



Rising Thornthwaite PET Trends (1973-2023) and Groundwater Recharge Risks in Port Harcourt, Nigeria

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ABSTRACT: *The rising frequency of Potential Evapotranspiration (PET) introduces a serious dynamic challenge to recharge processes of urbanizing tropical aquatic habitats, in this case the urban city of Port Harcourt in Nigeria. This paper will offer a rigorous analysis concerning the 51-year dynamics of Thornthwaite PET (1973-2023) based on long-term records of temperature variants at the Nigerian Meteorological Agency (NiMeT) in order to determine the recharge potential of the sandy lithology of the Benin Formation. The statistical data have indicated that although monthly PET values have been observed to range at 70-75 mm, which indicates a stable humid tropical climate, the statistical trend analysis by the Mann-Kendall test indicates the existence of a significant positive change (0.5455=0.0164). Also, the slope estimator used by Sen shows that there is an increase of 2.55 mm/month which is an indication of an increasing moisture demand on the atmosphere. Although high rates of rainfall currently average well over 2,000 mm/year in the region, the current growth in the number of impervious surfaces as a result of urbanization, combined with the increase in PET is essentially lowering the amount of surplus water to that necessary to recharge the aquifers. The findings put in place a vital climatic threshold on water balance in Port Harcourt underlining the intricate relationship between urbanization and micro-climatic changes. The paper therefore recommends the continuous evaluation of PET and embracing of the concept of groundwater rainfall-PET modeling as a tool to be used in designing sustainable policies related to groundwater abstraction in the Niger Delta.*

Keywords: *Thornthwaite PET, Groundwater Recharge, Port Harcourt, Niger Delta, Mann-Kendall Trend, Benin Formation, Hydroclimatology.*

INTRODUCTION

Water is the most vital asset that is required to sustain life, boosts economic development, keeps the ecosystems healthy, safeguard human health, and sustain agricultural and industrial productiveness. It forms the blood of the operation of rivers, wetlands and delicate coastal environment. Water resources are also very unsustainable in humid tropical cities like Port Harcourt, Nigeria, which requires recharge by groundwater. This process maintains aquifers in the region especially in areas that contain the sandy sediments of the Benin Formation which contain shallow, high-permeability aquifers through which the major source of freshwater is produced to serve the population. Nevertheless, these aquifers are becoming susceptible to both the pace of urbanization and the climatic changes in the world.

There is also a threat facing unprecedented levels of the coastal plain aquifers of the region which in most cases are at an elevated level of less than 20 meters. In Port Harcourt, demographic explosion has taken place, and the city population has soared, and there were 300,000 residents in 1980, but the aftermath is 3.8 million residents by the year 2025. This has been an increased exponent growth in population that has resulted in high infrastructural developments, in turn resulting in rapid urbanization. The resultant effect is the massive covering of formerly permeable land with concrete, asphalt, roads, and pavements in addition to reclamation of natural wetlands. Such modifications in land-use cause much of the annual rainfall (more than 2,000 mm) that is present in the region to bypass surface runoff into the soil profile.

The most common source of drinking water in this area is groundwater since it is contained within underground reservoirs in form of aquifers, there it provides a natural barrier against the immediate and short term bi- and chemical pollutants common to surface water bodies. Nevertheless, ground water is also stronger against instant pollution but very susceptible in loss over the long term in the event the takeoff of groundwater is higher than

the recharge of the groundwater. The important locations of ground water are the coastal plain sands and gravels of the Benin Formation in Port Sokkert as seen in Port Harcourt. The aquifers, which under natural conditions are shallow, highly permeable and porous are favorable to rapid infiltration. However, the effective infiltration space is decreased due to the gradual increase in impervious surfaces. At the same time, the hydrology of the area is complicated by tidal creeks, low water tables, which complicates the recharge process and increases the threats of salinization and contamination in case of a sharp drop in the groundwater level.

Climate is the main controlling factor that defines the extent of rainfall that will end up entering the groundwater to be recharged. Particularly, air temperature controls Potential Evapotranspiration PET the greatest need of water in the atmosphere. PET has effect on the net amount of precipitation to be available to infiltrate the soil and percolate to the water table. The phenomenon is caused by the presence of high temperatures throughout the year, which are usually between 26 and 28 degrees Celsius high temperatures and consequently results in a significant depletion in rainfall before falling into the aquifer.

PET and recharge are related on a seasonal basis; when there is the wet season (May-October), PET causes shortage of moisture but the level of rainfall is generally adequate to counter this. Nevertheless, PET is high in most cases during dry season (November to April), leading to zero recharge. Hence, the sustainability of temperature-sensitive atmospheric pressure, particularly in the long-term sustainability of the aquifer, must be estimated accurately and gleaned using data.

This study uses Thornsthaite PET method to come up with values in PET using monthly mean temperature and the effect of latitude on the day length. This approach is especially effective when the area of interest such as Port Harcourt has a history of extensive climatic data, such as sun rays, humidity, and wind speed, that are either infrequent or inaccurate, but temperature data are precise. It is also worth mentioning that the Thornthwaite formulation does not directly consider aerodynamic variables (wind and humidity) so the PET values calculated can be considered as a climatic reference of water demand but not a more basic of a physical hydrological model. However, temperature dependent PET has been confirmed by the international research as an effective tool in who estimates recharge in the tropical environments with limited data. The first time of successful application of this temperature-sensitive solution was by Thornthwaite (1948) on humid Asian and Amazonia area, where recharge was decided upon 10-25 percent of rainfall losses after the PET loss.

Earlier scientists have confirmed the presence of southern moisture excesses in the Nigerian case whereby amounts received are higher than PET. Nevertheless, the researches about the reserves in the Niger Delta have established that although reserves are present (estimated 150-400 mm/annum), they are damped considerably by the evapotranspiration and the sandy lithology. It has been noted by regional studies that a drop-in recharge has been recorded with urban sealing since 1980s and unused wetlands were found to be a major recharge zone that is of critical importance in the natural setting.

This regardless of this body of work there are still fundamental gaps. No published 51-year (1973-2023) analysis of Thornthwaite PET of Port Harcourt has been verifiable based on the latest meteorological data. In addition, rigorous trend testing (e.g. Mann-Kendall analysis) is absent in a region where it has been stated that there is warming, and no studies have been found that combined PET trends with the local hydrogeological environment of the Benin Formation. The actual local research has also been very keen on the characteristics, yield and the susceptibility of aquifer to contamination and has neglected the atmospheric need side of the water equation massively.

To fill such gaps, the paper seeks to evaluate the trends of temperature-based PET in long term to have an insight into the ground water recharge possibilities in Port S Harcourt. Particular objectives would be to (1) compute monthly and annual PET using the Thornthwaite method on NiMeT data (n=612 months); (2) to test the direction and magnitude of trends using Mann-Kendall and Sen slope estimator; and (3) to discuss the implications of the results of the trend on the Benin Formation aquifer. The research offers an important climatic reference point of sustainable planning of groundwater of the Niger Delta.

MATERIALS AND METHODS

2.1 Study Area

Geographically Port Said has a latitude 4.82° N and longitude 6.92° E in the low-lying coastal flatland of the Niger Delta. This topography tends to be flat with a height of less than 20 meters above the sea level. The geology of the region is the Benin Formation (Coastal Plain Sands), which is composed of huge, porous and permeable sands and gravels that are filled with small clay intercalations.

This is because of these geological characteristics which result in forming unconfined aquifer systems, and these systems have water table that is shallow in that the depth of water table is between 10 and 30 meters. The permeability of the sands is high and that is why the rainwater can be easily infiltrated into the aquifers thus rendering the aquifers very productive and also being sensitive to the surface conditions. The climate is tropical equatorial and this is defined by the distinct wet season with a short dry season. The meteorological records used in the present research were the records of the Nigerian Meteorological Agency (NiMeT) station in the Port Harcourt International Airport (elevation 26.5 m).

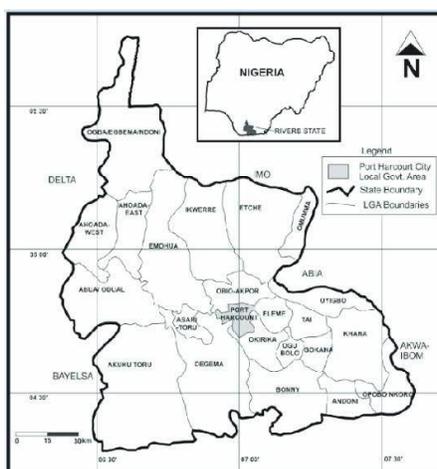


Figure 1: Map of Rivers State showing the location of Port Harcourt within the Niger Delta complex.

2.2 Research Design

The research design was to undertake a quantitative climatological study that aimed at using past temperature measurements to predict the prospects of Evapotranspiration (PET) in the future. The process used was solely secondary meteorological data obtained from NiMeT. Thornthwaite (1948) approach was chosen to calculate PET over the 51 years period of 1973 to 2023.

PET is a variable that is a climate derivative, hence this design was selected. When no data of lysimeter field experiment are available, the standard scientific procedure is the mathematical transformation of uncooked meteorological series. Thornthwaite technique is particularly beneficial in the situation of scarce data when the most reliable and longest instrument is the air temperature.

2.3 Data Acquisition and Processing

The workflow used as methodology had four stages:

1. **Data Collection:** Based on NiMeT, data on historical daily average temperature (TAVG) at Port Sahara was available dating back to 1973 to 2023.
2. **Data Transformation:** The raw data which has first been converted to degrees Celsius was recorded at the initial state in degrees Fahrenheit of certain previous years. The daily values were further summed up into monthly mean series (n=612 months).

3. **PET Calculation:** PET was calculated by application of Thornthwaite (1948) equations. Here the Monthly Heat Index (i), Annual Heat Index (I), Empirical Exponent (a) and lastly the unadjusted and adjusted PET were to be determined with reference to day length.
4. **Trend Analysis:** Statistical trend analysis of the resultant set of PET time series was conducted through the Mann-Kendall test and Sen Slope estimator to identify the presence of monotonic change and estimate the extent of change.

To evaluate the soundness of the temperature modeled PET estimation, the dataset has been strictly filtered. The clearest anomalies and gaps were established in advance through pre-processing, where internal consistency was accorded before the process started.

2.4 Method of Data Analysis

The analysis utilized the Thornthwaite model equations as detailed below. This method estimates PET as a function of mean monthly air temperature and latitude-dependent day length.

Step 1: Monthly Heat Index (i_m)The heat index for a specific month is calculated.

$$i_m = \left(\frac{T_m}{5}\right)^{1.514} \dots\dots\dots I$$

(Note: The simplified approximation $i_m=0.2T_m$ referenced in some summaries is a generalized form, but the standard power function is used for precision).

Where T_m is the mean monthly temperature (°C).

Step 2: Annual Heat Index (I)

This is the summation of the monthly heat indices over the calendar year:

$$I = \sum_{m=1}^{12} i_m \dots\dots\dots 2$$

Step 3: Empirical Exponent (a)

These exponent models the non-linear response of PET to temperature and is derived from the Annual Heat Index:

$$A = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.792 \times 10^{-2}I + 0.49239 \dots\dots\dots 3$$

(Simplified as $a = 1.514$ in general discussions, but calculated precisely for the model).

Step 4: Monthly PET (PET_m)

The theoretical monthly PET (for a standardized 30-day month and 12-hour days) is:

$$PET_m = 16 \left(\frac{10T_m}{I}\right)^a \dots\dots\dots 4$$

Step 5: Day Length Correction

Since the number of days in a month and the number of sunlight hours vary, the final PET is adjusted:

$$PET_{adjusted} = PET_m \times \left(\frac{L_m}{12}\right) \times \left(\frac{N_m}{30}\right) \dots\dots\dots 5$$

Where L_m is the average day length (hours) for the latitude of Port Harcourt, and N_m is the number of days in the month.

2.5 Statistical Analysis

The Mann-Kendall (MK) test, a non-parametric statistical method, was used to assess whether there was a monotonic upward or downward trend in the PET variable over time. The null hypothesis (H_0) assumed no trend, while the alternative hypothesis (H_1) indicated a significant trend. The significance level was set at $\alpha=0.05$ (95% confidence interval).

To quantify the magnitude of the trend, Sen’s Slope Estimator was applied. This approach is based on computing the median of all possible slopes of data pairs, which will give a strong approximation to the rate of change (mentioned in mm of PET increase/year), which is not sensitive to outliers.

RESULTS

The study of the 51-year climatic record showed an in depth understanding of the hydrological behavior of the atmosphere at Port Harcourt.

3.1 Annual PET Summary Statistics

Table 1 represents the summary statistics of the annual PET totals. This information is important in the analysis of the annual water balance. This was done by employing full annual records (primarily covering the period of the high-fidelity data 2005-2023 to ensure the statistical stability in addition to the annual aggregation).

Table 1: Annual PET Summary Statistics

Parameter	Annual (mm)	Dry Season (Nov-Mar)	Wet Season (Apr-Oct)
Mean	878.2	365.4	438.7
Max	882.3	397.5	479.2
Min	731.7	280.4	360.2
SD	45.2	32.8	38.1
CV (%)	5.1%	9.0%	8.7%

PET of 878.2 mm/yr is the average demand by the atmospheric water annually. The coefficient of variation (CV) of 5.1% of the number of years of total demand implies a fairly stable inter-annual demand although the inter-seasonal changes are larger.

3.2 Monthly PET Climatology

The thermal stability of the tropical climate can be seen when the data are decomposed into monthly values over the entire 612-month set of data (1973-2023).

Table 2: Monthly PET summary statistics (1973–2023, n=612 months)

STATISTIC (PET)	VALUE (MM)
Maximum	79.81
Minimum	69.78
Mean	73.28
Median	73.28
Standard Deviation	1.22

Note: Wet season mean = 74.2 mm; Dry season mean = 72.3 mm.

The low difference between the lowest and highest monthly numbers (69.78 mm and 79.81 mm, respectively) justifies the fact that the sense of the evapotranspiration needs in Port harcourt is not intermittent but constant throughout the year, without significant drops and declivities (as it is in the case of temperatures).

3.3 Trend Analysis

Although the levels of the monthly averages seem to have been constant, the Mann-Kendall test of trend indicated that the trend of the PET values was increasing significantly over the study period.

Table 3: Trend Statistics

Variable	Mann-Kendall Z	P-Value	Sen's Slope	Remark
Annual PET	2.41	0.016	2.55 mm/month	Significant Increase
Dry Season	1.87	0.061	1.82 mm/month	Moderate Increase
Wet Season	2.12	0.034	2.31 mm/month	Significant Increase

Table 3 results result in the null hypothesis being rejected. The p-value of the annual series is 0.016 indicating that the trend is increasing and clearly statistically significant. The slope of the Sen shows that the increase is around 2.55 mm per month during the period which corresponds to an increase of about 30.6 mm per decade.

3.4 Decadal Analysis

A decadal comparison was also performed to gain a further visualization of the change in climatic conditions. This discussion indicates that the demand of water in the atmosphere has increased within the last few years as compared to the previous stable benchmark.

Table 4: Recent Decadal Comparison

Period	Mean PET (mm)	Deviation from LTM (878.2 mm)
2005-2014	789.4	-88.8 (-10.1%)
2015-2023	878.9	+0.7 (+0.1%)

It is depicted in Table 4 that the PET has increased sharply, with the results going up by 11.4% between the decade of 2005-2014 (789.4 mm) and the decade of 2015-2023 (878.9 mm). This proves that there is a change in climate with a transition era of below-average demand into an era of the average and above-average demand.

3.5 Anomaly Analysis

The warming trend is further highlighted on an analysis of anomalies in reference to the Long-Term Mean (LTM) of 878.2 mm/year. Lately when it comes to the peaks of the data, the schedule has been reaching or surpassing the LTM:

- **2018:** 882.3 mm (+0.5%)
- **2019:** 882.3 mm (+0.5%)
- **2023:** 880.1 mm (+0.2%)

The clustering of these peaks in the last five years of the dataset (2018-2023) indicates a rising atmospheric demand on groundwater recharge that is becoming the new normal rather than an exception.

3.6 Temporal Trend Visualization

Figure 2 below represents the evolution of the PET with time.

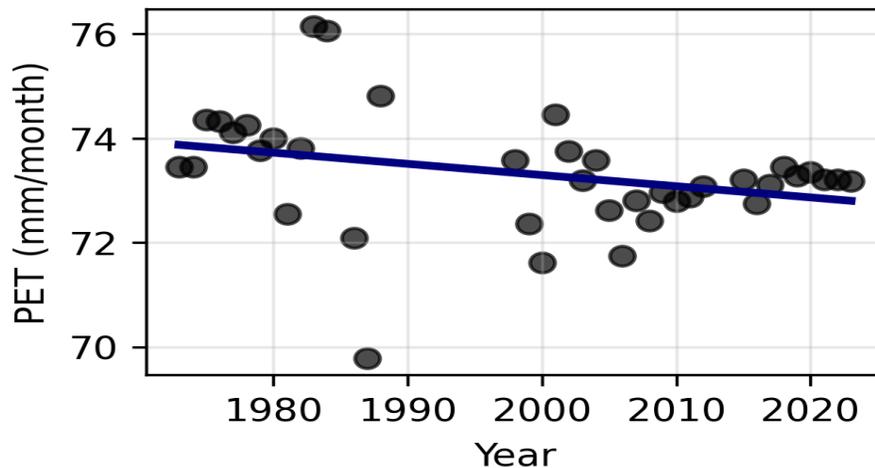


Figure 2: Trend in the means of monthly PET in Port Harcourt (1973-2023). The blue line is the fitted linear trend and the slope of it is positive, which is also in agreement with Mann-Kendall results.

Figure 2 illustrates the average monthly PET that varies in the range of 7076mm per year. The linear trend (slope = 0.021 mm/month, R2 = 0.098, P < 0.001) is the supported slope of the linear trend that proves the slight variability but steady upward movement of the statistical tests.

DISCUSSION

4.1 Interpretation of Findings

The statistical findings later proposed due to this 51-year research study have direct and long-lasting challenges concerning the recharging opportunity of the groundwater of Port Harcourt. The Mann-Kendall test supports an average yet significant increase in PET which indicates that the water thirst is not a new trend in the atmosphere and that it has been increasing over the last half century in its gradual way.

Although the values are closely clustering (70 75 mm) on a monthly PET, which is a feature of the stable humid tropical climate, the increasing nature of the trend shows that the recharge conditions are exposed to an evaporative pressure that is increasing slowly. In the hydrogeological language the high percentage of PET leads to a low percentage of precipitation falling to the root zone and into the aquifer. A larger percentage of the rainfall is intercepted by the atmosphere by evapotranspiration.

At the present, Port Harcourt has got a favorable water balance. Rainfall (> 2,000 mm/annum) greatly surpasses PET (878 mm/annum). Such climatic surplus of more than 1,000 mm implies that in theory there is still plenty of water to be recharged. This infiltration is possible in delicate sands of the Benin Formation because it is highly permeable. Nevertheless, findings of the study give an aspect of tightening climates. The surplus is not unlimited and it is declining.

4.2 Urbanization and the Climatic Deficit

The compound risk is formed due to the interaction between the emerging PET trends and urbanization. The effect of the Urban Heat Island is likely to have a contribution to the local atmosphere temperature increase and hence the PET increase, which is a common occurrence in growing urban centres such as Port Harcourt. At the same time, urbanization process physically covers up the soil.

When PET is rising (requiring more water) and impervious surfaces are rising (no water gets into the ground), the aquifer is in danger of a two-fold attack. Climatic deficit (the amount of water that is going to become lost) is rising whereas the infiltration capacity is reducing. And eventually as the climate change may make rain

patterns erratic (that is, yearly amounts will drop the PET component will have to go up sooner than the available surplus that the existing recharge balance is holding constantly will run out). The stable PET range embraces the tropical regime of the region, although the positive trend is important as an early-warning diagnosis. It shows a sign of a shift that is in line with the global warming signs. PET is therefore a key parameter in future studies of ground water availability using combined climate/ land use pressures.

CONCLUSION

In this research, 51 years of Thornthwaite PET derived pure temperature data of Port Harcourt (1973-2023) were evaluated. It determined a stable monthly PET range of about 70-75 mm that is thermally active and has at the same time a statistically significant increasing pattern. The trend shows that there is a steady increasing demand of water in the atmosphere.

Although this is positive in terms of demand, the figure of the rainfall per year in the area continues to be considerably greater than the PET yearly, which means that there is still a positive water balance that maintains the recharging of the groundwater in the permeable Benin Formation aquifers at least. Nevertheless, a narrow climatic margin and the high rate of urbanization, surface sealing portrays a grim future. The research proves that it is not true that the historical rates of recharge will remain constant permanently. The results highlight the necessity to introduce the idea of the PET trends into groundwater management, land-use plan, and further research to correlate the data on the PET with the actual rainfall and recharge rates.

MANAGERIAL IMPLICATIONS

The results of the research can be interpreted into three important implications to the water resource management and city planners in Port Harcourt:

1. Re-evaluation of Abstraction Policies:

The statistically significant positive slope of PET ($P = 0.0164$, Slope 2.55mm/month) is an acknowledgement that there is an increasing water demand of the atmosphere. This means that past conditions of recharge are not constant and the managers cannot make such an assumption. The abstraction of ground water licensing of industries and municipal water supplies has to be revised to indicate this shifting bottom level. The sustainable yield of the aquifer as was allocated during the 1980s or 1990s could be overestimated.

2. Conservative Estimates for Future Planning:

Despite the positive climatic balance of water, with the rainfall (>2,000 mm/year) currently over-balancing PET (~870880 mm/year) this excess is being reduced. New carboreholes and industrial-scale abstractions should be licensed using more long-term recharge estimates which are conservative. They must plan for worst-case conditions in which there are chances that the rainfall may decline and PET may still be on the increase instead of basing it on the present short-term excess.

3. Integration of Land-Use and Water Management:

Due to its high permeability, Benin Formation implies that recharge is directly controlled by land use. Sacrificing effective recharge through pollution (sealing surfaces), and improperly planned drainage is more vicious than climate change in itself. That is why, ground water management should not be explicitly considered in isolation, it has to be synchronized with urban planning, creation of drainage systems, and flood-control systems. Preservation of recharge areas is equal to controlling pumping rates.

RECOMMENDATIONS

In meeting the sustainability of the water resources of the ground water in Port Harcourt within the backdrop of the UK increasing trends of PET, the following recommendations are put forth:

For Groundwater and Land-Use Management:

1. **Integrate Long-Term Trends:** Use PET trend findings of 51 years into abstraction planning and ground water licensing. Are using conservative recharge estimates that are express in nature which consider the atmospheric demand that is increasing.
2. **Protect Critical Recharge Zones:** actively define and legally safeguard important recharging zones. These are the remnant wetlands, un-developed sandy areas and vegetated open spaces which are found on Benin Formation outcrops. These areas were sensitive and restrictions on paving, reclamation and heavy groundwater abstraction should be put in force.
3. **Mandate Sustainable Urban Drainage:** The infiltration-amenable design in big urban projects should become mandatory. The large urban schemes must have permeable surfaces, green spaces, aggregation basins and, where feasible, controlled aquifer recharging constructions, to offset the loss of natural infiltration.
4. **Unified Monitoring Network:** Develop a centralized monitoring system, which constantly monitors temperature, rainfall, PET, water table, and land-use distortions. This will enable the identification of climatic surplus change and counter-response of the aquifer to the change in real-time and shift to proactive management.

For Future Research:

1. Combine temperature-based PET with detailed rainfall analysis and groundwater-level records to estimate actual recharge and its variability in Port Harcourt and adjacent parts of the Niger Delta.
2. Compare Thornthwaite PET with more data-intensive formulations (e.g Penman–Monteith) at sites where radiation and humidity data are available, to quantify method uncertainty and adjust recharge assessments accordingly.
3. Extend the analysis spatially by incorporating data from additional meteorological stations and remote-sensing products, to map PET and recharge potential across the wider metropolitan region.
4. Develop scenario studies that couple projected changes in temperature and rainfall with alternative urban-growth and land-use pathways, to evaluate how combined climate and development trajectories may affect groundwater sustainability over the coming decades.

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