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An Assessment of Inter-Annual and Decadal Precipitable Water Vapour Variability and Trends Over North- East Nigeria (1991-2021)

*[1]Omopekunola, M. O., [1]Jacob, A., [2]Oladipupo, G. O., [1]Udeh, I., [1]John, J. J.

[1]Department of Pure and Applied Physics, Federal University Wukari. Taraba State, Nigeria.
[2]Department of Physics, University of Ibadan, Oyo State, Nigeria.

*Corresponding author's email: omopekunola@fuwukari.edu.ng

ABSTRACT

The availability of water for domestic, agricultural, and industrial usage in North-East Nigeria depends on the seasonal precipitation. The main reason for the region's crop failure and water scarcity over the past few decades has been the variability in the pattern of precipitation. This study assessed the variability of precipitable water vapour (PWV) over North-East Nigeria, from 1991 to 2021, using the ECMWF ERA5 reanalysis data sets. Mann Kendal, a monotonic trend test, the least square regression and Theil Sen slope estimator were used to analyze the trends and variation of PWV over the region within the period of study. The PWV peaked significantly twice within the duration of the study. The first peak was observed in the year 1997 and recently in the year 2019. The results showed that negative trends existed at Jalingo, Yola and Bauchi, while positive trends existed in Maiduguri, Yobe and Gombe. The negative trends range between -0.0153 $mm\ year^{-1}$ and -0.247 $mm\ year^{-1}$, while the positive trends range between 0.043 $mm\ year^{-1}$ and 0.243 $mm\ year^{-1}$. The analysis of the PWV decadal trends showed decreasing trend in all the states in the first decade (1991– 2000) and an increasing trend in the second and third decades over all the states within the region with the trend magnitude ranging from 0.259 $mm\ decade^{-1}$ in Jalingo to 2.252 $mm\ decade^{-1}$ in Bauchi. Based on this PWV trend, PWV is expected to be in its increase in the next decade which will translate to an increase in rainfall across the states in the region. Therefore, it is recommended that Government Agencies responsible for the environment should make adequate preparations to mitigate the incidences of flooding in the area.

Keywords:
Assessment,
Variability,
Trends,
PWV.

INTRODUCTION

The principal of the greenhouse gas in the Earth's atmosphere that contributes significantly to the physics of the atmosphere is water vapour. It is a significant contributor to climate change, hydrological processes, the energy balance of the planet, and weather patterns. 99% of water vapour is concentrated in the tropospheric layer of the atmsophere. It is a crucial part of the global energy flow that causes local and planetary weather patterns. It is a crucial component of the thermodynamics of the atmosphere because it transfers latent heat, contributes to absorption and emission across a range of wavelengths, and condenses into clouds that reflect and absorb solar radiation, directly altering the energy balance (Jacob, 2001, Follette et al., 2008). The amount of water vapour concentrations varies from place to place. Due to the extremely high temporal and spatial resolution required to understand the processes causing the strong gradients connected to the variability, this variability causes a fundamental issue in climate modelling. A major consequence of this variability is uncertainty about the future pattern of precipitation which is a major concern among meteorologists and climatologists as it is critical to human survival and particularly to people whose businesses depend heavily on rainfall. But one aspect that models have consistently emphasized is that heavier rainfall will occur in some areas while some areas will become drier. This can be understood in the context of the law of physics which states that every 1°C increase in temperature will translate to about 7% increase in water vapour and that a warmer atmosphere holds more water vapour that the cooler one. In view of this, water vapour loading is anticipated to rise as a result of the increased rate of evaporation across land and ocean due to the increase in global temperature. According to the Nigerian Meteorological Agency [NiMet], (2022), 2021 was the warmest year in Nigeria in the past four decades. This means that weather events like flooding or drought linked to a warming climate are expected to increase in the northern region, which has the highest temperature records compared to other regions. Therefore, adequate assessment and understanding of water vapour variation and trends will assist in predicting rainfall trends and thus, the climate in such region.

Precipitable water vapour (PWV)is a crucial gauge of water vapour. It is the total water vapour content in a vertical column of air with a unit area of horizontal cross-section stretching from the surface to the top of the atmosphere.It is the amount of water content that can be extracted from the surface level to the top of the atmosphere if all the water vapour condenses and precipitate. Higher values of precipitable water mean that more water is available for potential rainfall, in other words, a high PWV will translate to heavier rainfall under favourable atmospheric conditions.

Several studies have revealed the PWV trends in different regions of the world and over different periods using a variety of PWV datasets. Bengtsson (2004) and Trenberth et al. (2005) found that the global PWV has increased, using the ERA-40 reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) dataset. Xie, Zhang, and Ying (2011); from 1979 through 2001, deduced the magnitude of the global PWV increase to be 0.26 mm decade^{-1}. A study conducted in the United States and Canada using radiosonde observations reported an increased trend in precipitable water vapour between 1973 and 1993. Ross and Elliott (2001) have noted similar PWV trend, notably in the Northern Hemisphere. Radiosonde data were used to study the PWV trend in China from 1979 to 2005, an upward trend in PWV was seen at most sites in the northern part of the country, while a decrease trend was seen in the southern part. Similar to this, 27 years of radiosonde data in northern China have revealed a strong upward trend in PWV. But as observed by Xie, Zhang, and Ying (2011), there was a declining trend in Southern China from 1979 to 2005. In all these, datasets like ECMWF ERA5 and NASA MERRA-2 have been proven suitable for climate studies due to their high resolution and large datasets (Dai et al. 1997). Since there is no reported study of PWV assessment specific to North-East Nigeria, therefore, this study is undertaken to assess the inter-annual and decadal trends and variability of PWV and employ it as a better rainfall index to assist in making predictions of rainfall to support decision-making and reducing losses in rain-fed agricultural production.

MATERIALS AND METHODS

Materials

The meteorological parameter used in this study is the monthly mean precipitable water vapour from ERA-5 reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) and the surface meteorological data from the Nigerian Meteorological Agency (NiMet). The R programming software was used for the extraction and plotting of graphs.

The Study Area

The study area is located between latitude 6º26´ to 13º45´N and longitude 8º42´ to 14º39´E. This region comprises Borno, Yobe, Bauchi, Gombe, Adamawa and Taraba states (figure 2). It covers an area of 262,578 km^2 as the largest geopolitical zone covering about one-third of Nigeria's total land mass. It has a population of 18,984,299 persons (about 12% of the total population of the country), according to the 2006 Nigerian population census. Semi-desert Sahelian Savanna and the tropical west Sudanian savanna characterize the climate of this region, with relatively high temperatures throughout the year.

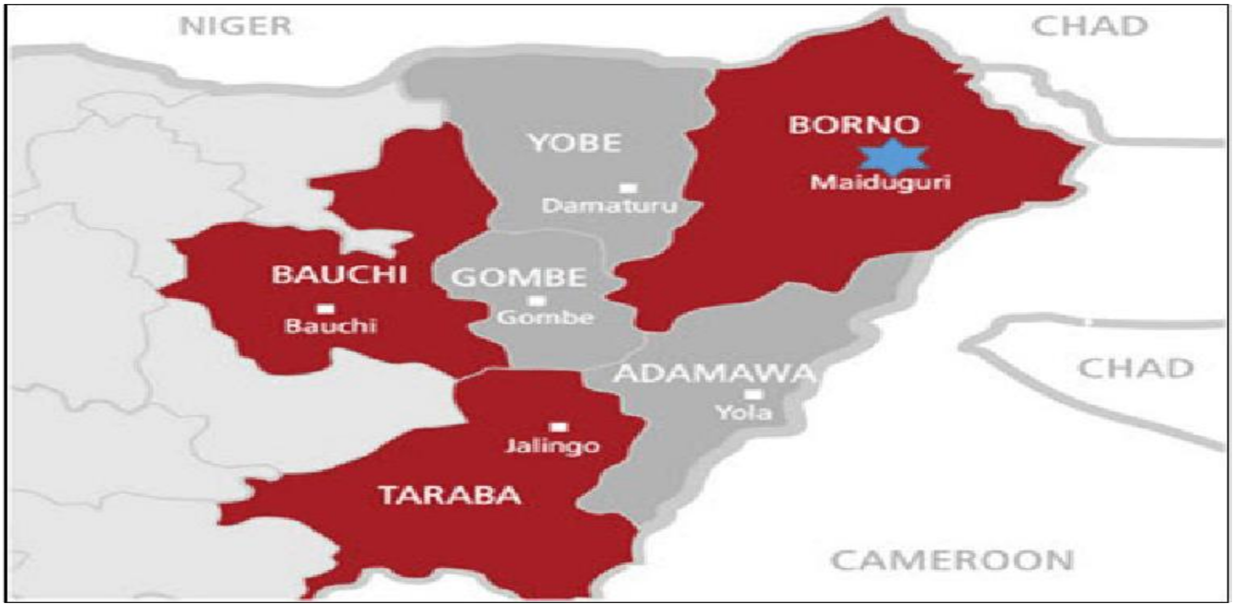

Figure1: The map showing the six states of the location under study. Source: Satellite maps, 2015

Table1: The table of the location under study, showing the latitudes (Degrees), Longitude (Degrees) and Elevations(metres) above the mean sea level

S/N	Station	Latitude (Degree)	Longitude (Degree)	Elevation(m)
1	Maiduguri	11.84	13.08	354
2	Yola	9.21	12.48	186
3	Jalingo	8.89	11.37	351
4	Bauchi	10.28	9.82	609
5	Yobe	11.88	13.15	373
6	Gombe	10.36	11.19	461

ERA-5 Reanalysis PWV Data

This data was collected from the archive of the fifth generation of European Centre for Medium Weather Forecasts (ECMWF-ERA5) Datasets web interface(https://cds.climate.copernicus.eu/cds). ERA5 is the fifth and most recent generation of ECMWF global atmospheric reanalysis from 1979 to the present. The annual mean PWV data were produced by averaging the monthly PWV data after calculating the monthly mean PWV data by averaging the daily PWV data.

Methods

The following methods were employed to analyze and estimate the data as well as the model and statistics to be applied.

The Butler's Model

Butler (1998) states that the amount of precipitable water in the atmosphere is calculated using an empirical method while considering the fact that the atmospheric water vapour is distributed exponentially.

$$PWV = \frac{m_w P_o H}{pl k T_O} \quad (1)$$

m_w *is* mass of water(18amu), P_o= partial vapour pressure of water, H= scale height (15km), pl *is* liquid water density($1000 kgm^{-3}$), k is Boltzman constant(($1.38 x 10^{-23}$J/K), T_O is ambient temperature.

Time Series Analysis

The trends in PWV over North-East Nigeria were estimated using the monthly time series data for 1991-2021. Three different estimation methods were used. Least square regression, Mann-Kendall test and Sen's slope estimator because they are the most effective statistical tests in detecting and analyzing trends in climate parameters (El-Tantawi, 2005).

The Mann-Kendall Trend Analysis

$$S = \sum_{i=1}^{n-1} \sum_{j=1+i}^{n} sign(x_j - x_i) \quad (2)$$

Where n, x_i, x_j and sign($x_j - x_i$) are the number of data points, data values and the sign function respectively.

$$Sign(x_j - x_i) = \begin{cases} +1 \text{ if } x_i - x_j > 0 \\ 0 \text{ if } x_i - x_j = 0 \\ -1 \text{ if } x_i - x_j < 0 \end{cases} \quad (3)$$

$$Var(s) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{p} t_i(t_i-1)(2t_i+5)}{18} \quad (4)$$

t_i is the number of data values in the Path group.

$$s=\begin{cases}\frac{S-1}{\sqrt{var(S)}}, \text{ if } S>0\\ 0, \text{ if } S=0\\ \frac{S+1}{\sqrt{Var(S)}}, \text{ if } S<0\end{cases} \quad (5)$$

The Least Square Regression (LSR)

$$y = a + bx \quad (6)$$

Where y, a, b, x *stands for* is the dependent variable (PWV), intercept, slope and time (year) respectively. According to Zhai and Eskridge (1997), a and b can be estimated as:

$$A= \frac{1}{N}\sum Y_I - \left|\frac{1}{N}\sum X_I\right| B \quad (7)$$

$$b=\frac{S_{xy}}{S_{xx}} \quad (8)$$

$$S_{xx}=\sum x_i^2 - \frac{1}{n}\left(\sum x_i\right)^2 \quad (9)$$

$$S_{yy}=\sum y_i^2 - \frac{1}{n}\left(\sum y_i\right)^2 \quad (10)$$

$$\sum x_i = \left[\sum x_i y_i - \frac{1}{2}\left(\sum x_i\right)\left(\sum y_i\right)\right] \quad (11)$$

The Sen's Slope Estimator

$$m_{ij}=\frac{Y_j-Y_i}{j-1} \quad (12)$$

i ranges from 1 to n - 1, jfrom 2 to n.

If there are n values of Y_j in the time series, N= n(n-2)/2 will give the slope. The mean slope of these slopes N values is the slope of the Sen Estimator given as;

$$m = m_{\left[\frac{N+1}{2}\right]} \quad \text{if n is odd} \quad (13)$$

$$m = \frac{1}{2}\left[m_{\frac{N}{2}} + m_{\frac{N+2}{2}}\right] \quad \text{if n is even} \quad (14)$$

RESULTS AND DISCUSSION

Annual PWV Trend Analysis

Table 2: Annual PWV trend for North-East Nigeria from 1991-2021

Location	Mean	Standard Dev.	Trend	P-value	CV (%)
Yola	420.600	13.330	-0.153	0.708	3.200
Maiduguri	339.500	13.730	0.077	0.759	4.000
Jalingo	430.900	12.750	-0.234	0.395	2.300
Bauchi	396.400	13.640	-0.247	0.918	3.400
Yobe	312.600	13.110	0.243	0.563	4.200
Gombe	356.700	13.890	0.043	0.945	3.900

The trend of the annual mean PWV for the study period is depicted in Figure 2a and 2b. Table 2 shows the descriptive statistics for mean annual PWV over the study area. The mean annual PWV is between 312.6 mm at Yobe to 430.9 mm at Jalingo. The figures show that the lowest annual PWV recorded was in year 2000 for all the states except in Jalingo and Yola where it was observed to be in year 2001. The line plots showed that PWV had peaked significantly twice within the duration of the study. The first peak was observed in the year 1997 and recently in the year 2019. The result indicates that negative trends existed at Jalingo, Yola and Bauchi, while positive trends existed in Maiduguri, Yobe and Gombe. The negative trends range between -0.0153 *mm year*$^{-1}$ and -0.247 *mm year*$^{-1}$, while the positive trends range between 0.043 *mm year*$^{-1}$ and 0.243 *mm year*$^{-1}$. The significance test shows that none of the states is highly significant at both 0.01 and 0.005 confidence levels. It is worth noting that the non- significant trend does not mean the trends are wrong, but the magnitude of the trend has a higher uncertainty. These results show that the overall PWV trends in northeastern Nigeria have decreased, especially at Bauchi and the southern states of the region. The increasing PWV trend observed in Maiduguri, Yobe and Gombe could be attributed to the increase in the volume of Lake Chad in recent time. The table also shows coefficient of variation (CV) for each location with the highest in Yobe with 4.2%. It can be inferred from the table that PWV has increased in the northern while it decreased in the southern state of this region. This conclusion is in line with those of Hassan et al. (2017), who found that rainfall increased in the same site from 1949 to 2014, with a trend value ranging from -0.02 to -0.04 mmyear-1.

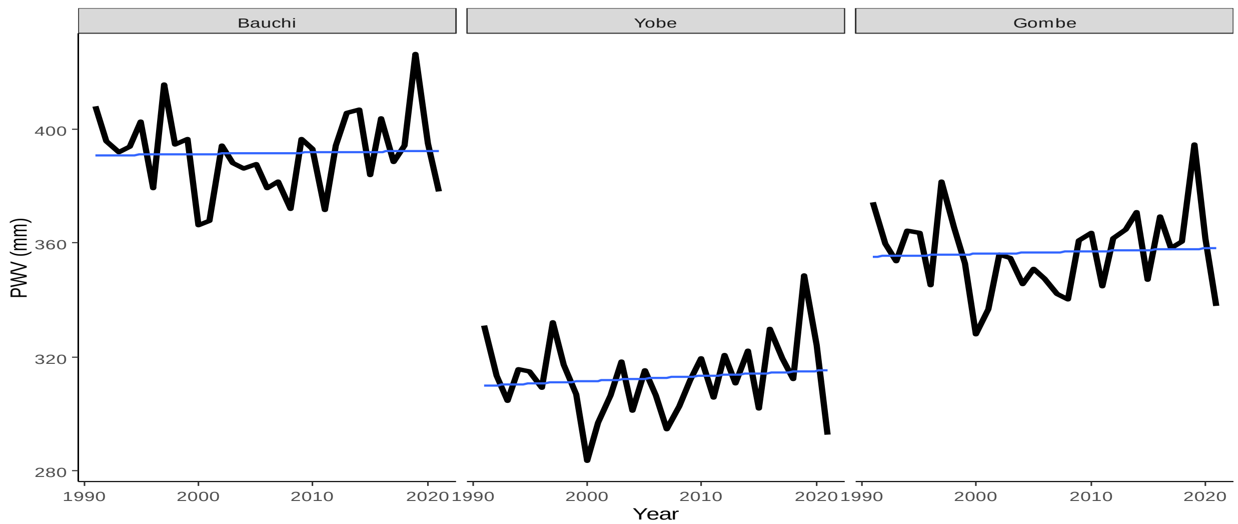

Figure 2a: Inter-annual variability trends of PWV from 1991-2021 for Jalingo, Maiduguri and Yola

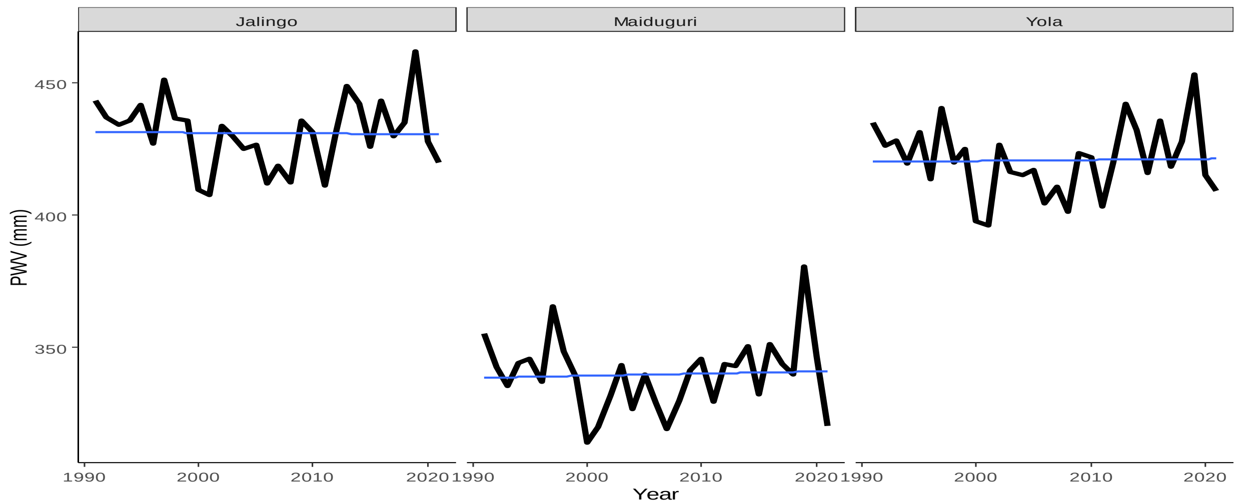

Figure 2b: Inter-annual variability trends of PWV from 1991-2021 for Bauchi, Yobe and Gombe

Decadal PWV Trends

The results of the decadal trend analysis utilizing the Sen's slope and the Mann-Kendal test are displayed in Tables 3 through 5. According to the findings, as shown in figures 3a to 5b, the mean PWV varied in three decades. Mann Kendal trend and Sen's slope checked the trend the magnitude of the trend respectively. The PWV variational trends over all the states are negative during the first decade (1991-2000), with the highest trend rate of 2.640 mm decade^{-1} at Gombe and the lowest trend rate of 0.943 mm decade^{-1} at Jalingo. Positive trends were noticed in the second decade (2001-2010) and third decade (2011-2020) over all the states within the region with trends rates of 0.259 mm decade^{-1} in Jalingo to 1.32 *mm decade*$^{-1}$ in Maiduguri and 1.325 *mm decade*$^{-1}$ in Yola to 2.252 *mm decade*$^{-1}$ in Bauchi. These results correlate with the work done by Adakayi (2006) who made a projection of increase in precipitation over Northern Nigeria from 2007-2030.

Table 3: Decadal trend of PWV over the six North-East states from 1991–2000

	Yola	Maiduguri	Jalingo	Bauchi	Yobe	Gombe
Kendall	-0.333	-0.156	-0.333	-0.200	-0.244	-0.289
P-Value	0.210	0.591	0.210	0.474	0.371	0.283
Sen's Slope	-2.170	-1.377	-0.943	-1.556	-1.944	-2.640

Table 4: Decadal trend of PWV over the six North-East states from 2001-2010

	Yola	Maiduguri	Jalingo	Bauchi	Yobe	Gombe
Kendall	0.066	0.289	0.111	0.066	0.200	0.156
P-Value	0.858	0.283	0.720	0.858	0.474	0.591
Sen's Slope	0.729	1.325	0.252	0.623	0.857	0.920

Table 5: Decadal trend of PWV over the six North-East states from 2011-2020

	Yola	Maiduguri	Jalingo	Bauchi	Yobe	Gombe
Kendall	0.111	0.333	0.156	0.289	0.378	0.244
P-Value	0.720	0.210	0.591	0.283	0.152	0.371
Sen's Slope	1.323	1.887	1.861	2.252	2.216	1.873

Table 6: Standardized Precipitation index

Range (mm)	Meaning
12.7 and below	Very low moisture content
12.7 – 31.75	Low moisture content
31.75- 44.45	Moderate moisture content
44.45 – 50.8	High moisture content
50.8 and above	Very high moisture content

Source: Karabulut, G. (2015).

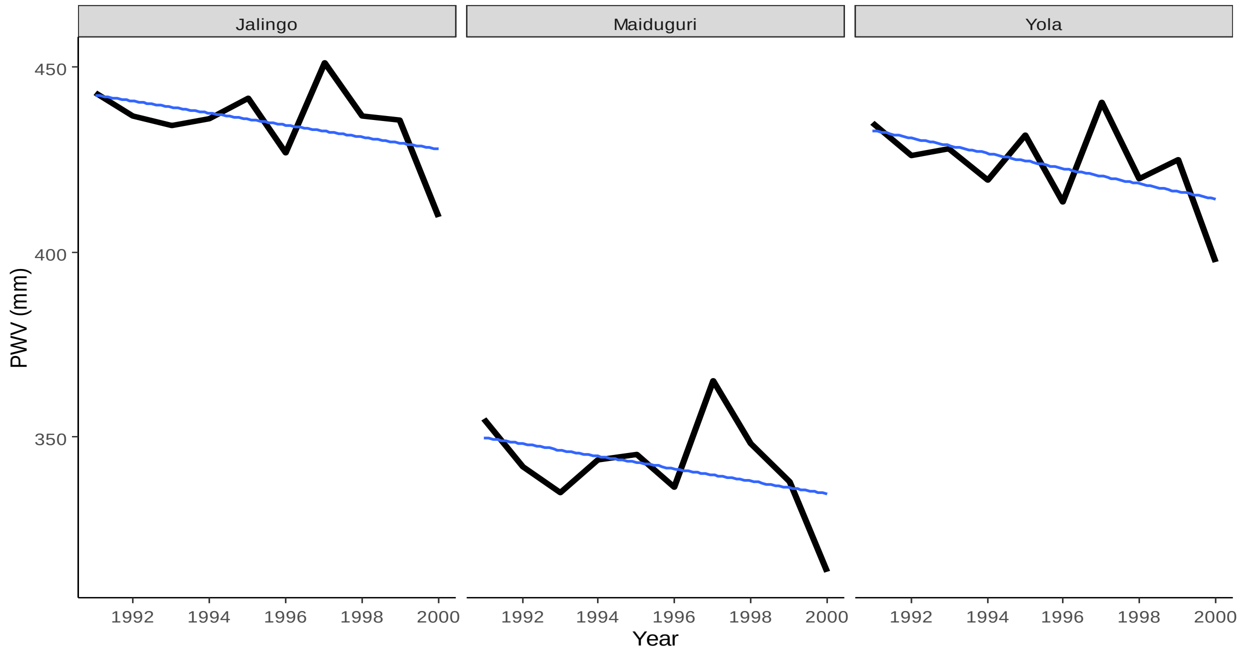

Figure 3a: Decadal trend of PWV from 1991-2000 for (a) Jalingo, Maiduguri and Yola

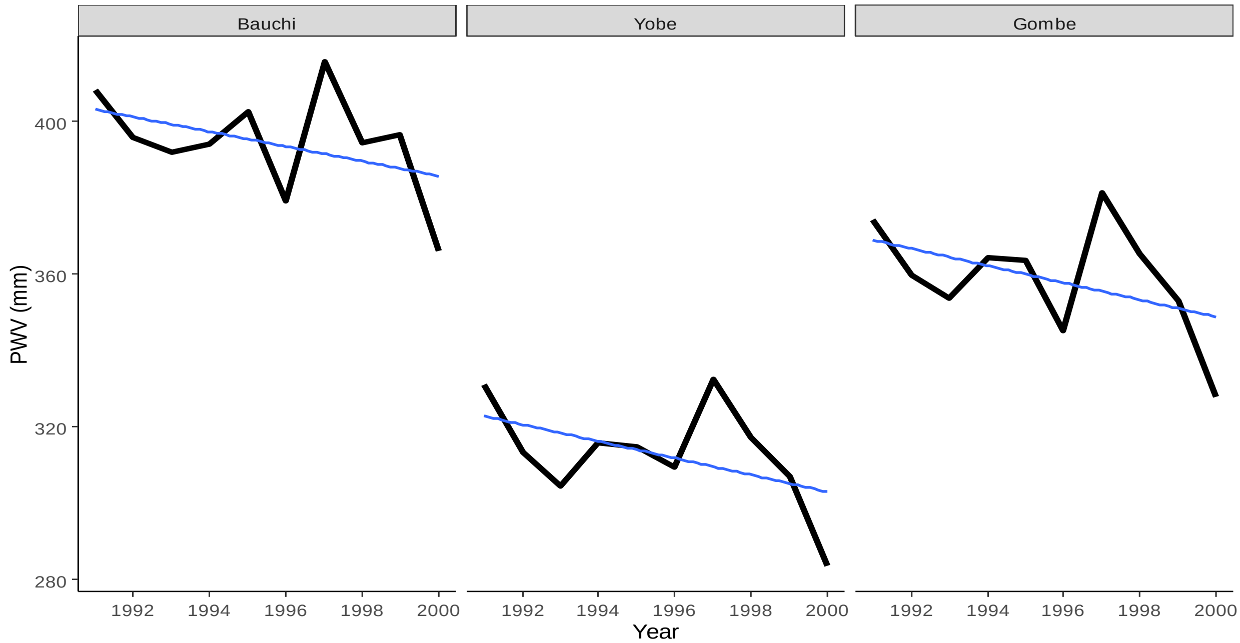

Figure 3b: Decadal trend of PWV from 1991-2000 for Bauchi, Yobe and Gombe

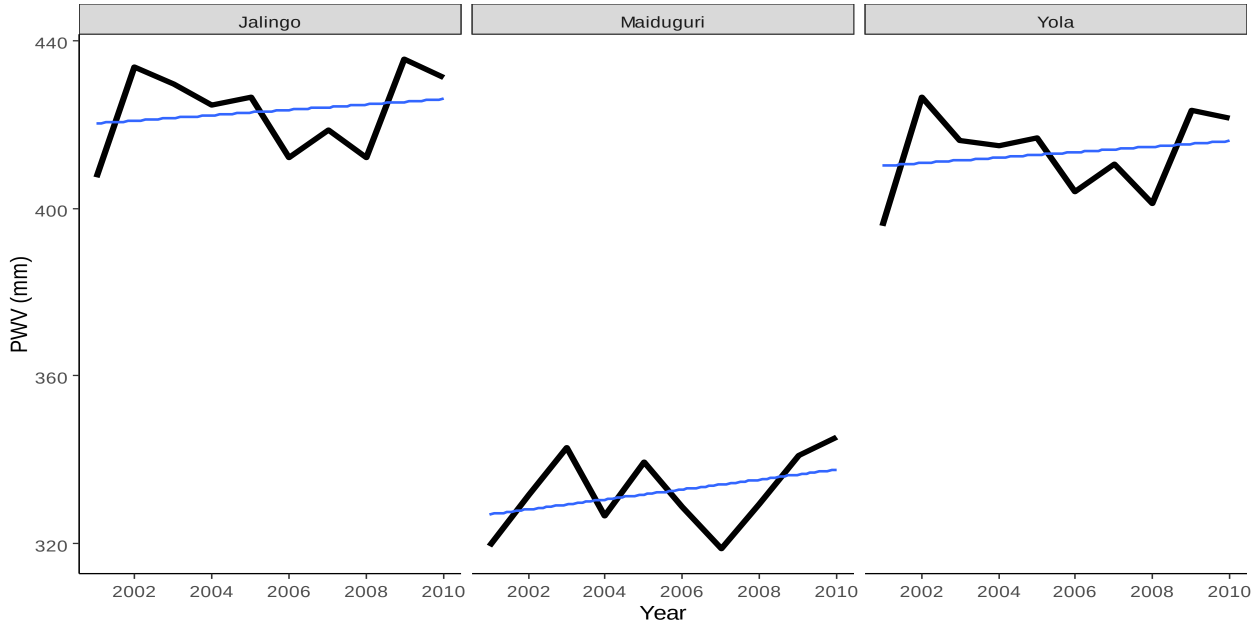

Figure 4a: Decadal trend of PWV from 2001-2010 for Jalingo, Maiduguri and Yola.

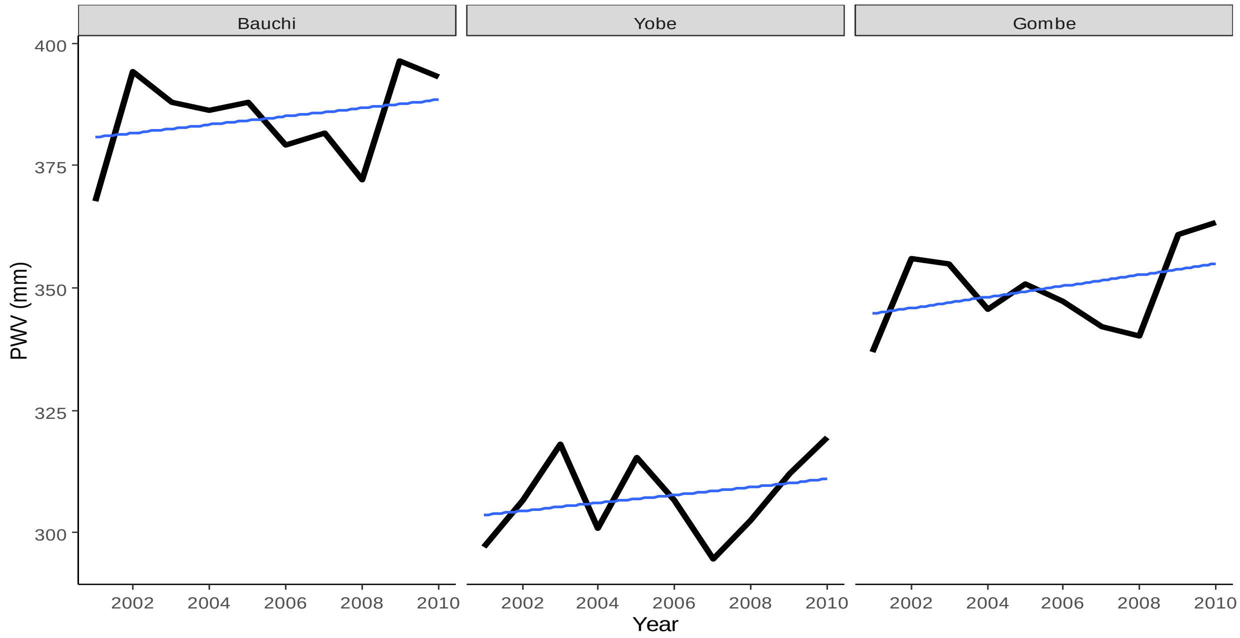

Figure 4b: Decadal trend of PWV from 2001-2010 for Bauchi, Yobe and Gombe

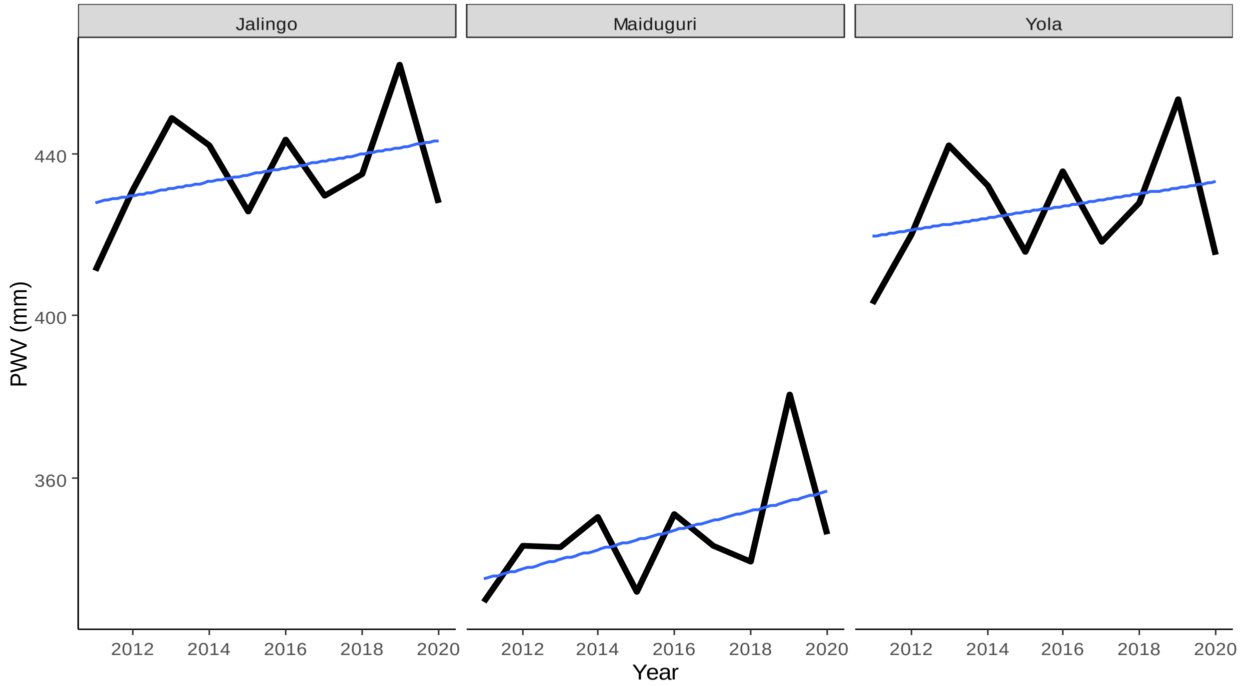

Figure 5a: Decadal trend of PWV from 2011-2020 for Jalingo, Maiduguri and Yola

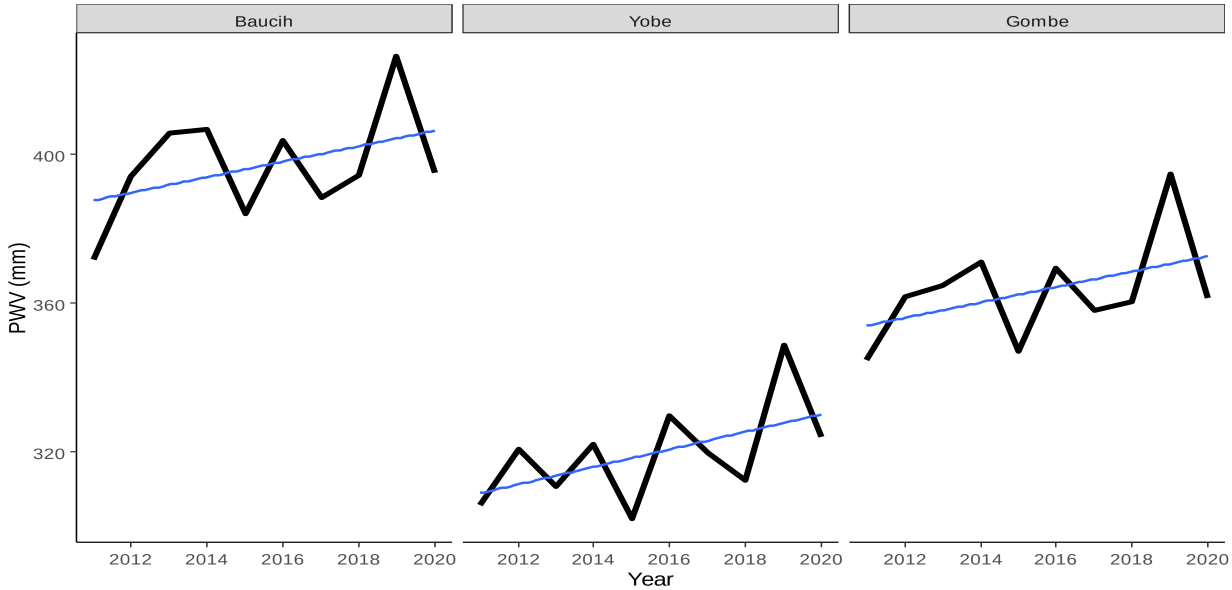

Figure 5b: Decadal trend of PWV from 2011-2020 for Bauchi, Yobe and Gombe

CONCLUSION

The study investigated PWV variability and trends over North-East Nigeria for the period 1991-2021. The results of inter- annual PWV showed that the overall PWV trends in North-East Nigeria have decreased, especially at Jalingo, Yola and Bauchi. The analysis of the PWV decadal trends showed a decreasing trend in the first decade (1991-2000) and an increasing trend in the second and third decades (2001-2010, 2011-2020) over all the states. An increasing annual PWV trend is expected for the next decade across the region. It is expected to be at maximum in Jalingo and minimum in Yobe. Based on the findings of this work, it is thereby recommended that early planting of crop varieties with low moisture resistant like millet and cowpea should be avoided. Effective flood control mechanism should be put in place by the Nigerian water regulatory agency for the expected increased rainfall in some parts of the region. Government Agencies responsible for the environment should put in place contingency plans to mitigate flooding and embark on tree planting campaigns to sensitize the citizens to plant trees.

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CONFLICT OF INTEREST

The authors want to make it clear that there is no conflict of interest in their scientific activity.

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