

Contributions of gas flaring to a global air pollution hotspot: spatial and temporal variations, impacts and alleviation

*Obinna C.D. Anejionu¹, J. Duncan Whyatt¹, G. Alan Blackburn¹ and Catheryn S. Price²

¹Lancaster Environment Centre, Gordon Manley Building,
Lancaster University, Lancaster. United Kingdom, LA1 4YQ

²Cambridge Environmental Research Consultants (CERC)
Cambridge, United Kingdom, CB2 1SJ

Abstract

Studies of environmental impacts of gas flaring in the Niger Delta are hindered by limited access to official flaring emissions records and a paucity of reliable ambient monitoring data. This study uses a combination of geospatial technologies and dispersion modelling techniques to evaluate air pollution impacts of gas flaring on human health and natural ecosystems in the region. Results indicate that gas flaring is a major contributor to air pollution across the region, with concentrations exceeding WHO limits in some locations over certain time periods. Due to the predominant south-westerly wind, concentrations are higher in some states with little flaring activity than in others with significant flaring activity. Twenty million people inhabit areas of high flare-associated air pollution, which include all of the main ecological zones of the region, indicating that flaring poses a substantial threat to human health and the environment. Model scenarios demonstrated that substantial reductions in pollution could be achieved by stopping flaring at a small number of the most active sites and by improving overall flaring efficiency.

Keywords: Gas Flares, Remote Sensing, Dispersion Modelling, Health Impacts, Environmental Impacts, Niger Delta

31

32 **1. Introduction**

33 A large proportion of Nigeria's oil facilities were developed in the early 1960s and 1970s in
34 response to increased international demand for oil (Rotty, 1974). Gas was not a popular
35 energy source at the time and environmental standards were not as stringent as they are today
36 (Kuranga, 2002 cited in Abdulkareem, 2005a; OGP, 2000), consequently most of the excess
37 gas associated with crude oil production was removed through the process of flaring (Figure
38 1). This combustion process has been going on for almost six decades in Nigeria, hence its
39 global recognition as a prominent flaring nation (Elvidge *et al*, 2009).

40 As there was little local awareness of the environmental impacts of gas flaring in the
41 1960s and because flaring technology was in its infancy, flaring efficiencies were low relative
42 to modern day standards (Leahey *et al.*, 2001; OGP, 2000) with large volumes of gas flared at
43 flow stations (where oil from different wells is initially gathered) and in refineries on an
44 almost continuous basis (Marais *et al.*, 2014). Although it is generally assumed that flares
45 attain high flaring efficiency, producing only non-toxic carbon dioxide (CO₂) and water, in
46 reality, combustion is incomplete and harmful by-products such as sulphur dioxide (SO₂),
47 nitrogen oxides (NO_x), hydrogen sulphide (H₂S), volatile organic compounds (VOC), total
48 hydrocarbons, heavy metals and particulates are released into the environment (Johnson and
49 Coderre, 2012; Abdulkareem, 2005a). Generally, flares are thought to operate at an average
50 efficiency of 68% ±7% (Leahey *et al.*, 2001).

51 **[Insert] Figure 1.** Open ground flare at Rumuekpe, Rivers State, surrounded by farmland (Ezeamalu, 2014).
52

53 The dangers posed by prolonged and continuous flaring have been a source of concern
54 to the inhabitants of the Niger Delta. Reported impacts include increased concentrations of
55 airborne pollutants, reduced agricultural yields, acidification of soils and rainwater, decreased
56 plant flowering and fruiting, corrosion of metal roofs, heat stress, deformities in children,

57 decreased lung function and damage, and skin problems (Ismail and Umukoro, 2012). These
58 impacts have prompted numerous studies as documented by Anejionu (2014).

59 Despite documented negative impacts of air pollution in the region (Tawari and
60 Abowei, 2012; Nwachukwu *et al.*, 2012), there is a paucity of information on the magnitude
61 and extent of air pollution associated with such activities due to weak government regulation
62 and enforcement of environmental standards (Ismail and Umukoro, 2012). This necessitates
63 the requirement for modelling studies to assess the air pollution impacts of gas flaring on the
64 surrounding environment.

65 Atmospheric dispersion models are commonly used to simulate pollution levels and
66 confirm the ambient concentrations. They can also be used to quantify impacts from
67 individual sources and test scenarios (U.S. EPA, 2011). This study incorporates remotely-
68 sensed estimates of emissions from gas flaring in a conventional dispersion model in order to
69 assess the likely air pollution impacts across the Niger Delta over an extended time period.

70 The objectives are as follows:

- 71 i. use remotely-sensed inputs to parameterise a conventional atmospheric dispersion
72 model to simulate the flaring process and model the dispersion of pollutants;
- 73 ii. use the model to determine how the magnitude and extent of pollution linked to
74 flaring activity have varied over time (including comparisons with established
75 environmental standards);
- 76 iii. investigate the contributions from different source sectors (onshore/offshore) and
77 states;
- 78 iv. identify candidate sources for emission reduction;

79 **2. Study Area**

80 The Niger Delta is at the centre of oil and gas exploration in Nigeria. In addition, it provides
81 the natural habitat for a wide variety of endemic coastal and estuarine fauna and flora,
82 supporting over 60% of the total species in Nigeria (Anejionu *et al.*, 2015b). It is therefore

83 ranked as one of the highest conservation priorities in West Africa (IUCN, 1994). The region
84 is very humid with average ambient temperatures ranging from 21⁰C to 35⁰C. It generally
85 experiences light south-westerly winds ranging from 1.6m/s to 5.4m/s for most of the year,
86 due to its proximity to the Atlantic Ocean; although during the few dry months of Harmattan
87 (late November to early February), some north-easterly winds are recorded (Marais *et al.*,
88 2014; Odu, 1994).

89 **3. Methodology**

90 The methodology adopted in this study involves the calculation of emission rates from
91 volume flow rates (estimated from flaring sites detected on satellite images), the use of a
92 conventional atmospheric dispersion model to incorporate flare sources (see section 3.3.2)
93 and consequent verification and modelling of the pollutant concentrations for multiple
94 sources and time periods.

95 ***3.1 Modelling system description***

96 The Atmospheric Dispersion Modelling System (ADMS) comprises a robust group of models
97 developed by Cambridge Environmental Research Consultants (CERC) to simulate
98 dispersion of pollutants from industrial, road, domestic and other sources. ADMS-Urban,
99 used in this research, models emissions from point, line and area sources over large urban
100 areas (CERC, 2011). It has become an integral part of air quality management in the United
101 Kingdom (Arciszewska and McClatchey, 2001) and has been employed in a number of
102 studies including exposure from traffic pollution and more general air quality assessment
103 (Davies and Whyatt, 2014, Abdul-Raheem and Adekola, 2013). It has however not been
104 previously used in combination with remotely-sensed information to model the impact of gas
105 flares.

106

107 3.2 Data

108 3.2.1 Flare volume flow rate

109 The volume flow rates used to derive emission rates for each pollutant were obtained from
110 previous research by Anejionu *et al.* (2015a), who developed techniques to detect active
111 flaring sites and estimate the volume of gas flared from each site from Moderate Resolution
112 Imaging Spectroradiometer (MODIS) satellite imagery (Figure 2). The MODIS Flare
113 Detection Technique (MODET) was developed to detect active flare sites, while the MODIS
114 Volume Estimation Technique (MOVET) was used to estimate the annual quantity of gas
115 flared from individual flare sites based on radiation detected from such sites. These
116 techniques were used to determine the location of active flare sites and volume flow rates
117 included in the modelled assessment.

118
119 **[Insert] Figure 2.** The total volume of gas combusted at individual flare sites in the Niger Delta (2000-2014),
120 reproduced from Anejionu *et al.*, (2015a).

121 3.2.2. Meteorological data

122 Historic meteorological data (wind speed, wind direction, ambient temperature and cloud
123 cover) were obtained from a weather data archive (Weather Underground, 2013). Given the
124 limited hourly meteorological data for Port Harcourt and other weather stations in the region,
125 hourly data for a neighbouring country (Malabo, Equatorial Guinea) in the Atlantic Ocean
126 (Figure 2), were utilised. The hourly data did not include rainfall amount, hence, mean
127 monthly rainfall values and rainfall days for the Niger Delta (Climate Charts, 2010;
128 Norwegian Meteorological Institute, 2014) were used to compute hourly rainfall values for
129 each month.

130 3.2.3 Emission factors

131 There are practical challenges in obtaining accurate estimates of emissions associated with
132 flaring (OAQPS, 1984; Backshall, 2013). As a result, predetermined emission factors are

133 typically used to compute emission rates for flares. The emission factors relate the quantity of
134 a pollutant released with an activity associated with the release of that pollutant (e.g. amount
135 of gas flared per unit time) (U.S. EPA, 2014a). The emission factors adopted in the study
136 (Table 1) were established by the UK Department of Energy and Climate Change (EEMS,
137 2008) and are similar to those recommended by the Exploration and Production Forum (E&P
138 Forum, 1994).

139 **[Insert] Table 1.** Emission factors used in the modelling. The units for the emission factors are ‘mass of
140 pollutant per unit mass of flared gas’. (Source: EEMS, 2008; E&P Forum, 1994).
141

142 **3.3 Methods**

143 *3.3.1 Computing gas flare emission rates*

144 The following equation for estimating emission rates taken from OAQPS (1995) and Ontario
145 (2007) was used to calculate pollutant emissions:

$$146 \quad E = A * EF * \left(1 - \frac{ER}{100}\right) \quad (1)$$

147 Where: E is the emission rate of a pollutant (g/s), A is the activity rate (g/s) which is the
148 mass of gas flared, EF is emission factor of a pollutant, and ER is the overall emission
149 reduction efficiency (flaring efficiency in %). Flaring efficiency of 75% was assumed for
150 flares in the Niger Delta based on findings of earlier studies (Leahey *et al.*, 2001; Sawaragi
151 and Akashi, 1978 cited in Abdulkareem, 2005a). Ismail and Umukoro (2012) stated that “on
152 a casual observation of the flares in the Niger Delta one sees that they are sooty and evidently
153 burn at low efficiency.” Flaring efficiency is thus used in this context as a primary measure of
154 the overall performance of the flare systems and not necessarily as the combustion efficiency,
155 which relates to the percentage of the natural gas that is completely oxidized to CO₂ and
156 water (US. EPA, 1983).

157 The volume of gas flared (in m³/year) from each flare site was estimated from remote
158 sensing (Anejionu *et al.*, 2015a). This was converted to a mass flow rate (g/s) assuming that

159 the flared gas has the density of methane (the dominant component of the gas extracted in the
160 Niger Delta (Isichei and Sanford, 1976).

161 3.3.2 Computation of effective diameter and height

162 Gas is typically flared from stacks of fixed height and diameter, however actual combustion
163 occurs beyond the tip of the flare stacks (Figure 3). As a result, flare stack parameters such as
164 effective height and diameter are calculated to account for this.

165 Effective stack height is calculated as the sum of the stack height and the height of the
166 flame above the stack exit point to the flame tip. The effective diameter is derived from the
167 flare buoyancy flux. To compute the effective height (H_{eff}) and effective diameter (D_{eff}),
168 various factors such as heat release are required to compute flame buoyancy and height
169 increase (see section 3.3.2.1 for details).

170 **[Insert] Figure 3.** Effective stack height and diameter (Price, 2013).
171

172 3.3.2.1. Details of computation of flaring parameters

173

174 Heat released was computed using the following expression (San Joaquin Valley APCD,
175 2014).

$$176 \quad Q = (W / 3.6) * \sum w_i q_i \quad (2)$$

177 Where: Q is heat released per hour (kW), W is gas flow rate (kg/hr), w_i is mass fraction
178 of component i, and q_i is heating value of gas component i (MJ/kg). The methane heating
179 value of 55.53MJ/kg was used.

180 The heat released was further converted from kW to J/s, and the net heat released in J/s
181 (Q_n) computed by assuming a 25% heat loss (recommended as default) by Ontario Ministry
182 of Environment (2003) using:

$$183 \quad Q_n = (75/100) * Q_j \quad (3)$$

184 The height increase (Δh) was computed using the following equation:

185 $\Delta h = 0.00456 \times (Q_c)^{0.478}$ (Ontario Ministry of the Environment, 2003) (4)

186 Where Q_c is the net heat release in units of calories/s.

187 Subsequently, the effective height (H_{eff}) is computed as:

188 $H_{eff} = H + \Delta h$ (5)

189 Where H is the measured stack height.

190 The flare buoyancy flux (F_b) in turn was computed using the following expression:

191
$$F_b = \frac{g * Q_n}{\pi * \rho * T_a * C_p}$$
 (6)

192 Where g is acceleration due to gravity (m/s^2), ρ is air density (kg/m^3), T_a is air
 193 temperature (K) and C_p is the specific heat of dry air ($J/(kg K)$). The flare buoyancy flux was
 194 subsequently used to compute the effective diameter (D_{eff}), using the following expression:

195
$$D_{eff} = \left(\frac{2 \left(F_b \left(\frac{T_f}{(T_f - T_a)} \right) \right)^{1.96}}{(gv)^{0.5}} \right)$$
 (7)

197

198 Where T_f = flare exit temperature and v = the stack exit velocity. Flare exit temperature of
 199 1,273 K (1000° C), which matches those in the region (Abdulkareem, 2005a) and exit
 200 velocity of 20m/s (U.S EPA, 1995; Ontario Ministry of Environment, 2003) was used.

201 *3.3.3 Pollutant concentration verification*

202 As noted by Marais *et al.* (2014), there is a paucity of monitored air pollution data for the
 203 Niger Delta. However, we were able to use a spatially and temporally limited set of ambient
 204 monitoring data (Osuji and Avwri, 2005) for the purposes of model verification. The
 205 monitoring sites were used as receptors, and modelled concentrations were compared to
 206 observed concentrations at each site.

207 The model input and setup were initially verified for a single source (flare) using lower,
208 central and upper volume estimates from the MODIS volume estimation technique
209 (Anejionu, 2015a). The resulting concentration profiles were similar to those reported by
210 Abdulkareem (2005b), with peak concentrations occurring 500m – 600m downwind of the
211 source (Supplementary Figure 1). Subsequently, the verification was extended to other sites
212 within the region.

213 A binary validation matrix was computed and Factor-2 analysis conducted
214 (Supplementary Tables 1 and 2). In addition, a semi-quantitative approach using data from
215 the satellite-based Scanning Imaging Absorption Spectrometer for Atmospheric Cartography
216 (SCIAMACHY) was used to guide the verification process. This semi-quantitative approach,
217 which effectively indicated an upper limit for the modelled estimates was used in conjunction
218 with the Factor-2 matrix to select the most appropriate modelling parameters including
219 volume flow rates (low, medium and high estimates) and background ozone concentration
220 (Vingarzan, 2004). Marais *et al.*, (2014) similarly used satellite (including SCIAMACHY)
221 and aircraft observations of atmospheric and tropospheric column-integrated concentrations
222 to verify atmospheric composition over Nigeria produced by a chemical transport model.
223 Consequently, lower estimates of flaring volumes were used with a background ozone
224 concentration of $10\mu\text{g}/\text{m}^3$ in the modelling (see Supplementary Tables 1 & 2).

225 3.3.4 Modelling gas flare pollutant concentrations

226 Having verified the method and determined the relevant model parameters ADMS-Urban was
227 used to model the dispersion of flare-related pollutants (NO_2 , SO_2 , CO and O_3) across the
228 Niger Delta for the period 2000 to 2013 inclusive. To establish a baseline for the modelling,
229 various scenarios representing typical and possible conditions in the region were simulated.
230 About half of the flares in the region are thought to be ground flares (open and horizontally-
231 directed flares lying about 1.5m above the ground – Figure 1) with the remainder thought to
232 be short stacks (10m above the ground) (Dung *et al.*, 2008; Isichei and Sanford, 1976). As

233 we have no official information on flare locations and heights, sensitivity to model stack
234 height was tested by assuming all flares were ground-based in one scenario and released from
235 15m stacks in another. Pollutant concentrations across the region did not vary significantly
236 between scenarios (about $1\mu\text{g}/\text{m}^3$ difference) hence a height of 10m was adopted for all the
237 flares included in the study.

238 A variable surface roughness file was implemented to account for onshore and offshore
239 environments with values of 0.3m and 0.001m adopted for land and sea areas accordingly.
240 Chemical reactions between the primary pollutants and the atmosphere were modelled to
241 obtain secondary pollutants NO_2 and O_3 from NO_x and VOC. Wet and dry deposition was
242 also modelled.

243 *3.3.5 Spatial modelling and analysis of pollutant concentration*

244 The results of the modelling were incorporated within a Geographical Information System
245 (GIS). This enabled pollution estimates to be integrated with other spatial data for the region
246 including flare locations, state boundaries, ecological zones and population data. The GIS
247 also facilitated the investigation of contributions from onshore and offshore flares, as well as
248 individual states. WHO Air Quality Limits (Table 2) were used to delineate areas of risk.

249 **[Insert] Table 2.** Selected Annual Mean Air Quality Standards (U.S EPA, 2014B; WHO 2005; CERC,
250 2011).

251
252

253 **4. Results**

254 Figure 4 illustrates the spatial distribution of modelled pollutant concentrations across the
255 Niger Delta region for the representative year 2000. This year was chosen because emissions
256 in 2000 were higher than present day levels but lower than those experienced in 2005 and
257 2006. Results are presented for NO_2 and O_3 since these are key pollutants that affect human
258 and plant health. Other pollutants showed similar overall patterns of dispersion.

259 **[Insert] Figure 4.** Modelled annual mean NO_2 concentrations from flares operating in the Niger Delta in 2000.
260 Active flare sites are also shown.
261

262 States with few (Imo and Abia) or no (Enugu and Cross River) active flare sites
263 experienced higher levels of pollution than states containing multiple active flare sites
264 (Bayelsa, Rivers and Delta) due to the predominant south-westerly wind in the region. Imo,
265 Akwa Ibom, Abia and some parts of Rivers State experienced the highest levels of pollution
266 overall with annual mean concentrations of NO₂ and O₃ exceeding WHO annual limits (Table
267 2) in some years (Figure 5). Limits for other pollutants such as CO and SO₂ were not
268 exceeded.

269 Figure 5 illustrates mean NO₂ concentration across the region for the period 2001-2013.
270 Concentrations (of all pollutants) increase to a peak in 2005/2006 before declining to the
271 present day. This trend is consistent with crude oil production in Nigeria over this period and
272 with increased gas flaring noted by Anejionu *et al.*, (2014, 2015a). These findings are
273 consistent with statements from the oil and gas companies in the region regarding reduced
274 flaring activities (SPDC, 2013).

275 **[Insert] Figure 5.** Modelled time series of annual mean NO₂ concentrations across the Niger Delta (2000 –
276 2013). Areas of highest concentration exceed the WHO limit of 40 µg m⁻³
277

278 Separate models containing only flares from onshore and offshore sources were run in
279 order to determine relative and absolute contributions on a state-by-state basis. The results
280 reveal that the majority of air pollution is generated by onshore sources (Figure 6) and that
281 the impact of offshore flares is negligible. However, a significant (>30%) proportion of air
282 pollution received by Akwa Ibom State and to a lesser extent the coastal areas of Bayelsa and
283 Delta States, originates from offshore sources, because a lot of flaring activity takes place just
284 off the coast of Akwa Ibom (Figure 2).

285 **[Insert] Figure 6.** Modelled annual mean NO₂ concentration across the Niger Delta in 2000 revealing specific
286 pollution contributions from offshore and onshore source sectors. Note: The sum of source sector contributions
287 does not equate to modelled total concentration (all flares) due to non-linearities in the NO₂ chemistry.
288

289 In order to determine inter-state contributions to pollutant concentrations across the
290 region, the model was run 8 times using emissions from each flaring state in turn. The

291 concentrations produced from each run were aggregated for each receiving state and
292 statistically summarised. The resulting 'blame matrix' for NO₂ is shown in Table 3. Analysis
293 of the 'blame matrix' revealed Rivers State to be the largest single contributor to air pollution
294 in many states, exporting more pollution to Abia, Imo and Akwa Ibom, than it generated
295 locally. Other states, which are not officially classed as oil-producing, such as Enugu,
296 Anambra, Cross River and Ebonyi, also experienced high concentrations. Approximately 20
297 million people live in the towns and cities of these densely populated states (NPC, 2010) and
298 are exposed to high levels of pollution from sources beyond their immediate control.

299 **[Insert] Table 3.** Blame matrix using mean NO₂ concentration (µg/m³) for the year 2000 data to
300 illustrate the pollutant contribution of individual states on neighbours.
301

302 Figure 7 illustrates the potential impact of air pollution on major population centres in
303 and around the Niger Delta in addition to impacts on vegetation and ecosystems. Major towns
304 and cities such as Enugu, Aba and Calabar all experienced high levels of pollution in
305 2005/06, while others such as Port Harcourt, Benin City and Warri experienced much lower
306 levels in comparison. Elevated ozone levels were found across the Niger Delta, suggesting
307 significant harmful impacts on plants in all ecological zones (Figure 7c and Table 4). The
308 rainforest was found to be the most susceptible to damage with 51% of this zone being
309 exposed to high ozone levels (Table 4). This is important not only for the natural ecosystem,
310 but because the majority of farming in the region is carried out within this zone, implying
311 strong negative impacts on biodiversity and agriculture. The freshwater swamp, mangrove
312 and savannah zones were also heavily impacted by secondary pollutants, with moderate or
313 high ozone levels being experienced over 58%, 33% and 43% of their areas, respectively.

314 **[Insert] Table 4.** Modelled impacts (km²) of ozone on main ecological zones in the Niger Delta in 2005.
315

316 **[Insert] Figure 7.** Modelled impacts of NO₂ and O₃ on human health and natural ecosystems. Maps show: (a)
317 NO₂ concentration (b) NO₂ concentration in relation to underlying population (c) O₃ concentration and (d) O₃
318 concentration in relation to underlying ecological zones. 2005 results were used in this case to illustrate
319 maximum impact.

320 Figure 8 illustrates the spatial distribution of pollutant deposition. In contrast to the
321 dispersion of gases such as NO₂, patterns of wet and dry deposition are much more localised
322 within the main flaring areas.

323 **[Insert] Figure 8.** Map showing annual rates of total (wet + dry) deposition across the Niger Delta, 2000.
324

325 To understand the extent to which present day levels of air pollution could be reduced
326 further in the region the model was re-run using 2013 sources with assumed flaring
327 efficiencies of 85% and 95% respectively. The results are summarised in Table 5.

328 **[Insert] Table 5.** Statistical summary of pollution surfaces obtained using different flaring
329 efficiencies tested based on 2013 emissions ($\mu\text{g}/\text{m}^3$). Percentage improvements were obtained by
330 subtracting the pollutant concentrations for 95% efficiency from the corresponding 75% efficiency,
331 and using the difference to calculate percentage improvement from 75% concentration levels.
332

333 5. Discussion

334 In this study, the gas flaring process was implemented within a conventional dispersion
335 model using emission estimates derived from remotely-sensed imagery. The results suggest
336 that gas flaring remains a major contributor to air pollution across the region with states
337 containing few or no active flare sites often experiencing higher levels of pollution than states
338 actively involved in the flaring process (Figures 4 and 7). This large dispersion range may be
339 explained by the high momentum and buoyancy of the flare plumes. This is important
340 because prior to this finding, it has always been assumed that the effects of gas flaring were
341 highly localised in nature (Ovri and Iroh, 2013; Dung *et al.*, 2008; Isichei and Sanford, 1976).
342 Consequently, fiscal intervention and compensation from the Federal Government of Nigeria
343 to cushion the effects of environmental degradation resulting from oil exploration activities
344 such as gas flaring has not been extended to the non-oil-producing states. The findings from
345 this research provide clear evidence justifying the need for the revision of such compensatory
346 policies.

347 The pollution risk maps (Figure 5) revealed that major towns and cities located some
348 distance from major flaring activity have experienced pollutant levels in excess of WHO

349 limits, while towns in prominent flaring states, have experienced much lower levels in
350 comparison. It should, however, be noted that although some major cities (Warri and Benin
351 City) were found not to be among the very high risk areas, pollution from other sources
352 (transport and industry) could lead to exceedance of WHO limits. Analysis of the modelled
353 deposition (Figure 8) revealed that Rivers State was at the greatest risk of acid deposition,
354 followed by Akwa Ibom. This corroborates previous studies, where rainwater was found to
355 be acidic around flaring locations (Ovri and Iroh, 2013; Ekpoh and Obia, 2010, Nduka *et al.*,
356 2008).)

357 Analyses of results obtained from a model scenario of increasing flaring efficiency
358 (Table 5), based on simple treatment of emissions (Equation 1), suggest that significant
359 improvements in air quality could be achieved by increasing the flaring efficiency of sites in
360 the region. Even at 85% flaring efficiency, no part of the region would experience pollution
361 levels exceeding the WHO standards.

362 The results obtained from modelling a hypothetical scenario in which emissions were
363 suppressed at some of the most active flaring sites in the region revealed that the proportion
364 of pollution generated by these flares was relatively high compared to that generated by the
365 remaining flares in the region (Table 6) with 27% of the pollution in the study area (and
366 much higher proportions in some states) generated by only 14 out of the 103 active flares.
367 This suggests that air quality in the Niger Delta could be improved further through targeted
368 interventions of selected sources.

369 **[Insert] Table 6.** The impact of suppressing emissions from the 14 largest flaring sites in the region (2013).
370 Note: the sum of concentrations from the 14 largest sites and the other sites does not equate to corresponding
371 modelled concentrations for all flares due to non-linearities in the NO₂ chemistry
372

373 Whilst the outcomes of this research cast an interesting light on the environmental
374 impacts of gas flaring in the Niger Delta, it should be acknowledged that the results presented
375 are illustrative as opposed to definitive, with large uncertainty bounds. In this study we had
376 limited access to hourly meteorological data from the region, no reliable information on

377 emission rates, limited information on flare stack heights and limited ambient monitoring
378 data for verification purposes. Despite these limitations, which may affect the absolute
379 accuracy of our results, this study does provide important insights into the impacts of flaring
380 on local and regional air pollution. It has shown the value of combining flaring volume
381 estimates from remotely-sensed data with emission factors to generate credible emission rates
382 that can be employed in a dispersion model. Given the lack of official information on
383 pollutant concentrations in the region, these model estimates are invaluable. We expect that
384 our results will serve as a guide to researchers, who now have some empirical basis with
385 which to underpin their observations of flaring impacts. It may also catalyse the release of
386 monitored data by multinational companies operating in the region and prompt further
387 research. The results may also result in policy changes, as state governments in the high risk
388 areas who are not receiving commensurate compensations from the Federal Government
389 could base their arguments on the findings of this research. It is also our expectation that
390 techniques developed in the research will play significant role in the future monitoring and
391 management of air quality in the Niger Delta. Based on the modelled time-series, we have
392 shown that pollutant concentrations are now declining across the region as flaring activities
393 are reduced, but we have also demonstrated that further improvements in air quality can be
394 achieved through the adoption of more efficient flaring technologies.

395

396 **6. Conclusion**

397 This research pioneered the use of emission information derived from remotely-sensed data
398 in estimating air pollution linked to gas flaring in the region. The results indicate the likely
399 magnitude and extent of pollution across the region associated with the gas flaring process.
400 We hope that the results from this study will prompt the release of more flaring information,
401 leading to better source characterisation and further refinement of the modelling process.

402 Despite limitations encountered, we conclude that the process of gas flaring has been,
403 and continues to be, a major influence on air pollution in the region. Since flaring has been
404 practiced for close to 60 years, the environmental and health impacts are likely to have been
405 significant. Looking forwards, future impacts can be minimised with improved flaring
406 efficiency and suppression of flaring activity from some of the larger sites.

407 **Acknowledgements**

408 We wish to acknowledge the Petroleum Technology Development Fund (PTDF Nigeria) who
409 sustained the later stages of this research via a scholarship, the Surveyors Council of Nigeria
410 (SURCON), who partly supported the initial stages of this project with a research grant, and
411 the Department of Geoinformatics and Surveying, University of Nigeria Enugu Campus, for
412 the provision of the political map that was used in this research. We also thank Dr David
413 Carruthers (CERC) for his invaluable feedback and acknowledge the free use of tropospheric
414 NO₂ column data from the SCIAMACHY sensor from www.temis.nl.

415

416 **References**

- 417 Abdulkareem, A. S. (2005a). Evaluation of ground level concentration of pollutant due to gas flaring
418 by computer simulation: A case study of Niger - Delta area of Nigeria.
- 419 Abdulkareem, A. S. (2005b). Urban air pollution evaluation by computer simulation: A case study of
420 petroleum refining company Nigeria. *Leonardo Journal of Sciences*, 6, 17-28
- 421 Abdul-Raheem, A.M.O. and Adejola, F.A. (2013). Variation of source distribution of total oxidants:
422 Contributions of oxides of nitrogen, sulphur (IV) oxide emissions and background ozone from
423 Lagos-Nigeria. *International Journal of Physical Sciences*, 8 (11), 411-420.
- 424 Anejionu, O.C.D. (2014). Remote survey of gas flares and associated environmental and health
425 impacts in the Niger Delta. PhD thesis submitted to the Lancaster University.
- 426 Anejionu, C.D.O., Blackburn, G.A., and Whyatt, J.D. (2014). Satellite survey of gas flares:
427 development and application of a Landsat-based technique in the Niger Delta. *International*
428 *Journal of Remote Sensing*, 35(5), 1900-1925.
- 429 Anejionu, C.D.O., Blackburn, G.A., and Whyatt, J.D. (2015a). Detecting gas flares and estimating
430 flaring volumes at individual flow stations using MODIS data. *Remote Sensing of*
431 *Environment*, 158, 81-94.
- 432 Anejionu, O.C.D. Ahiamunnah, P.A.N., and Nri-ezedi, C.J. (2015b). Hydrocarbon pollution in
433 the Niger Delta: Geographies of impacts and appraisal of lapses in extant legal framework.
434 *Resources Policy*, 45, 65-77.
- 435 Arciszewska, C. and McClatchey, J. (2001).The importance of meteorological data for modelling air
436 pollution using ADMS-Urban. *Meteorological Application Journal*, 8, 345-350.

437 Backshall, D. (2013). Atmospheric dispersion modelling of discharges to air from the flaring of
438 fracturing fluid. *Prepared for Taranaki Regional Council by Air Quality Management Ltd.*
439 Report Number 13-008.

440 Boersma, K.F., Eskes, H.J., and Brinkma, E.J. (2004). Error Analysis for Tropospheric NO₂
441 Retrieval from Space. *Journal of Geophysical Research*. 109 (D04311), 1-20.

442 CERC (Cambridge Environmental Research Consultants). (2011). ADMS-Urban: An urban air
443 quality management system. *User Guide -Version 3.1*.

444 Climate Charts (2010). Port Harcourt, Nigeria: Climate, Global Warming, and Daylight Charts and
445 Data. <http://www.climate-charts.com/Locations/n/NI65250.php> (accessed 17th December,
446 2013).

447 Davies, G., and Whyatt, J.D. (2014). A network-based approach for estimating pedestrian journey-
448 time exposure to air pollution. *Science of the Total Environment* (485–486), 62 – 70.

449 Dung, E.J., Bombom, L.S., Agusomu, T.D. (2008). The effects of gas flaring on crops in the Niger
450 Delta, Nigeria. *GeoJournal*, 73, 297–305.

451 E&P Forum (Exploration and Production Forum). (1994). Methods for estimation of atmospheric
452 emissions from E&P Operations. The Oil Industry International Exploration and Production
453 Forum Report No 2.59/197.

454 EEMS (Environmental Emissions Monitoring System). (2008). Atmospheric Emissions Calculations.
455 [https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/136461/atmos-
456 calcs.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/136461/atmos-calcs.pdf) (accessed 17th December, 2013).

457 Ekpoh, I.J. and Obia, A.E. (2010).The role of gas flaring in the rapid corrosion of zinc roofs in the
458 Niger Delta Region of Nigeria. *Environmentalist*, 30, 347–352.

459 Elvidge, C.D., Ziskin, D., Baugh, K.E., Tuttle, B.T., .Ghosh, T., Pack, D.W., Erwin, E.H & Zhizhin,
460 M. (2009). A fifteen year record of global natural gas flaring derived from satellite data.
461 *Energies*, 2., 592-622.

462 Ezeamalu, B. (2014). Investigation: How decades of gas flaring is harming Nigerians (Part 1).
463 *Premium Times Newspaper*. [http://www.premiumtimesng.com/news/160899-investigation-
464 decades-gas-flaring-harming-nigerians-part-1.html](http://www.premiumtimesng.com/news/160899-investigation-decades-gas-flaring-harming-nigerians-part-1.html) (accessed 17th May, 2014).

465 Isichei, A.O., and Sanford, W.W. (1976). The effects of waste gas flares on the surrounding
466 vegetation in South- Eastern Nigeria. *Journal of Applied Ecology*, 13 (1), 177-187.

467 Ismail, O.S. and Umukoro, G. E. (2012). Global Impact of Gas Flaring. *Energy and Power
468 Engineering*, 4, 290-302.

469 IUCN (International Union for the Conservation of Nature). (1994). *A Guide to the Convention to the
470 Biological Diversity. Environmental Policy and Law Paper*, No. 30.
471 <https://portals.iucn.org/library/efiles/documents/EPLP-no.030.pdf> (Accessed 10th, December,
472 2011).

473 Johnson, M.R. and Coderre, A.R. (2012). Compositions and Greenhouse Gas Emission Factors of
474 flared and vented Gas in the Western Canadian Sedimentary Basin, *Journal of the Air & Waste
475 Management Association*, 62(9):992-1002.

476 Leahey, D.M. Preston, K., Strosher, M. (2001). Theoretical and Observational Assessments of Flare
477 Efficiencies. *Journal of the Air and Waste Management Association*, 51, 1610-1616.

478 Marais, E.A., Jacob, D.J., Wecht, K., Lerot, C., Zhang, L., Yu , K., Kurosu, T.P., Chance, K., and
479 Sauvage, B. (2014). Anthropogenic emissions in Nigeria and implications for atmospheric
480 ozone pollution: A view from space. *Atmospheric Environment*, 99, 32-40.

481 Nigeria Population Commission. (2010). 2006 population and housing census: Population distribution
482 by state, LGA, and senatorial districts.
483 [http://www.ibenaija.org/uploads/1/0/1/2/10128027/vol_03_table_dsx_lgapop_by_sdistrict-
484 pdf.pdf](http://www.ibenaija.org/uploads/1/0/1/2/10128027/vol_03_table_dsx_lgapop_by_sdistrict-pdf.pdf) (accessed 15th June, 2013).

485 Norwegian Meteorological Institute (2014). Weather statistics for Port Harcourt, Rivers (Nigeria).
486 http://www.yr.no/place/Nigeria/Rivers/Port_Harcourt/statistics.html (accessed 17th December,
487 2013).

488 Nwachukwu A. N., Chukwuocha E. O., and Igbudu O. (2012). A survey on the effects of air pollution
489 on diseases of the people of Rivers State, Nigeria. *African Journal of Environmental Science
490 and Technology* 6(10), 371-379.

491 Nduka, J.K.C., Orisakwe, O.E., Ezenweke, L.O., Ezenwa, T.E., Chendo, M.N., and Ezeabasili, N.G.
492 (2008). Acid Rain Phenomenon in Niger Delta Region of Nigeria: Economic, Biodiversity and
493 Public Health Concern. *The Scientific World Journal*, 8, 811–818.

494 OAQPS (U.S. EPA Office of Air Quality Planning and Standards). (1984). Evaluation of the
495 efficiency of industrial flares.
496 http://www.tceq.state.tx.us/assets/public/implementation/air/rules/Flare/Resource_2.pdf
497 (accessed on 20th March, 2014)

498 OAQPS (U.S. EPA Office of Air Quality Planning and Standards). (1995). Compilation of air
499 pollution emission factors: Volume 1 – stationary points and area sources. *AP 42 document*.
500 <http://www.epa.gov/ttn/chief/ap42/index.html> (accessed 19th February, 2014).

501 Odu, C. T. I. (1994). Gas flare emissions and their effects on the acidity of rain water in the
502 Ebocha area. <https://www.elaw.org/system/files/Ng.GasFlares.AcidRain.Ebocha.doc> (accessed
503 9th March, 2013).

504 OGP (International Association of Oil and Gas Producers). (2000). Flaring and venting in the oil and
505 gas exploration and production industry: An overview of purpose, quantities, issues, practices
506 and trends. *Report No. 2.79/288*. <http://www.ogp.org.uk/pubs/288.pdf> (accessed 14th January,
507 2014).

508 Ontario Ministry of the Environment. (2003). Proposed guidance for air dispersion modelling.
509 http://www.weblakes.com/products/aermod/resources/Ontario_MOE_Proposed_Air_Dispersio
510 [n_Modelling_Guidance.pdf](http://www.weblakes.com/products/aermod/resources/Ontario_MOE_Proposed_Air_Dispersio) (accessed 19th February, 2014).

511 Ontario Ministry of the Environment. (2007). Step by step guideline for emission calculation, record
512 keeping and reporting for airborne contaminant discharge. (accessed 14th April, 2014).

513 Osuji, L.C., and Avwiri GO (2005). Flared Gases and Other Pollutants Associated with Air Quality in
514 Industrial Areas of Nigeria: An Overview. *Chemistry and Biodiversity*, 2, 1-8.

515 Ovuakporaye, S.I., Aloamaka, C.P., Ojeh, A.E., Ejebe, D.E., and Mordi, J.C. (2012). Effect of gas
516 flaring on lung function among residents in gas flaring community in Delta State, Nigeria.
517 *Research Journal of Environmental and Earth Sciences* 4(5): 525-528.

518 Price, C. (2013). Modelling flares in ADMS 5. Presented at ADMS 5 User Group Meeting at The
519 Assembly Rooms, Newcastle (13th November).

520 Rotty R.M. (1974). First estimates of global flaring of natural gas. *Atmospheric Environment*,
521 8, 681-686.

522 San Joaquin Valley Air Pollution Control District. (2014).
523 <http://www.valleyair.org/busind/pto/Resources/Modeling/Source%20Parameters/Flare%20Mod>
524 [eling%20Parameters.xlsx](http://www.valleyair.org/busind/pto/Resources/Modeling/Source%20Parameters/Flare%20Mod) (accessed 19th January, 2014).

525 SPDC (Shell Petroleum Development Company of Nigeria). (2013). Shell in Nigeria: Gas Flaring.
526 [http://s02.static-shell.com/content/dam/shell-](http://s02.static-shell.com/content/dam/shell-new/local/country/nga/downloads/pdf/2013bnotes/gas-flaring.pdf)
527 [new/local/country/nga/downloads/pdf/2013bnotes/gas-flaring.pdf](http://s02.static-shell.com/content/dam/shell-new/local/country/nga/downloads/pdf/2013bnotes/gas-flaring.pdf) (Accessed 9th, March, 2014).

528 Tawari, C.C. and Abowei, J.F.N. (2012). Air Pollution in the Niger Delta Area of Nigeria.
529 *International Journal of Fisheries and Aquatic Sciences* 1(2), 94-117.

530

531 U.S. EPA (United States Environmental Protection Agency). (2011). Dispersion modelling.
532 <http://www.epa.gov/air/aqportal/management/modeling/dispersion.htm> (accessed 4th
533 October, 2013).

534 U.S. EPA (United States Environmental Protection Agency). (2014a). Emissions Factors & AP
535 42, Compilation of Air Pollutant Emission Factors.
536 <http://www.epa.gov/ttn/chief/ap42/index.html> (accessed 21st February, 2014).

537 U.S. EPA (United States Environmental Protection Agency). (2014b) National Ambient Air Quality
538 Standards (NAAQS). <http://www.epa.gov/air/criteria.html>

539 Vingarzan, R. (2004). A review of surface ozone background levels and trends. *Atmospheric*
540 *Environment*, 38, 3431–3442.

541 Weather Underground. (2013). Weather History for Malabo, Equatorial Guinea.
542 <http://www.wunderground.com/history/airport/FGSL> (accessed 12th December, 2013).

543 WHO (World Health Organisation). (2005). WHO Air quality guidelines for particulate matter,
544 ozone, nitrogen dioxide and sulfur dioxide. *Global Update. Summary of risk assessment*.
545 WHO/SDE/PHE/OEH/06.02.

546

548 Figure 1



549

550

551

552

553

554

555

556

557

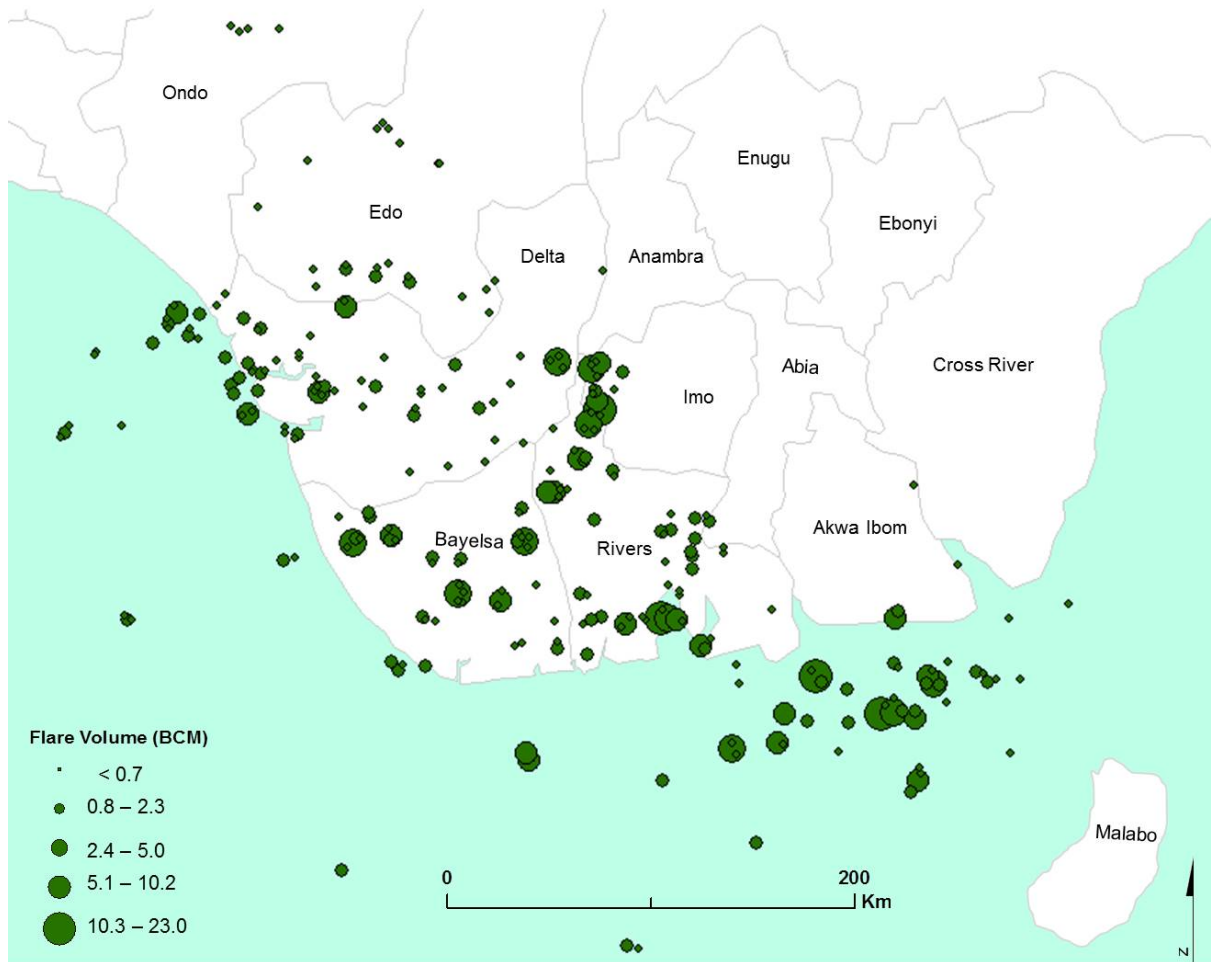
558

559

560

561

562



564

565

566

567

568

569

570

571

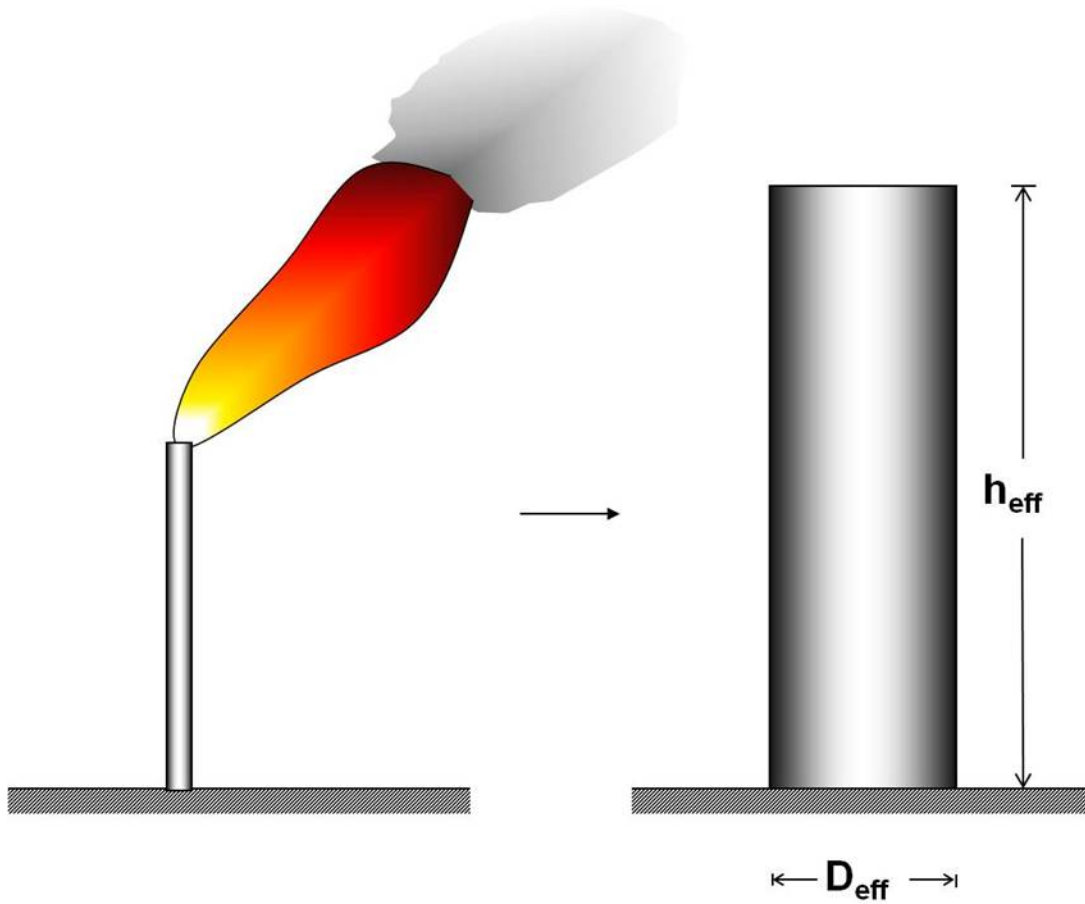
572

573

574

575

576



578

579

580

581

582

583

584

585

586

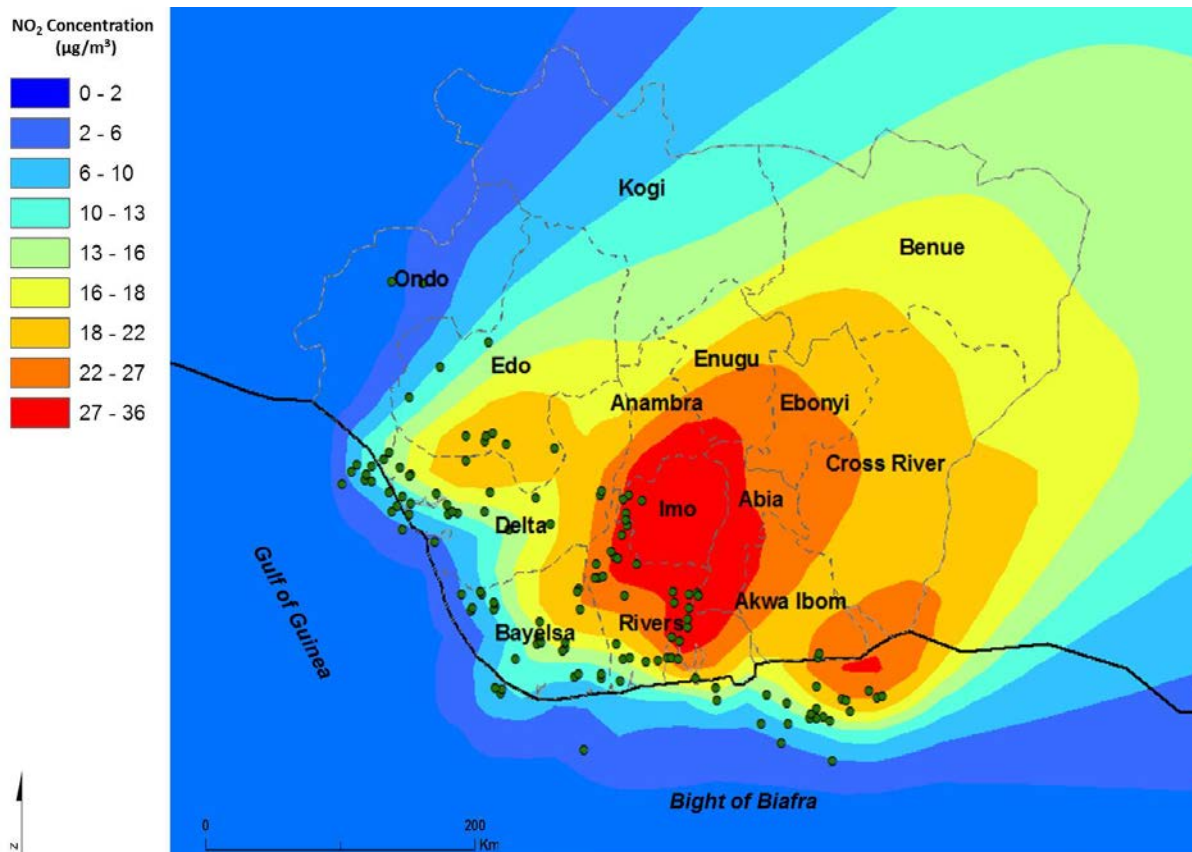
587

588

589

590

591 Figure 4



592

593

594

595

596

597

598

599

600

601

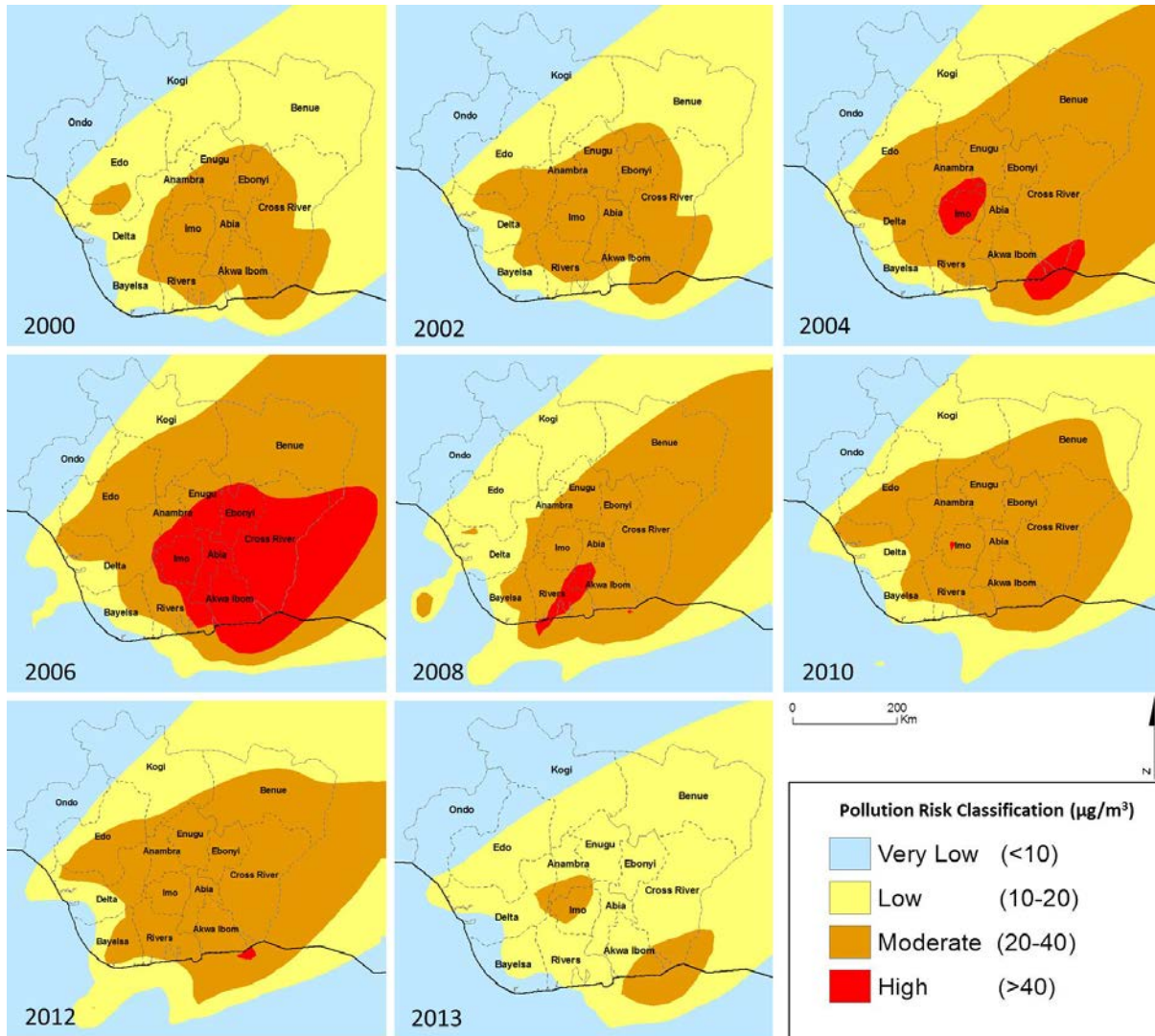
602

603

604

605

606 Figure 5



607

608

609

610

611

612

613

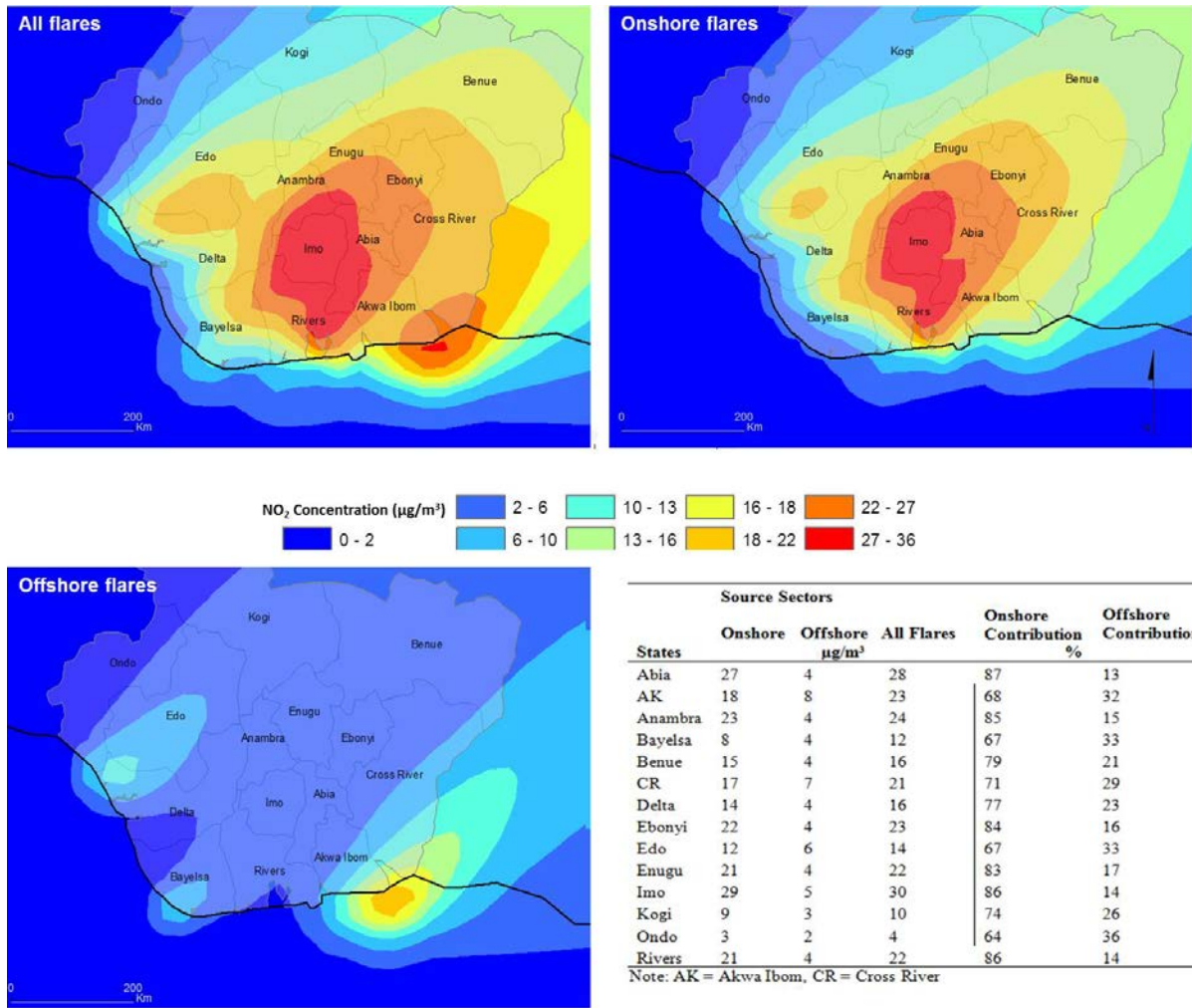
614

615

616

617

618 Figure 6



619

620

621

622

623

624

625

626

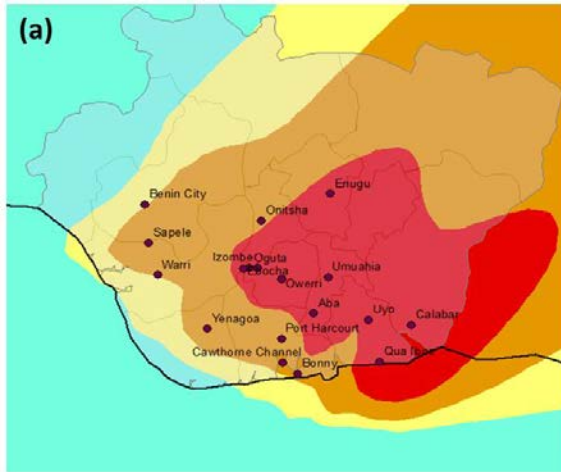
627

628

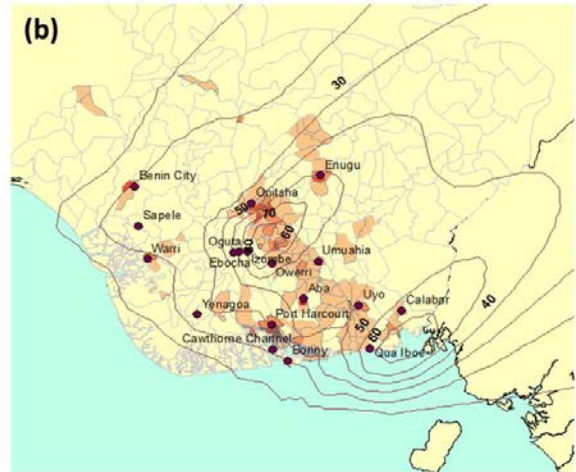
629

630

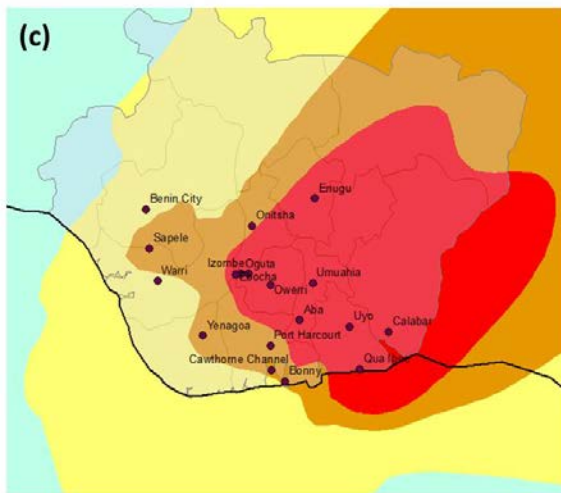
631 Figure 7



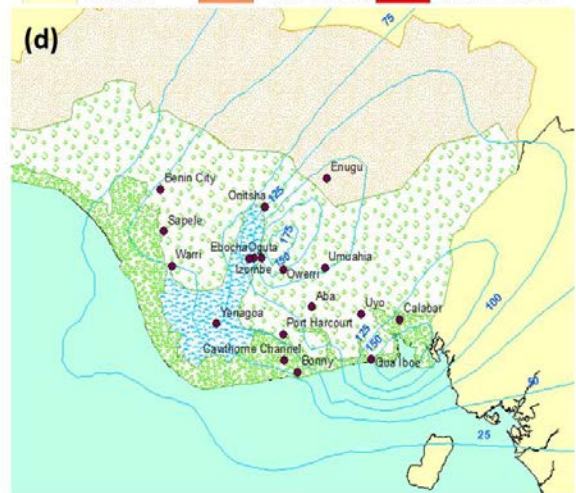
NO₂ Pollution Risk Classification (µg/m³)
 Very Low (<10) Low (10-20) Moderate (20-40) High (>40)



Population Density (population/Km²)
 Major Cities
 < 500.0 500 - 1500 1501 - 2500 2501 - 5000 5001 - 13560



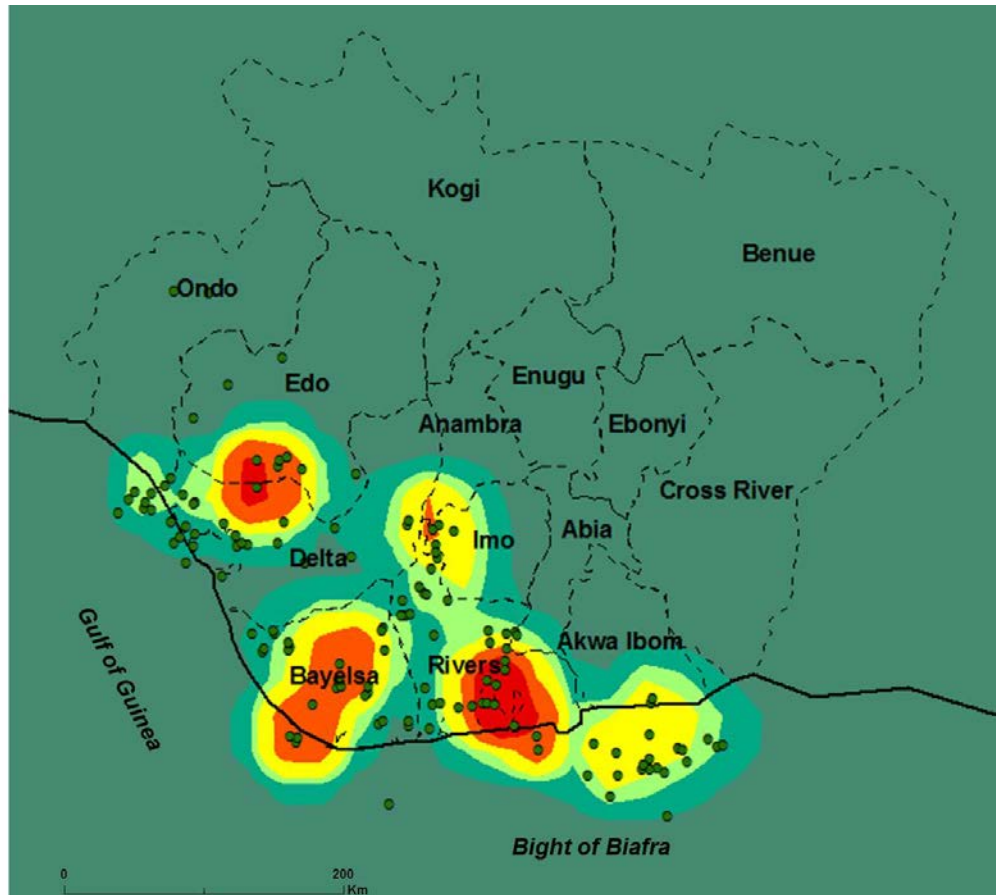
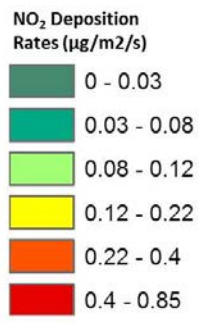
O₃ Pollution Risk Classification (µg/m³)
 Very Low (<20) Low (20-60) Moderate (60-100) High (>100)



Ecological zones
 0 200 Km
 Freshwater Mangrove Rainforest Savannah

632
 633
 634
 635
 636
 637
 638
 639
 640
 641

642 Figure 8



643