Evaluation of Factors Influencing Changes in Land Surface Temperature at Gas Flaring Sites in the Niger Delta, Nigeria

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Abstract
This research investigates factors that can affect changes in Land Surface Temperature (LST) retrieved from satellites data at 11 gas flaring sites in Rivers State, Nigeria. Landsat 5 Thematic Mapper (TM), 22 Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and 4 Landsat 8 Operational Land Imager and Thermal Infrared Sensor (OLI-TIRS) data from 14/12/1984 to 05/02/2022 with < 3% cloud cover were used. LST was derived from the atmospherically corrected thermal band; difference between vegetation LST at 60m from the flare stack and vegetation LST at 450m from the flare stack was computed as ($\delta$LST$_{60-450m}$). Available factors that can affect ($\delta$LST$_{60-450m}$) considered are facility size, flare stack height and time. Pairwise linear regression analysis was applied to the relationship between each of the factor considered and ($\delta$LST$_{60-450m}$) in North, East, South, and West directions with $\alpha = 0.01$ to obtain r-values and p-values. Analysis of the relationships among multiple variables ($x_1 = \text{month}$, $x_2 = \text{facility size}$ and $x_3 = \text{stack height}$, $y_1 = (\delta$LST$_{60-450mN}$) and $y_2 = (\delta$LST$_{60-450mE}$) was carried out using multiple linear regression analysis. The results ($r^2 = 0.05$, and p-value = 0.016) show that only 5% of the variability in ($\delta$LST$_{60-450m}$) could be accounted for by the variables considered. From these results, it can be concluded that facility size, flare stack height and time could only account for 5% of the variability in ($\delta$LST$_{60-450m}$) at the flaring sites examined.

Keywords: Evaluation, Factors, Satellites data, Landsat, Land Surface Temperature.

Introduction
The role of Land Surface Temperature (LST) in heat and energy exchange between land surfaces and the atmosphere is of great significance (Bechtel, 2015; Sun et al., 2011). The knowledge of LST is a bedrock for others Earth sciences system (Li et al., 2013; Kerr et al., 2000). For example, LST was used for detection of gas flares platforms (Morakinyo et al., 2021; Morakinyo et al., 2020), examination of urban heat island (Anastasios et al., 2018), soil moisture (Zhao et al., 2016), evapotranspiration (Song et al., 2018a), evaluation of environmental changes (Song et al., 2018b), climatic change analysis (Chapin et al., 2005), and geothermal area detection (Qin et al., 2011).

Some researchers have studied gas flaring temperatures globally as a strategy for discriminating gas flares hotspots from forest fires, bush burning and others using various Earth Observation (EO) satellites data. For example, the gas flaring temperatures of (1000-2600) K was derived from the Visible Infrared Imaging Radiometer Suite (VIIRS) Nightfire database by Liu et al. (2018) and Elvidge et al. (2016) derived. Caseiro et al. (2020) reported (1200-2500) K as gas
flares temperatures from shortwave and mid-infrared (SWIR and MIR) channels of Sentinel-3A Sea and Land Surface Temperature Radiometer (SLSTR) data. In addition, Elvidge et al. (2013) observed temperatures ranges of (1200-1750) K from VIIRS data. Furthermore, Zhang et al. (2015) and Elvidge et al. (2016) recorded (1450-2200) K as the radiant temperature retrieved from VIIRS data for the flaring sites investigated. A typical flaring site in the Niger Delta is shown in Figure 1.

In Nigeria, limited studies have been carried out on measurement of gas flaring temperatures whether by remote sensing technology (Morakinyo et al., 2022; Morakinyo et al., 2021; Morakinyo et al., 2020; Morakinyo, 2015) or conventional method (Morakinyo, 2015; Ubani and Onyejekwe, 2013; Dung et al., 2008). Specifically, no paper has been published on the examination of factors that can influence changes in LST retrieved from EO satellites at flaring sites in the Niger Delta. In addition, methods considered have not been used in any prior research for the Nigeria. Consequently, in order to close this gap the examination of the available factors that can influence changes in LST; and the application of remote sensing technology are required for the study. Research questions considered for this paper are: (1). What are the available factors (parameters) that can influence changes in LST at gas flaring sites in the Niger Delta? (2). What is the quantitative analysis of the relationship between each of the available parameter considered and the changes in LST in the North, East, South, and West directions? (3) What is the % contribution of the examined parameters to the changes in LST? Based on these 3 questions, the aim of the study is to evaluate factors that can influence changes in LST at the flaring sites in the Niger Delta and their % of contribution. Therefore, the definite objectives for the research questions are: (1) Selection of suitable flaring sites in the Niger Delta; (2) Retrieval of LST from atmospherically corrected Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) data; (3) Computation of changes in LST as (δLST60-450m) in North, East, South and West directions; (4) Application of pairwise and multiple linear regression of statistical analyses to the relationship between each of the available parameter and (δLST60-450m) in the N, E, S and W directions.

Materials and Methods

Study Area

This research was conducted with 11 oil and gas facilities flaring sites located in Rivers State, Niger Delta of Nigeria. The study area is bounded by Latitude 4° 40’ and 5° 01’ N and Longitude 6° 50’ and 7° 01’ E (Morakinyo et al., 2021). The name and dimension of the facility within each site is Eleme Petroleum Refinery Companies I (1.6 × 1.1) km; and II (2.2 × 1.3)
km; Bonny Liquefied Natural Gas (LNG) plant (4.2 × 2.8) km; Onne (175 × 130) m; Rukpokwu (350 × 350) m; Umurolu (4.2 × 2.4) km; Obigbo (650 × 650) m; Alua (170 × 90) m; Umudioga (100 × 100) m and Chokocho (350 × 120) m Flow Stations, and Sara oil well (350 × 250) m (Figures 2 and 3A). The height of the flare stack for each of the facility is presented in Figure 3B. Among the 11 sites studied, Bonny LNG and Sara oil well are located at coastal areas that are not accessible by road; while the rest of the 9 are inland facilities. In order to explore the LST results for adequate analysis, (12 × 12) km area was examined around the flare stacks.

Figure 2: A) Map of Africa showing Nigeria, (ESRI, 2022); B) Location of Rivers State in the Niger Delta, Nigeria (Google Earth, 2022); C) The 11 flaring sites studied in Rivers State, Nigeria.
Data and Processing Methods using MATLAB Programming Codes

Data used in this research are Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI-TIRS, and high resolution images from IKONO. 8 Landsat 5 TM imagery dated 1984 to 1991; 22 Landsat 7 ETM+ imagery dated 1999 to 2013; and 4 Landsat 8 OLI-TIRS data dated 2018 to 2022 with < 3 % cloud cover from the months of January to April, and November to December acquired from the USGS Earth Resources Observation and Science (EROS) Data Centre website (http://earthexplorer.usgs.gov/) were used. The datasets were selected because they are less affected by clouds and that they fall within the dry season in Nigeria. The spatial resolution for Landsat 5 and Landsat 7 band 6 (Thermal Infrared) are 120 m and 60 m respectively while that of Landsat 8 OLI-TIRS bands 10 and 11 (Thermal Infrared) is 100 m but all are resampled to 30m pixels (USGS, 2022; Chander and Markham, 2003).

Landsat 5 and Landsat 7 thermal band Digital Numbers (DN) values were processed to top of atmosphere (TOA) spectral radiance with equation 1 using MATLAB codes.

\[ L_\lambda = \frac{(L_{\text{MAX}} - L_{\text{MIN}})}{(Q_{\text{CAL MAX}} - Q_{\text{CAL MIN}})} \times (Q_{\text{CAL}} - Q_{\text{CAL MIN}}) + L_{\text{MIN}} \]  

(Eq. 1)

Where:
- \( L_{\lambda} \) = Spectral radiance at the sensor’s aperture (Wm\(^{-2}\)sr\(^{-1}\)µm\(^{-1}\));
- \( Q_{\text{CAL}} \) = The quantized calibrated pixel value in DN;
- \( L_{\text{MIN}} \) = The spectral radiance that is scaled to QCALMIN (Wm\(^{-2}\)sr\(^{-1}\)µm\(^{-1}\));
- \( L_{\text{MAX}} \) = The spectral radiance that is scaled to QCALMAX (Wm\(^{-2}\)sr\(^{-1}\)µm\(^{-1}\));
- QCALMIN = The minimum quantized calibrated pixel value (corresponding to \( L_{\text{MIN}} \)) in DN = 1 for LPGS (a processing software version) products;
- QCALMAX = The maximum quantized calibrated pixel value (corresponding to \( L_{\text{MAX}} \)) in DN = 255.
Also, the spectral reflectance for Landsat 5 and Landsat 7 multispectral bands (1-4); and bands 2-5 for Landsat 8 were computed using (Eq. 2) (Song et al., 2018a).

\[
\rho_p = (\pi \times L_\lambda \times d^2) \div (\text{ESUN}_\lambda \times \cos \theta_s)
\]  

\text{(Eq. 2)}

Where: \( \rho_p \) = Unitless effective at-satellite planetary reflectance; 
\( L = \) is measured per unit solid angle; 
\( \pi L = \) Upwelling radiance over a full hemisphere; 
\( d = \) Earth-Sun distance in astronomical units; 
\( \text{ESUN}_\lambda = \) Mean solar exoatmospheric irradiances; 
\( \theta_s = \) Solar zenith incident angle in degrees.

**Application of K-means Function of MATLAB**

The unsupervised cluster analysis (Morakinyo et al., 2019) of the Landsat 5 and Landsat 7 atmospherically corrected reflectance (bands 1-4), and that of Landsat 8 OLI-TIRS (bands 2-5) using the k-means function of MATLAB for land cover (LC) classification was carried out for all the sites to obtain 4 classes of LC (vegetation, soil, built up and water) (Maaharjan, 2018) (Figure 4). The % of each of the LC type were identified at the study sites during ground validation fieldwork from 04/08/2012-21/09/2012 and 05/08/2020-21/09/2020. Red, Green, Blue (RGB) pseudo-true colour composite images, high resolution images from Google Earth, and Digital Global were used for further clarifications of the 4 LC types.

The emissivity (\( \varepsilon \)) value for the 4 LC types available at each site is obtained by considering the \( \varepsilon \) value of each of the LC type on pixel basis for the entire site. Minimum and maximum \( \varepsilon \) values were acquired from the literature for the computation of the mean \( \varepsilon \) values for the 4 LC types for each pixel with the % of each LC within a pixel applied (Morakinyo et al., 2021; Morakinyo et al., 2019). Consequently, the \( \varepsilon \) value for a Landsat pixel’s LC is a combination of the \( \varepsilon \) value of all the 4 LC types present within the pixel.

**Landsat LST Retrieval**

The retrieval of LST from Landsat data was carried out using radiative transfer equation. This method has 3 stages (Zhang et al., 2009; Yuan and Bauer, 2007). Stage 1 is to convert the DN of thermal bands to TOA radiance using (1) for Landsat 5 and Landsat 7 data. For Landsat 8 images, TIRS band data can be converted to TOA spectral radiance using (Eq. 3).

\[
L_\lambda = M_\lambda \ast \text{QCAL} + A_\lambda
\]  

\text{(Eq. 3)}

Where:

\( M_\lambda = \) The band specific multiplicative rescaling factor; 
\( A_\lambda = \) The band specific additive rescaling factor.

\( M_\lambda \) and \( A_\lambda \) are provided in the metadata file of the Landsat 8 data. \( L_\lambda \) and QCAL in (3) are the same as those in (1). Conversion of TOA radiance of the thermal band to surface-leaving radiance using the atmospheric correction tool MODTRAN 4.1 to remove the effects of the atmosphere (Berk et al., 1999) is the stage 2. The surface-leaving radiance \( L_T \) is calculated using (Eq. 4) (Barsi et al., 2005).

\[
L_T = (L_\lambda - L_{\mu} - \tau (1 - \varepsilon)L_d) / \tau \varepsilon
\]  

\text{(Eq. 4)}

Where \( L_{\mu} \), \( L_d \) and \( \tau \), are the upwelling radiance, downwelling radiance, and atmospheric transmission respectively; and they are atmospheric correction parameters for the Landsat thermal band. \( \varepsilon \) is the emissivity of the surface LC types. For this study, \( \varepsilon \) was calculated based...
on the land cover types of each site. Stage 3 is the conversion of radiance to LST using the Landsat-specific estimate of the Planck curve (Eq. 5) (Chander, and Markham, 2003):

\[
\text{LST} = \frac{K_2}{\ln((K_1/L_\lambda) + 1)}
\]

(Eq. 5)

Where:
\(\text{LST} = \) Temperature in Kelvin (K) (Figure 4); \(K_1\) and \(K_2\) are thermal band calibration constants calculated for the Landsat sensor characteristics (Table 1).

| Table 1: Calibration Constants \(K_1\) and \(K_2\) for Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 TIRS data |
|-----------------|-----------------|-----------------|-----------------|
|                  | Landsat 5 TM    | Landsat 7 ETM+  | Landsat 8 Band 10 | Landsat 8 Band 11 |
| \(K_1\) (Wm\(^{-2}\)sr\(^{-1}\)μm\(^{-1}\)) | 607.76          | 666.09          | 774.89          | 480.89           |
| \(K_2\) (K)      | 1260.56         | 1282.71         | 1321.08         | 1201.14          |

Source: (USGS, 2022)

Large uncertainty in the band 11 values for Landsat 8 were recorded at the product information on 14/11/2013 (http://landsat.usgs.gov/Landsat8_U sing_Product.php); and so, using band 10 data to retrieve LST was recommended. Hence, for Landsat 8, band 10 data while for Landsat 5 and Landsat 7 band 6 data were used for the retrieval of LST accordingly. LST were determined for all the 4 (Vegetation, soil, built up, and water) LC types present at the 11 study sites.

**Computation of Change in LST for Vegetation as \((\delta\text{LST}_{60-450m})\)**

LST for vegetation was used for further study, hence changes in LST for vegetation was computed as \((\delta\text{LST}_{60-450m})\) which is the difference between the LST for vegetation at 60 m distance from the flare stack and the LST for vegetation at 450 m distance from the flare stack (Morakinyo, 2015). The 60 m was chosen and used for the pixel after the flare stack to know the LST for vegetation at a near distance from the flare. Also, 450 m was adopted as a far distance from the flare; and this is supported by Dung et al. (2008) and Isichei and Sandford (1976) that the maximum distance of the impact of flare on vegetation is between 100 to 120 m.

\[\text{LST}_{60} - \text{LST}_{450m} = (\delta\text{LST}_{60-450m})\]

(Eq. 6)

\((\delta\text{LST}_{60-450m})\) was applied to each of the available factor that can influence it; and the relationship between them in the N, E, S and W directions were examined for the purpose of this study.

![Flowchart showing the stages for the processing of Landsat 5, Landsat 7 and Landsat 8 data for land cover classification and LST retrieval.](image-url)
Factors that can Influence ($\delta$LST$_{60-450m}$) at Flaring Sites in the Niger Delta

Factors that can impact ($\delta$LST$_{60-450m}$) at flaring sites in the Niger Delta include volume and rate of the burning gas, facility size, flare stack height, vegetation type and density, and time (Julian day, month and year). However, those 3 factors that cannot be derived from satellite data and are available and investigated for this study are facility size, stack height and time (Julian day, month and year).

Size of the facility is considered in order to compare the results ($\delta$LST$_{60-450m}$) obtained from various oil and gas facilities of different sizes ranging from small, medium to large. For example, comparing results obtained from Eleme Refinery II, Bonny LNG and Sara oil well. Height of the flare stack helps to evaluate the impact of the height of the stack on the $\delta$LST$_{60-450m}$, since the height of the flare stacks of all the facilities considered are not equal, as well as the location of some of the facilities is different (Coastal and inland). Similarly, time which is the acquisition date (Julian day, month and year) for the acquired Landsat data is considered in order to assess the effect of the period of satellite observation on ($\delta$LST$_{60-450m}$).

**Analysis of Variance (ANOVA): Determination of r-values, p-values and Correlation Type**

To establish the reliability on ($\delta$LST$_{60-450m}$) as a true measure of flare impact, an analysis of variance (ANOVA) was carried out to test whether both near and far temperatures from the flare were significantly different (with $\alpha = 0.01$). Linear relationships between each of the 3 factors and ($\delta$LST$_{60-450m}$) were tested against the North, East, South and West directions, and it gives better results. Furthermore, the pairwise linear regression analysis was applied to the relationships between each of the factors considered and ($\delta$LST$_{60-450m}$) in the N, E, S and W directions with $\alpha = 0.01$ to give the first set of correlation coefficients (r-values and p-values) (Table 18). Also, Table 19 presented the second set of r-values and p-values determined with a condition that ($\delta$LST$_{60-450m}$) with a p-value $> \alpha = 0.01$ should not be considered for the computation.

**Investigation with Multiple Linear Regression**

The purpose of multiple linear regression analysis is to analyze relationships among multiple variables. The analysis is carried out through the estimation of a relationship $y = f(x_1, x_2, ..., x_k)$ and the results serve the following purposes:

1. Answer the question of how much $y$ changes with changes in each $x(x_1, x_2, ..., x_k)$, and
2. Predict the value of $y$ based on the $x$ values.

For this research, $x_1 = $ Month, $x_2 = $ Facility size and $x_3 = $ Flare stack height.

$y_1 = \delta$LST$_{fs-450mN}$ and $y_2 = \delta$LST$_{fs-450mE}$.

$x_1$, $x_2$, $x_3 = $ Predictor variables.

$y_1, y_2 = $ Response variables.

Each variable is standardized as shown in equations 8-10. Generally, the linear model for multiple regressions is:

$$y = bx$$  \hspace{1cm} (Eq. 7)

Where $b = $ Relative quantitative contribution of each $x$ predictor variable

Month = $[\text{month} - (\text{meanmonth})] ÷ \sigma_{\text{month}}$  \hspace{1cm} (Eq. 8)

Facility size = $[\text{facility size} - (\text{meanfacility size})] ÷ \sigma_{\text{facility size}}$  \hspace{1cm} (Eq. 9)

Flare stack height = $[\text{flare stack height} - (\text{meanflare stack height})] ÷ \sigma_{\text{stack height}}$  \hspace{1cm} (Eq. 10)

For this research, (Eq. 7) has become the following:

For $y_1$,

$$\delta$LST$_{fs-450mN} = b_0 + b_1 \times (\text{Month}) + b_2 \times (\text{Facility size}) + b_3 \times (\text{Flare stack height})$$  \hspace{1cm} (Eq. 11)
For $y_2,$
\[
\delta LST_{60-450mE} = b_0 + b_1 \times \text{(Month)} + b_2 \times \text{(Facility size)} + b_3 \times \text{(Flare stack height)} \quad \text{(Eq. 12)}
\]

Where,
\[b_0 = \text{constant.}\]

Results and Discussion

Landsat LST Retrieval and Computation of Change in LST as $\delta LST_{60-450m}$

LST’s for vegetation, soil, built up and water were determined for all the 11 sites examined (Eq.5). The computed changes in LST for vegetation ($\delta LST_{60-450m}$) (Eq. 6) in the N, E, S and W directions for 1990, 2000, 2010 and 2022 are presented in Tables 2-17.

**Table 2: ($\delta LST_{60-450m}$) (K) (North direction, 1990)**

<table>
<thead>
<tr>
<th>Site</th>
<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
<th>($\delta LST_{60-450m}$) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eleme Refinery I</td>
<td>317</td>
<td>284</td>
<td>33</td>
</tr>
<tr>
<td>Eleme Refinery II</td>
<td>320</td>
<td>286</td>
<td>34</td>
</tr>
<tr>
<td>Onne</td>
<td>317</td>
<td>274</td>
<td>43</td>
</tr>
<tr>
<td>Umurolu</td>
<td>318</td>
<td>290</td>
<td>28</td>
</tr>
<tr>
<td>Bonny LNG</td>
<td>358</td>
<td>301</td>
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<tr>
<td>Alua</td>
<td>350</td>
<td>304</td>
<td>46</td>
</tr>
<tr>
<td>Rukpokwu</td>
<td>334</td>
<td>298</td>
<td>36</td>
</tr>
<tr>
<td>Obigbo</td>
<td>337</td>
<td>307</td>
<td>30</td>
</tr>
<tr>
<td>Chokocho</td>
<td>345</td>
<td>305</td>
<td>40</td>
</tr>
<tr>
<td>Umudioga</td>
<td>319</td>
<td>290</td>
<td>29</td>
</tr>
<tr>
<td>Sara</td>
<td>333</td>
<td>300</td>
<td>33</td>
</tr>
</tbody>
</table>

**Table 3: ($\delta LST_{60-450m}$) (K) (East direction, 1990)**

<table>
<thead>
<tr>
<th>Site</th>
<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
<th>($\delta LST_{60-450m}$) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eleme Refinery I</td>
<td>324</td>
<td>286</td>
<td>38</td>
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<td>Eleme Refinery II</td>
<td>316</td>
<td>280</td>
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</tr>
<tr>
<td>Onne</td>
<td>320</td>
<td>286</td>
<td>34</td>
</tr>
<tr>
<td>Umurolu</td>
<td>308</td>
<td>287</td>
<td>21</td>
</tr>
<tr>
<td>Bonny LNG</td>
<td>322</td>
<td>289</td>
<td>33</td>
</tr>
<tr>
<td>Alua</td>
<td>343</td>
<td>311</td>
<td>32</td>
</tr>
<tr>
<td>Rukpokwu</td>
<td>313</td>
<td>280</td>
<td>33</td>
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<tr>
<td>Obigbo</td>
<td>330</td>
<td>300</td>
<td>30</td>
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<tr>
<td>Chokocho</td>
<td>323</td>
<td>287</td>
<td>36</td>
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<tr>
<td>Umudioga</td>
<td>312</td>
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</tr>
<tr>
<td>Sara</td>
<td>321</td>
<td>282</td>
<td>39</td>
</tr>
</tbody>
</table>

**Table 4: ($\delta LST_{60-450m}$) (K) (South direction, 1990)**

<table>
<thead>
<tr>
<th>Site</th>
<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
<th>($\delta LST_{60-450m}$) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eleme Refinery I</td>
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<td>Eleme Refinery II</td>
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<td>Umurolu</td>
<td>306</td>
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<td>33</td>
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<td>Umudioga</td>
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<tr>
<td>Sara</td>
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<td>281</td>
<td>32</td>
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</table>
Table 5: ($\Delta$LST$_{60-450m}$) (K) (West direction, 1990)

<table>
<thead>
<tr>
<th>Site</th>
<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
<th>($\Delta$LST$_{60-450m}$) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eleme Refinery I</td>
<td>310</td>
<td>275</td>
<td>35</td>
</tr>
<tr>
<td>Eleme Refinery II</td>
<td>328</td>
<td>283</td>
<td>45</td>
</tr>
<tr>
<td>Onne</td>
<td>308</td>
<td>265</td>
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<td>Umurolu</td>
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<td>Bonny LNG</td>
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</tr>
<tr>
<td>Sara</td>
<td>317</td>
<td>286</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 6: ($\Delta$LST$_{60-450m}$) (K) (North direction, 2000)

<table>
<thead>
<tr>
<th>Site</th>
<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
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<td>295</td>
<td>42</td>
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Table 7: ($\Delta$LST$_{60-450m}$) (K) (East direction, 2000)

<table>
<thead>
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<th>LST (K) at 60 m</th>
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<th>($\Delta$LST$_{60-450m}$) (K)</th>
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Table 8: ($\Delta$LST$_{60-450m}$) (K) (South direction, 2000)

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<th>LST (K) at 60 m</th>
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### Table 9: $(\delta LST_{60-450m})$ (K) (West direction, 2000)

<table>
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### Table 10: $(\delta LST_{60-450m})$ (K) (North direction, 2010)

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### Table 11: $(\delta LST_{60-450m})$ (K) (East direction, 2010)

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### Table 12: $(\delta LST_{60-450m})$ (K) (South direction, 2010)

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### Table 13: (\(\delta LST\)) (K) (West direction, 2010)

<table>
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<th>Site</th>
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### Table 14: (\(\delta LST\)) (K) (North direction, 2022)

<table>
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<th>LST (K) at 450 m</th>
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<td>Onne</td>
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<td>336</td>
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### Table 15: (\(\delta LST\)) (K) (East direction, 2022)

<table>
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<th>LST (K) at 450 m</th>
<th>((\delta LST)) (K)</th>
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<td>33</td>
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<tr>
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<td>Sara</td>
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### Table 16: (\(\delta LST\)) (K) (South direction, 2022)

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<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
<th>((\delta LST)) (K)</th>
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</table>
Morakinyo, et al., ... Evaluation of Factors Influencing Changes in Land Surface Temperature

Table 17: \( \delta \text{LST}_{60-450m} \) (K) (West direction, 2022)

<table>
<thead>
<tr>
<th>Site</th>
<th>LST (K) at 60 m</th>
<th>LST (K) at 450 m</th>
<th>( \delta \text{LST}_{60-450m} ) (K)</th>
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<td>344</td>
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</table>

Relationship between Factors that can Influence LST and \( \delta \text{LST}_{60-450m} \) in the North, East, South and West Directions

Analysis of ANOVA was used to obtain the results presented in Tables 18 and 19 which show the results of the first and second sets of the values of \( r \) and that of \( p \), and the correlation type that resulted from the relationship between each of the facility size, the flare stack height and the time, and \( \delta \text{LST}_{60-450m} \) in the N, E, S and W directions. The range of \( p \)-values and that of the \( \delta \text{LST}_{60-450m} \) obtained in the 4 cardinal directions are presented in Table 20. Furthermore, Figures 5-9 also show the graphical presentation of the results obtained from the relationship between each of the facility size, flare stack height, and time (Julian day, month and year) and that of \( \delta \text{LST}_{60-450m} \) in the N, E, S and W directions.

Table 18: First set of \( r \) and \( p \) values and their correlation type for the relationship between each of the factor considered and \( \delta \text{LST}_{60-450m} \) when \( \alpha = 0.01 \)

<table>
<thead>
<tr>
<th>Relationship</th>
<th>( r )-value</th>
<th>( p )-value</th>
<th>Correlation type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility size against ( \delta \text{LST}_{60-450m} )N</td>
<td>-0.191</td>
<td>3.390 \times 10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>Facility size against ( \delta \text{LST}_{60-450m} )E</td>
<td>-0.202</td>
<td>1.669 \times 10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>Facility size against ( \delta \text{LST}_{60-450m} )S</td>
<td>-0.180</td>
<td>9.979 \times 10^{-4}</td>
<td>-</td>
</tr>
<tr>
<td>Facility size against ( \delta \text{LST}_{60-450m} )W</td>
<td>-0.152</td>
<td>0.004</td>
<td>-</td>
</tr>
<tr>
<td>Flare stack height against ( \delta \text{LST}_{60-450m} )N</td>
<td>-0.121</td>
<td>0.055</td>
<td>-</td>
</tr>
<tr>
<td>Flare stack height against ( \delta \text{LST}_{60-450m} )E</td>
<td>-0.103</td>
<td>0.131</td>
<td>-</td>
</tr>
<tr>
<td>Flare stack height against ( \delta \text{LST}_{60-450m} )S</td>
<td>0.470</td>
<td>0.028</td>
<td>+</td>
</tr>
<tr>
<td>Flare stack height against ( \delta \text{LST}_{60-450m} )W</td>
<td>-0.162</td>
<td>0.012</td>
<td>-</td>
</tr>
<tr>
<td>Julian day against ( \delta \text{LST}_{60-450m} )N</td>
<td>0.071</td>
<td>0.225</td>
<td>+</td>
</tr>
<tr>
<td>Julian day against ( \delta \text{LST}_{60-450m} )E</td>
<td>0.122</td>
<td>0.029</td>
<td>+</td>
</tr>
<tr>
<td>Julian day against ( \delta \text{LST}_{60-450m} )S</td>
<td>0.101</td>
<td>0.064</td>
<td>+</td>
</tr>
<tr>
<td>Julian day against ( \delta \text{LST}_{60-450m} )W</td>
<td>0.073</td>
<td>0.166</td>
<td>+</td>
</tr>
<tr>
<td>Month against ( \delta \text{LST}_{60-450m} )N</td>
<td>0.071</td>
<td>0.190</td>
<td>+</td>
</tr>
<tr>
<td>Month against ( \delta \text{LST}_{60-450m} )E</td>
<td>0.123</td>
<td>0.025</td>
<td>+</td>
</tr>
<tr>
<td>Month against ( \delta \text{LST}_{60-450m} )S</td>
<td>0.104</td>
<td>0.061</td>
<td>+</td>
</tr>
<tr>
<td>Month against ( \delta \text{LST}_{60-450m} )W</td>
<td>0.081</td>
<td>0.150</td>
<td>+</td>
</tr>
<tr>
<td>Year against ( \delta \text{LST}_{60-450m} )N</td>
<td>0.003</td>
<td>0.958</td>
<td>+</td>
</tr>
<tr>
<td>Year against ( \delta \text{LST}_{60-450m} )E</td>
<td>-0.004</td>
<td>0.947</td>
<td>-</td>
</tr>
<tr>
<td>Year against ( \delta \text{LST}_{60-450m} )S</td>
<td>-0.009</td>
<td>0.875</td>
<td>-</td>
</tr>
<tr>
<td>Year against ( \delta \text{LST}_{60-450m} )W</td>
<td>0.032</td>
<td>0.552</td>
<td>+</td>
</tr>
</tbody>
</table>
Table 19: Second set of $r$ and $p$ values and their correlation type for the relationship between each of the factor considered and $(\delta LST_{60-450m})$ when $\alpha = 0.01$

<table>
<thead>
<tr>
<th>Relationship</th>
<th>r-value</th>
<th>p-value</th>
<th>Correlation type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility size against $(\delta LST_{60-450m})_N$</td>
<td>$-0.182$</td>
<td>$0.002$</td>
<td>$-$</td>
</tr>
<tr>
<td>Facility size against $(\delta LST_{60-450m})_E$</td>
<td>$-0.202$</td>
<td>$5.078 \times 10^{-4}$</td>
<td>$-$</td>
</tr>
<tr>
<td>Facility size against $(\delta LST_{60-450m})_S$</td>
<td>$-0.171$</td>
<td>$0.003$</td>
<td>$-$</td>
</tr>
<tr>
<td>Facility size against $(\delta LST_{60-450m})_W$</td>
<td>$-0.140$</td>
<td>$0.020$</td>
<td>$-$</td>
</tr>
<tr>
<td>Flare stack height against $(\delta LST_{60-450m})_N$</td>
<td>$-0.152$</td>
<td>$0.035$</td>
<td>$-$</td>
</tr>
<tr>
<td>Flare stack height against $(\delta LST_{60-450m})_E$</td>
<td>$-0.103$</td>
<td>$0.142$</td>
<td>$-$</td>
</tr>
<tr>
<td>Flare stack height against $(\delta LST_{60-450m})_S$</td>
<td>$-0.126$</td>
<td>$0.074$</td>
<td>$-$</td>
</tr>
<tr>
<td>Flare stack height against $(\delta LST_{60-450m})_W$</td>
<td>$-0.169$</td>
<td>$0.019$</td>
<td>$-$</td>
</tr>
<tr>
<td>Julian day against $(\delta LST_{60-450m})_N$</td>
<td>$0.101$</td>
<td>$0.088$</td>
<td>$+$</td>
</tr>
<tr>
<td>Julian day against $(\delta LST_{60-450m})_E$</td>
<td>$0.110$</td>
<td>$0.061$</td>
<td>$+$</td>
</tr>
<tr>
<td>Julian day against $(\delta LST_{60-450m})_S$</td>
<td>$0.113$</td>
<td>$0.050$</td>
<td>$+$</td>
</tr>
<tr>
<td>Julian day against $(\delta LST_{60-450m})_W$</td>
<td>$0.070$</td>
<td>$0.244$</td>
<td>$+$</td>
</tr>
<tr>
<td>Month against $(\delta LST_{60-450m})_N$</td>
<td>$0.105$</td>
<td>$0.078$</td>
<td>$+$</td>
</tr>
<tr>
<td>Month against $(\delta LST_{60-450m})_E$</td>
<td>$0.112$</td>
<td>$0.055$</td>
<td>$+$</td>
</tr>
<tr>
<td>Month against $(\delta LST_{60-450m})_S$</td>
<td>$0.115$</td>
<td>$0.047$</td>
<td>$+$</td>
</tr>
<tr>
<td>Month against $(\delta LST_{60-450m})_W$</td>
<td>$0.075$</td>
<td>$0.213$</td>
<td>$+$</td>
</tr>
<tr>
<td>Year against $(\delta LST_{60-450m})_N$</td>
<td>$-0.027$</td>
<td>$0.647$</td>
<td>$-$</td>
</tr>
<tr>
<td>Year against $(\delta LST_{60-450m})_E$</td>
<td>$-0.005$</td>
<td>$0.927$</td>
<td>$-$</td>
</tr>
<tr>
<td>Year against $(\delta LST_{60-450m})_S$</td>
<td>$-0.029$</td>
<td>$0.620$</td>
<td>$-$</td>
</tr>
<tr>
<td>Year against $(\delta LST_{60-450m})_W$</td>
<td>$0.043$</td>
<td>$0.479$</td>
<td>$+$</td>
</tr>
</tbody>
</table>

Table 20: Limit of $p$-values and that of $(\delta LST_{60-450m})$ (K)

<table>
<thead>
<tr>
<th>$(\delta LST_{60-450m})_N$</th>
<th>Limit of $p$-values</th>
<th>Limit of $(\delta LST_{60-450m})$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\delta LST_{60-450m})_E$</td>
<td>$\ll 0.00001-0.146$</td>
<td>$0.6-35.5 = 34.9$</td>
</tr>
<tr>
<td>$(\delta LST_{60-450m})_S$</td>
<td>$\ll 0.00001-0.127$</td>
<td>$0.9-36.7 = 35.8$</td>
</tr>
<tr>
<td>$(\delta LST_{60-450m})_W$</td>
<td>$\ll 0.00001-0.143$</td>
<td>$0.7-28.6 = 27.9$</td>
</tr>
<tr>
<td>$(\delta LST_{60-450m})_E$</td>
<td>$\ll 0.00001-0.146$</td>
<td>$0.7-32.0 = 31.3$</td>
</tr>
</tbody>
</table>

Multiple Linear Regression Analysis

The $r^2$, $p$-value, $b_0$, $b_1$, $b_2$ and $b_3$ results obtained from (Eq. 11) are:

$r^2 = 0.05; p = 0.016$;

$b_0 = \sim 0; b_1 = 0.09; b_2 = -0.146; b_3 = -0.103$.

Similarly, (Eq. 12) gives the following results,

$r^2 = 0.05; p = 0.011$;

$b_0 = \sim 0; b_1 = 0.069; b_2 = -0.195; b_3 = -0.053$. 
Figure 5: Facility size: Upper left) $\Delta (\text{LST}_{60-450m})_N$; Lower left) $\Delta (\text{LST}_{60-450m})_E$; Upper right) $\Delta (\text{LST}_{60-450m})_S$; Lower right) $\Delta (\text{LST}_{60-450m})_W$

Figure 6: Flare stack height: Upper left) $\Delta (\text{LST}_{60-450m})_N$; Lower left) $\Delta (\text{LST}_{60-450m})_E$; Upper right) $\Delta (\text{LST}_{60-450m})_S$; Lower right) $\Delta (\text{LST}_{60-450m})_W$
Figure 7: Julian day: Upper left) $v(\Delta LST_{60-450m})_N$; Lower left) $v(\Delta LST_{60-450m})_E$; Upper right) $v(\Delta LST_{60-450m})_S$; Lower right) $v(\Delta LST_{60-450m})_W$

Figure 8: Month: Upper left) $v(\Delta LST_{60-450m})_N$; Lower left) $v(\Delta LST_{60-450m})_E$; Upper right) $v(\Delta LST_{60-450m})_S$; Lower right) $v(\Delta LST_{60-450m})_W$
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The changes in vegetation LST ($\delta$LST$_{60-450m}$) (K) obtained for the study (Table 2-17) varies. This suggests that some factors are responsible for it, among which are the volumes and rates of the burning gas, vegetation type and density, time of satellite overpass etc. However, data on both the volumes and the rate of the burning gas are not available; and so their impacts on the results could not be accounted for.

In Tables 18 and 19, all relationships with significant impact are shown in bold. Table 20 show the range of p-values, and that of ($\delta$LST$_{60-450m}$) (K) in the N, E, S and W directions. The results obtained from the relationship of each of the factor considered with ($\delta$LST$_{60-450m}$) in the 4 cardinal directions are presented in Figures 5-9. For Figures 5, 7, 8 and 9, the colour bar represents the flare stack height but for Figure 6, the colour bar is representing the facility number.

In Table 18, the relationship between the facility size and each of the ($\delta$LST$_{60-450m}$)$_N$, ($\delta$LST$_{60-450m}$)$_E$, ($\delta$LST$_{60-450m}$)$_S$ and ($\delta$LST$_{60-450m}$)$_W$ give statistically significant results but negative correlation. For the flare stack height and each of the ($\delta$LST$_{60-450m}$)$_N$, ($\delta$LST$_{60-450m}$)$_E$ and ($\delta$LST$_{60-450m}$)$_W$, the relationship show negative correlation except ($\delta$LST$_{60-450m}$)$_S$ that show positive correlation. The p-values recorded show that only the relationship between the flare stack height and the ($\delta$LST$_{60-450m}$)$_W$ give statistically significant result. For Julian day, and each of the ($\delta$LST$_{60-450m}$)$_N$, ($\delta$LST$_{60-450m}$)$_E$, ($\delta$LST$_{60-450m}$)$_S$ and ($\delta$LST$_{60-450m}$)$_W$, statistically insignificant results and positive correlation were recorded. Furthermore, the relationship between Month and the ($\delta$LST$_{60-450m}$)$_N$, ($\delta$LST$_{60-450m}$)$_E$, ($\delta$LST$_{60-450m}$)$_S$ and ($\delta$LST$_{60-450m}$)$_W$ give statistically insignificant results but positive correlation. Finally, results obtained from the relationship between Year and each of the ($\delta$LST$_{60-450m}$)$_N$ and the ($\delta$LST$_{60-450m}$)$_W$ show positive correlation. However, the relationship between Year and ($\delta$LST$_{60-450m}$)$_E$ and ($\delta$LST$_{60-450m}$)$_S$ show negative correlation. All relationships give statistically insignificant results. The results presented in Table 19, is similar to that of Table 18 except the relationship between the flare stack height and the ($\delta$LST$_{60-450m}$)$_S$, and Year and ($\delta$LST$_{60-450m}$)$_N$ that show negative correlation. In Table 20, East direction show the highest value of 35.8 K, followed by North with 34.9 K, and the West has 31.3 K. The South direction recorded the lowest value of 27.9 K which
suggests that the effect of the South prevailing wind in the Niger Delta (Morakinyo et al., 2022) could be the reason for the results. The wind blew from the South, directed more towards the East direction, followed by the North and the West directions.

From the multiple linear regression analysis, the \( r^2 = 0.05 \) obtained from (Eq. 11 and Eq. 12) show that only 5% of the variability in the \((\delta \text{LST}_{60-450m})_N\) and the \((\delta \text{LST}_{60-450m})_E\) were explained by the variables examined; and are accounted for in the resulting relationship. Vegetation density, vegetation types, volume of the burning gas, rate of the burning gas etc are some of the factors that would account for the unexplained variability.

The impact of the 3 available variables considered on the change in the LST \((\delta \text{LST}_{60-450m})\) retrieved at the 11 flaring sites in Nigeria have been assessed. Facility size in the N, E, S and W directions, and height of the flare stack in the West direction gives significant results. However, their correlation is negative. Firstly, the 2 largest facilities are Umurolu (4 flare stacks) and Bonny LNG (5 flare stacks) with inland and coastal sites respectively show similar results. This suggests that the facility size and the number of flare stack on each facility contributed to the results. Secondly, the medium and small sizes inland flow stations investigated are Alua, Rukpokwu, Obigbo and Chokocho. The acquired results show that the impact of the facility size on \((\delta \text{LST}_{60-450m})\) is statistically significant, which suggest that the volume of the burning gas is large, and the rate at which the gas is burning is quite high at these facilities. Sara is a coastal oil well facility with limited size, rough terrain, and connected with several pipes. However, the enormity of the recorded \((\delta \text{LST}_{60-450m})\) suggested that the oil well is performing at a high capacity with large volume and high rate of the burning gas. Eleme I and II refineries are large facilities with one flare stack at each refinery; and their results show a non-significant impact. This suggests that the effect of a single flare stack at both refineries, and damaged to them in 1988 has affected the results. Since 1988, their usage and production capacity has been reduced to between (15-25%) (Ogbuigwe, 2018). Furthermore, the results from the multiple linear regression analysis also supported the ANOVA results by showing that the facility size may exert a negative influence on \((\delta \text{LST}_{60-450m})\). However, the overall percentage of variability explained by the 3 variables is low.

**Conclusion**

Landsat data used for this study covered a period of 38 years, which is good enough to give reliable indisputable results. From the pairwise linear regression analysis, the research showed that the facility size in the N, E, S and W directions, and the flare stack height in the West direction have significant results on the \((\delta \text{LST}_{60-450m})\). Also, the results from multiple regression analysis show that \( r^2 = 0.05 \). From these results, it can be concluded that the facility size, flare stack height and time contributed only 5% to the \((\delta \text{LST}_{60-450m})\). Major limitations encountered in this research include lack of data on the volume and the rate of the burning gas. This requires further research to enable the author to draw firm conclusions about what exactly drives \((\delta \text{LST}_{60-450m})\). Hence, the following recommendations are made: The enforcement of the multinational oil companies in Nigeria to release information on all activities regarding oil and gas exploration and exploitation to the general public especially to the stakeholders, organizations, educational and research institutions involved in the oil and gas business through appropriate and standard policies must be carried out by the Nigerian Government. Finally, the insecurity issue in Nigeria is a very big challenge that hinders accessibility to the oil and gas facilities; and also causes vandalism of these facilities. Nigerian Government needs to find a lasting solution to this problem in order to have a safe and peaceful country.
References
Google Earth (2022). Location of Rivers State in the Niger Delta, Nigeria; and the 11 flaring sites studied in Rivers State, Nigeria.


