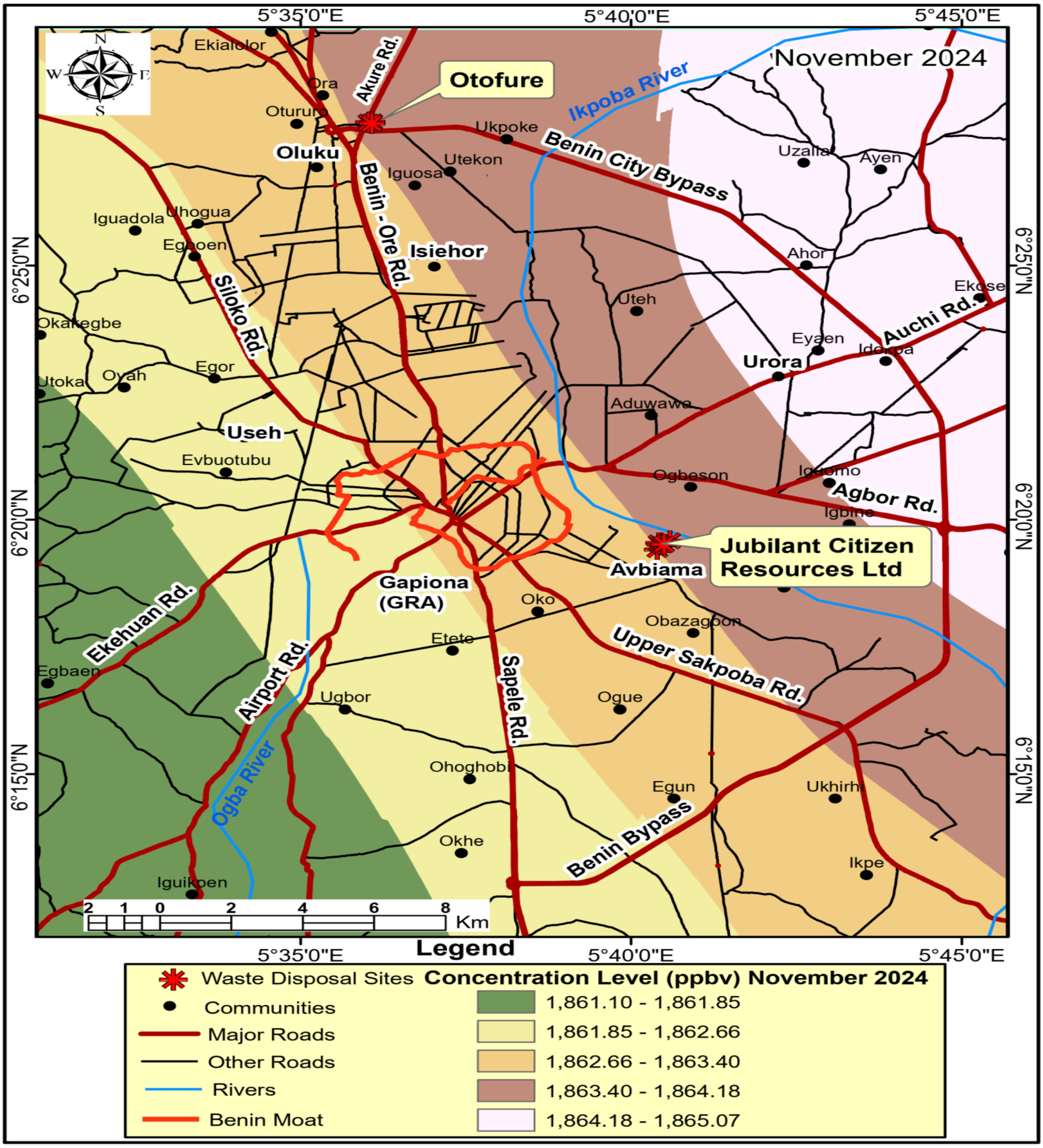

Figure 4: Concentration of Methane in November 2024 in Benin City

Source: GIS Data Analysis by the Research (2025)

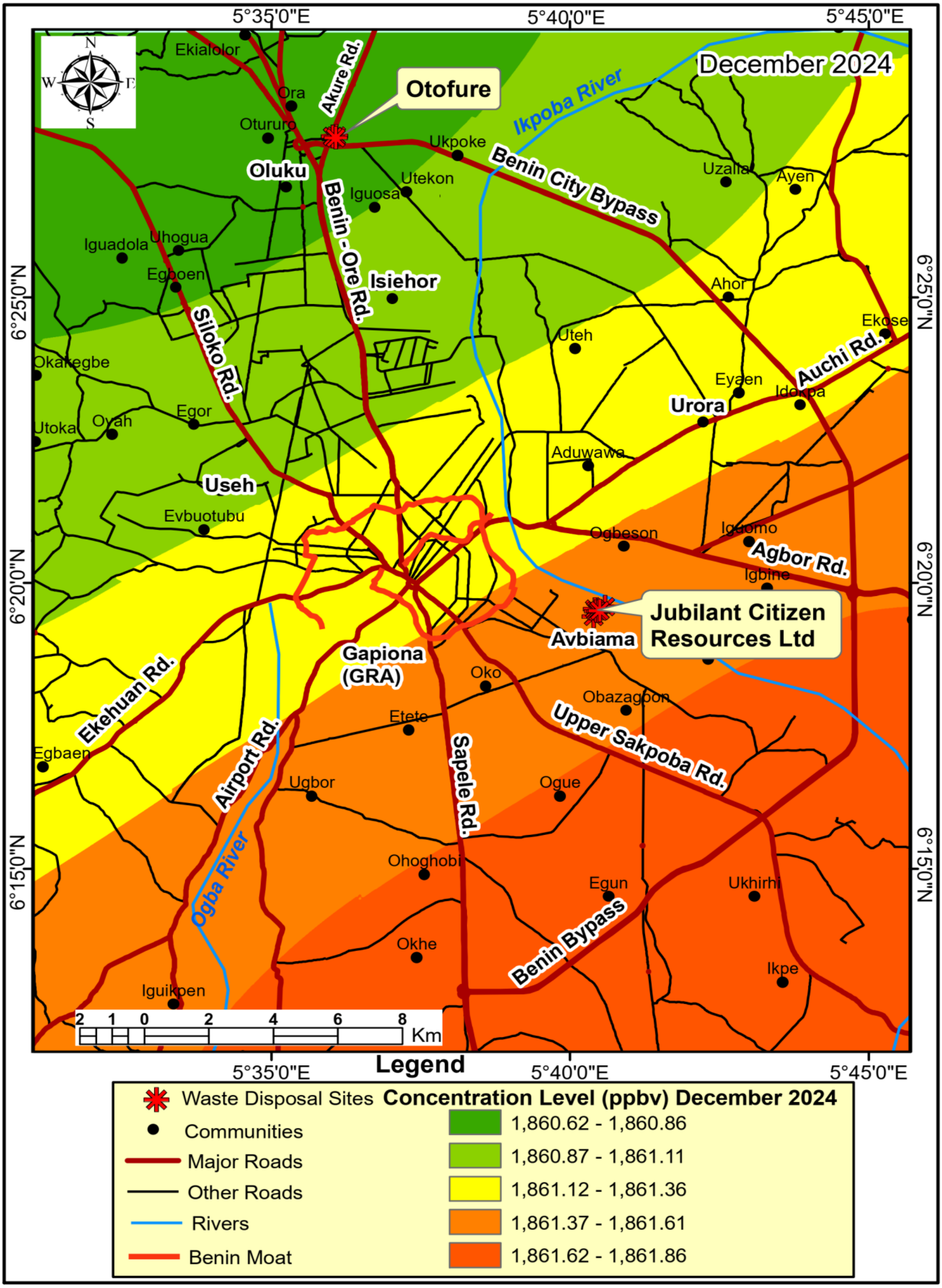

Figure 5: Concentration of Methane in December 2024 in Benin City
Source: GIS Data Analysis by the Research (2025)

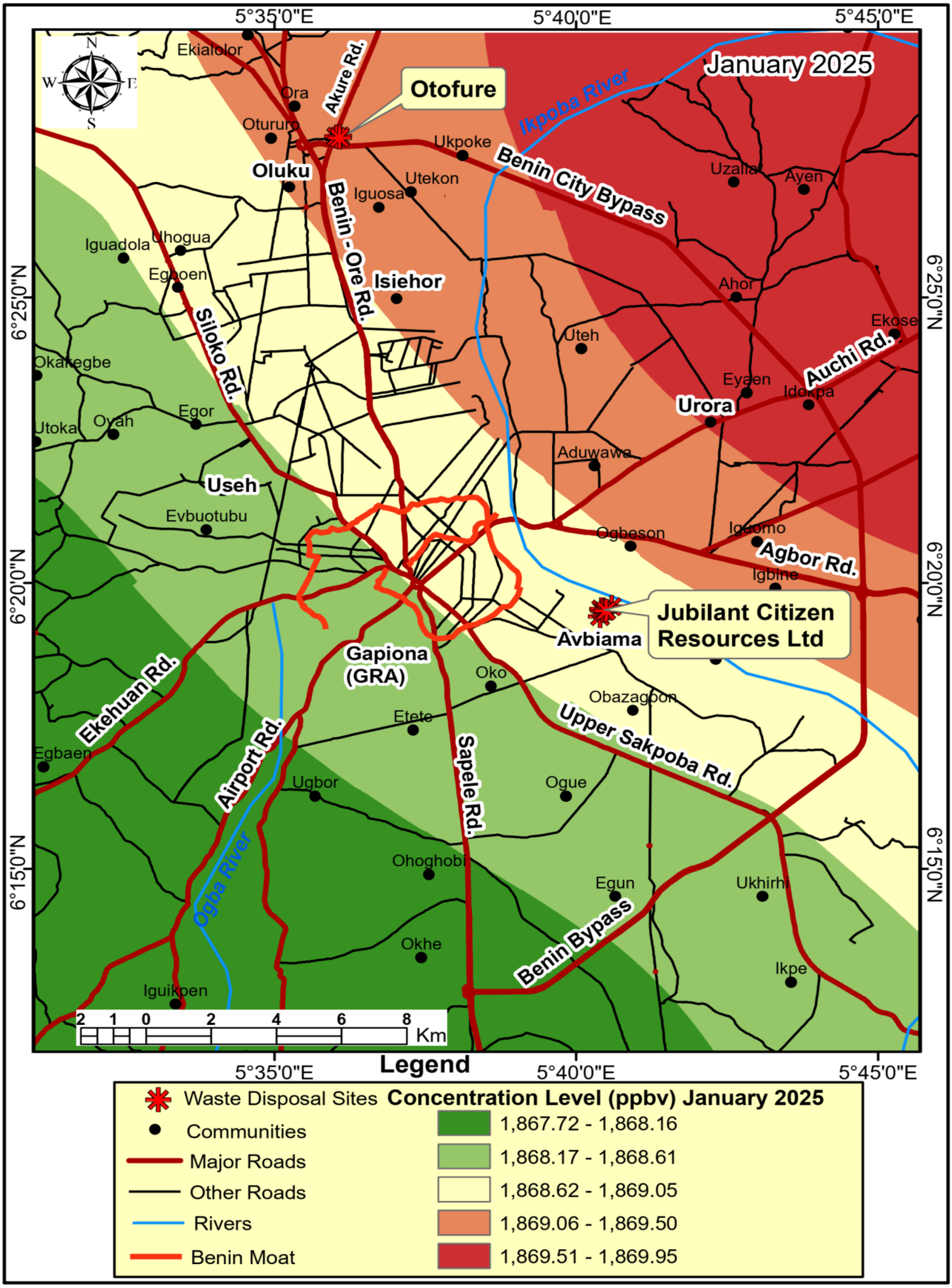

Figure 6: Concentration of Methane in January 2025 in Benin City
Source: GIS Data Analysis by the Research (2025)

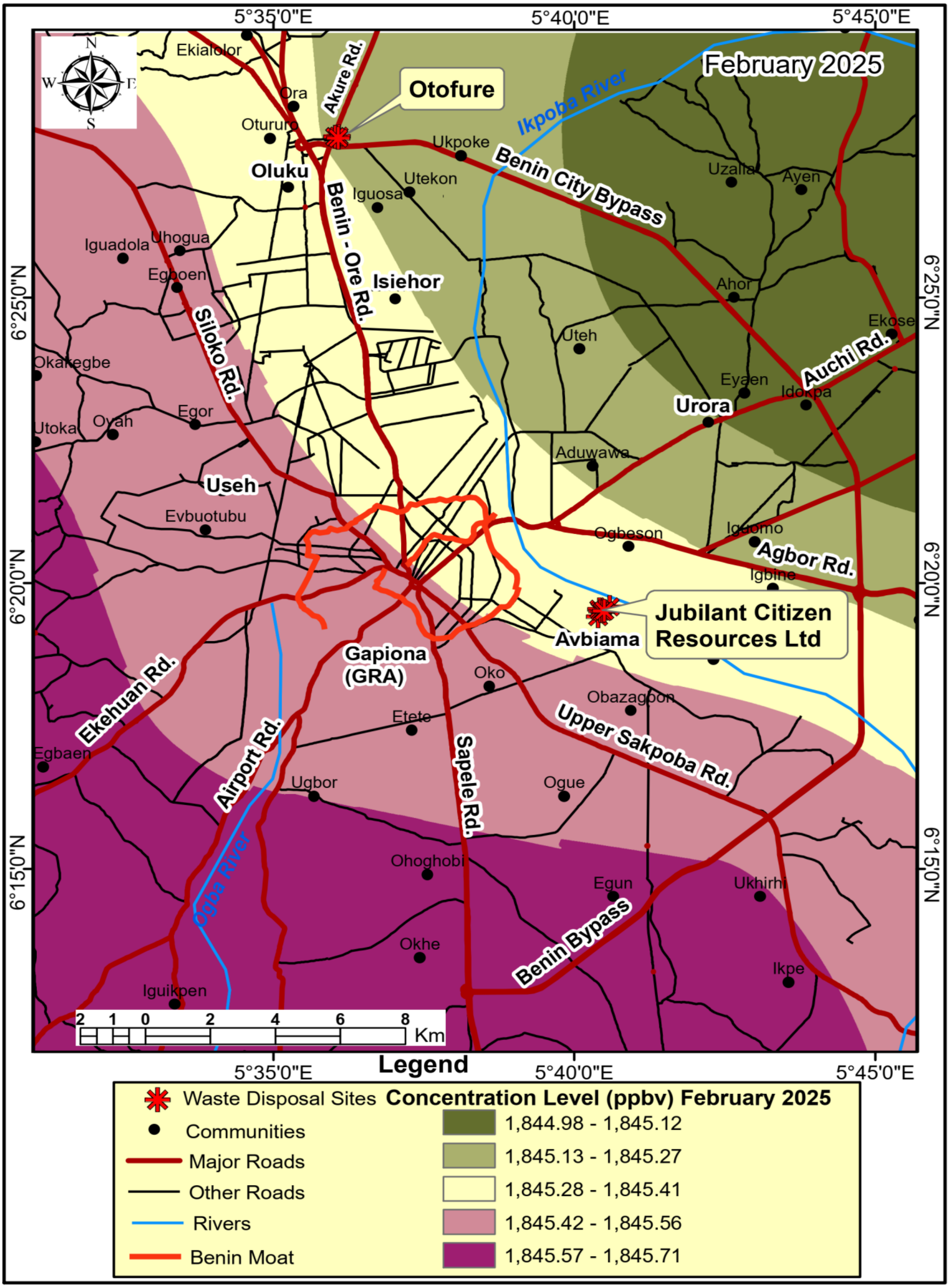

Figure 7: Concentration of Methane in February 2025 in Benin City
Source: GIS Data Analysis by the Research (2025)

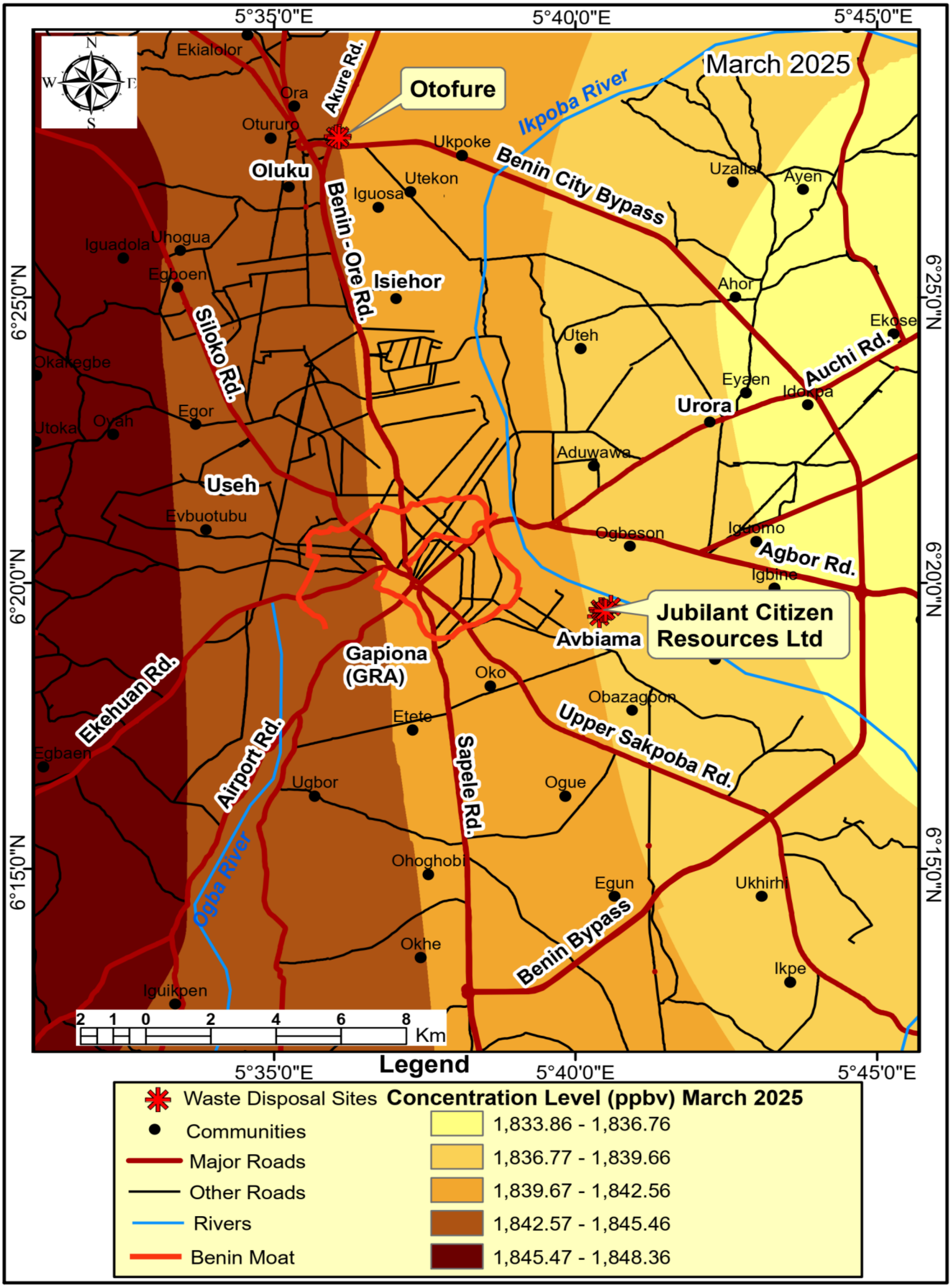

Figure 8: Concentration of Methane in March 2025 in Benin City
Source: GIS Data Analysis by the Research (2025)

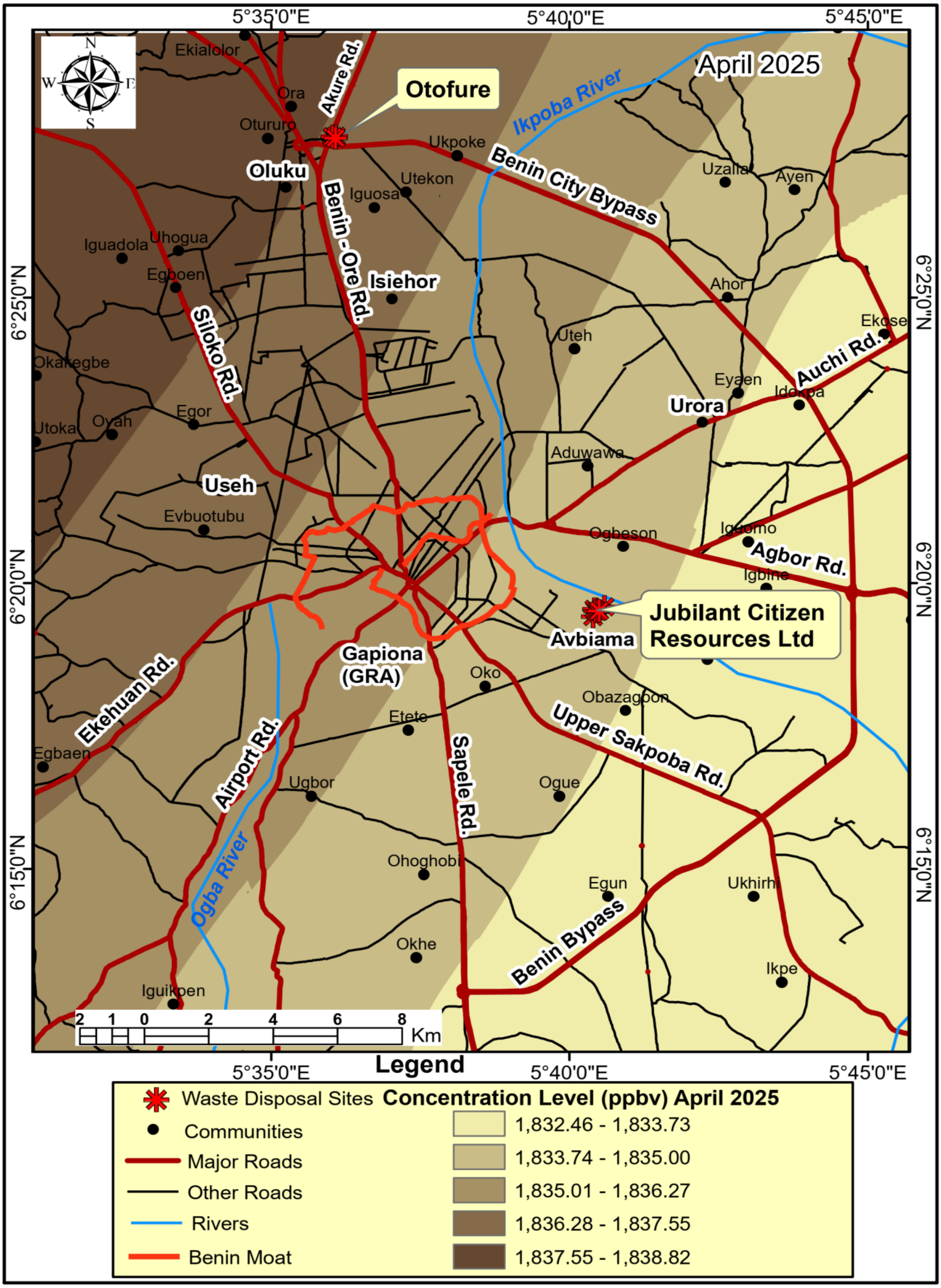

Figure 9: Concentration of Methane in April 2025 in Benin City

Source: GIS Data Analysis by the Research (2025)

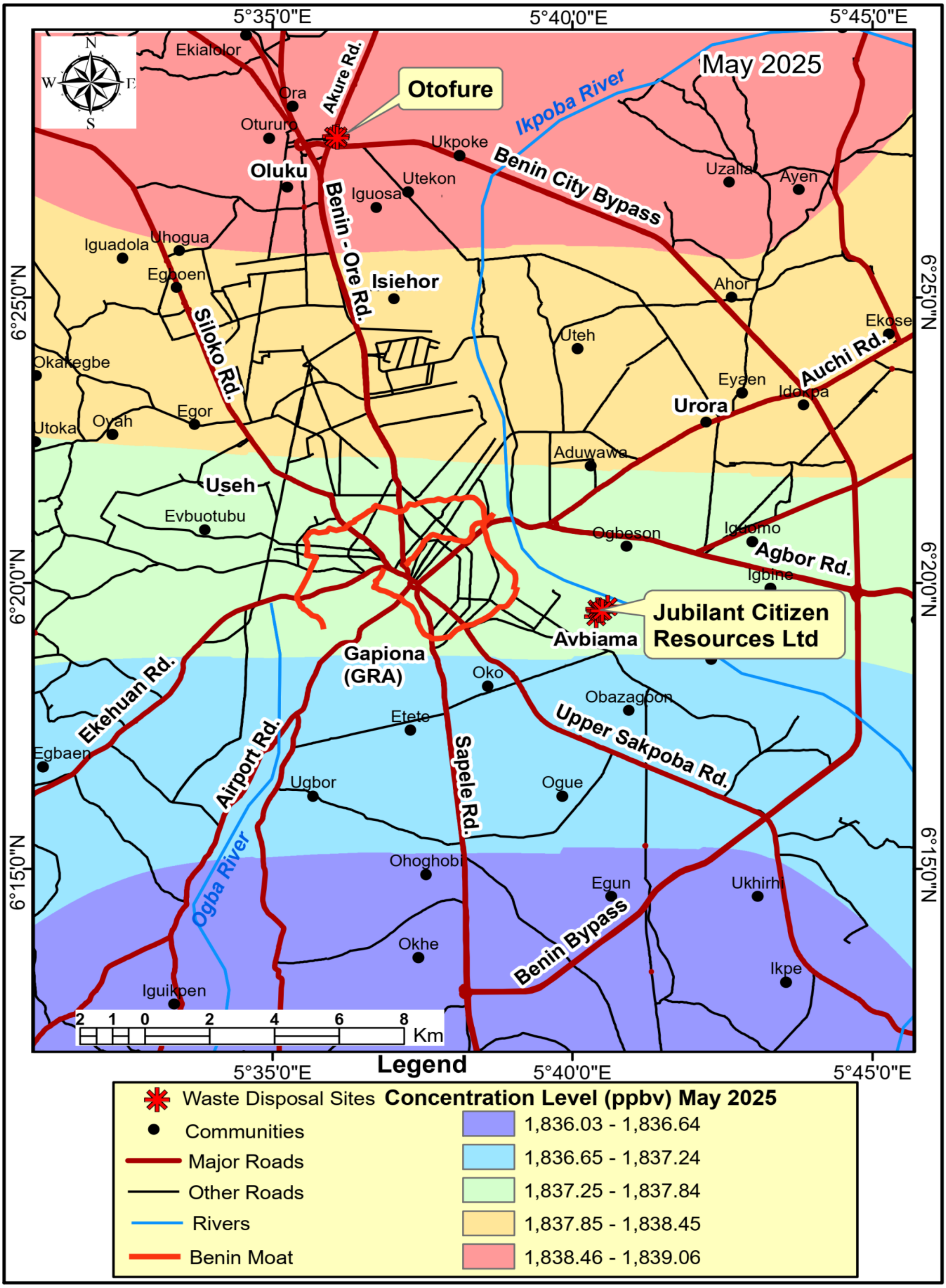

Figure 10: Concentration of Methane in May 2025 in Benin City
Source: GIS Data Analysis by the Research (2025)

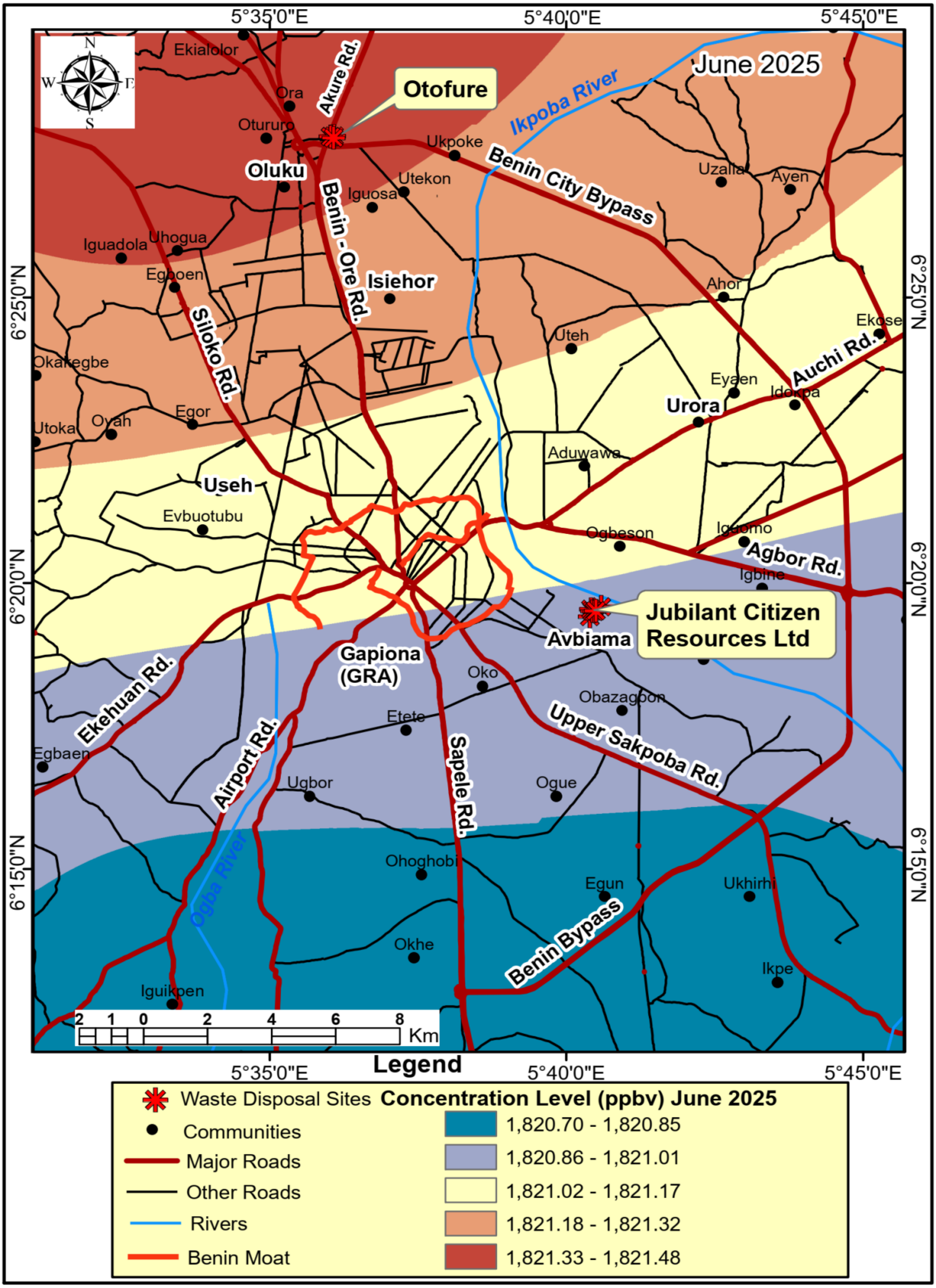

Figure 11: Concentration of Methane in June 2025 in Benin City

Source: GIS Data Analysis by the Research (2025)

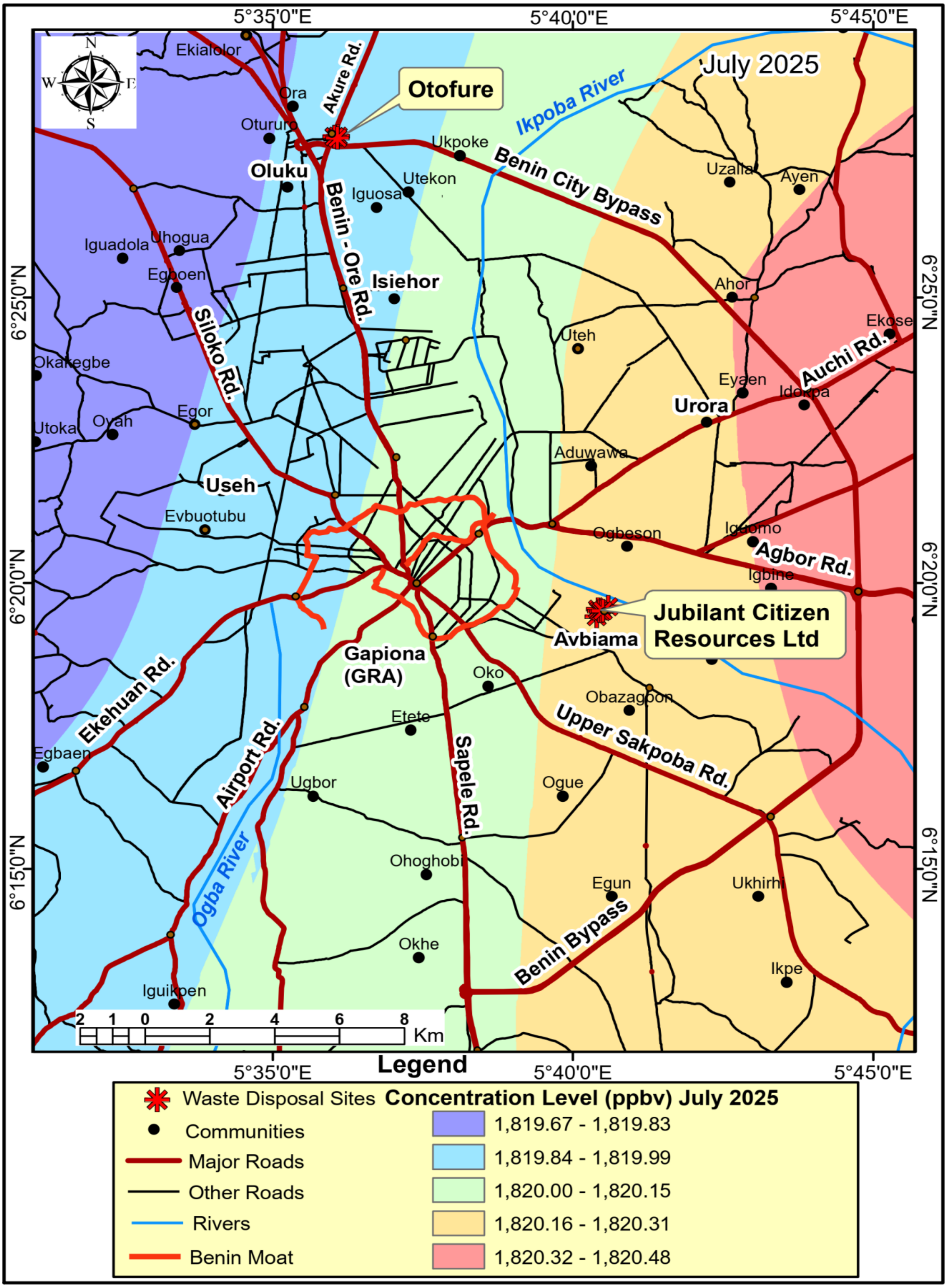

Figure 12: Concentration of Methane in July 2025 in Benin City

Source: GIS Data Analysis by the Research (2025)

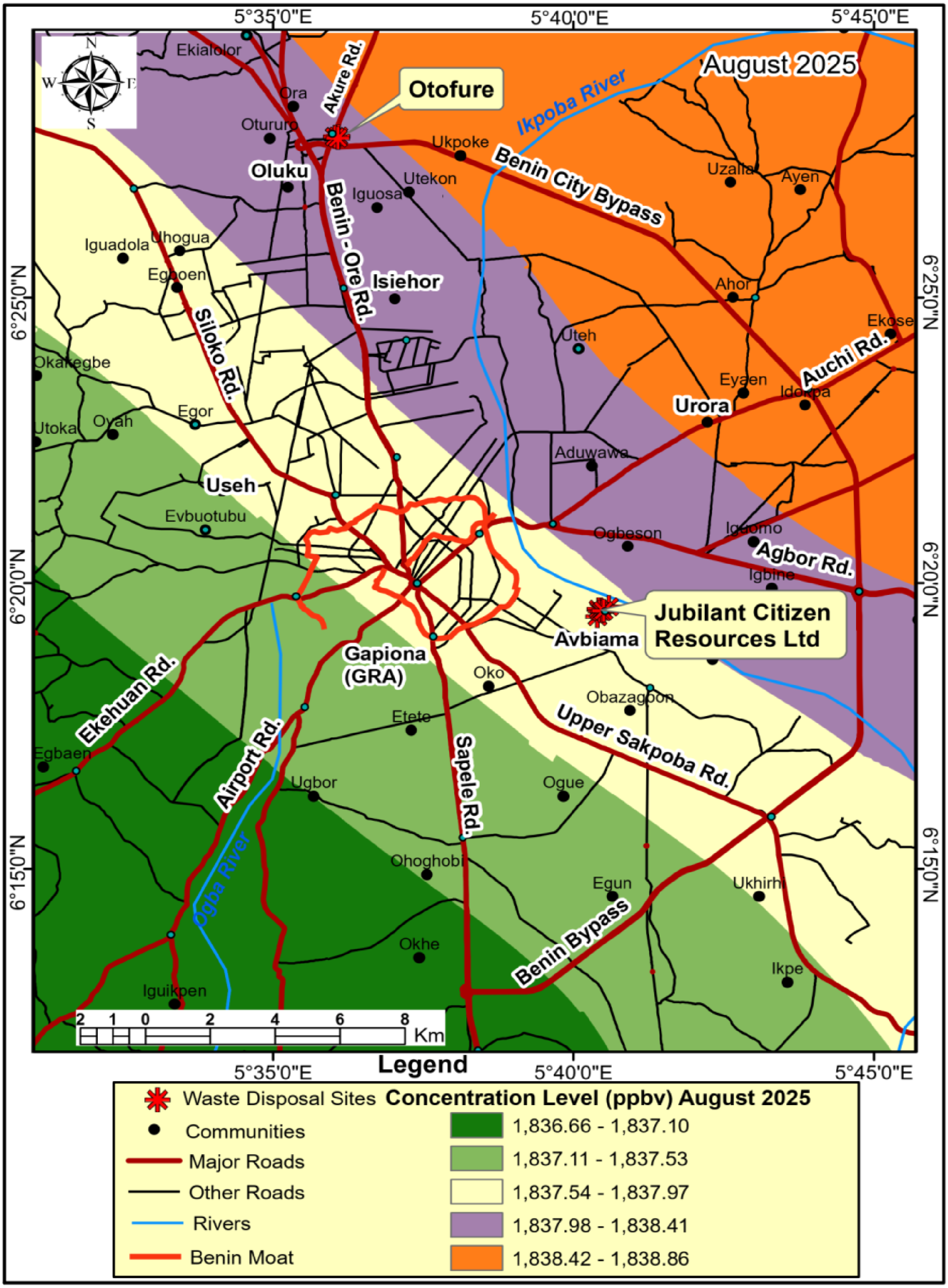

Figure 13: Concentration of Methane in August 2025 in Benin City

Source: GIS Data Analysis by the Research (2025)

Again, the methane rebound in August can be traced to wet-season biogenic and waste-sector emissions, including wetlands and landfills very common in the season which corroborate that of Riman et al (2022) and Feng et al (2022). Riman et al (2022) reported substantially higher methane generation during the wet season (~0.331 Gg) in Lagos municipality compared to the dry season (~0.134 Gg), and driven by enhanced anaerobic decomposition in saturated environments. Similarly, Feng et al (2022) regional modeling of tropical African emissions also highlighted seasonal peaks tied to wetland extent, which rise alongside groundwater storage and floodplain inundation. Despite these increased emissions, ambient methane remains lower than dry-season peaks due to still-elevated OH activity and mixing. The August rise therefore coheres with the emission–sink–transport equilibrium rather than signaling higher net atmospheric methane.

4. Conclusion and Recommendations

This study evaluated methane emission from two active dumpsites in Benin City which are located at Otofure Waste Disposal Site (Oluku, Benin Bypass) and the Jubilant Citizen Resources Limited dumpsite (Omo Imasuen Street, Avbiama). CH_4 was sourced from Giovanni web archive, established and serviced by the United States (US) National Aeronautics and Space Administration's (NASA) Goddard Earth Sciences Data and Information Services Center (GES DISC). On the whole, CH_4 buildup during the dry months was generally higher when compared to levels observed in the rainy season months. There was also a substantial drop in methane during June–July (~1,820–1,821ppbv) underscores the dominant role of atmospheric sinks and transport, notably hydroxyl radicals (OH) and the West African monsoon. Methane values were generally higher in Jubilant Resource dumpsite compared to levels in Otofure even though mean composition of organic waste is higher at Otofure dumpsite. This goes to suggest the effects of population density coupled with socio-economic variables such as household income level, urban lifestyle expanding commercial land use on total waste generation and hence methane production in Benin City. Hence, it can be concluded that methane production from dumpsite is proportional to the volume of organic waste fraction of MSW. Hence to effectively reduce emission, there is need for diversion of organic waste from dumpsites. This can be achieved through policies and initiatives that encourage source separation of organic materials, large-scale deployment of organics recovery technologies, and development of organics processing infrastructure. There is also need to promote medium and large-scale anaerobic digestion facilities, where organic waste is used as feedstock to produce biogas. There is also need for policies that promote the conversion of open landfills to safer disposal sites. The present practices in Benin City is the Open dumps that are typically uncovered and uncompacted sites. These practices have implications for environmental sustainability as well as pose health and safety risks to informal waste pickers who are considered very important for sustainable material recovery initiatives. The impact of proactive policies on greenhouse gas mitigation cannot be overemphasised. Such policies should advance efforts among key actors in solid waste management including owners, operators, project developers, and financiers to reduce waste methane emissions.

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