Atmospheric Environment 118 (2015) 184–193

Contents lists available at ScienceDirect

Atmospheric Environment

journal homepage: www.elsevier.com/locate/atmosenv

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

Obinna C.D. Anejionu [a,*], J. Duncan Whyatt [a], G. Alan Blackburn [a], Catheryn S. Price [b]

[a] Lancaster Environment Centre, Gordon Manley Building, Lancaster University, Lancaster LA1 4YQ, United Kingdom
[b] Cambridge Environmental Research Consultants (CERC), Cambridge CB2 1SJ, United Kingdom

## HIGHLIGHTS

- Flare-related air pollution derived through combination of geospatial technologies.
- Extended pollution series constructed in the absence of *in situ* monitoring data.
- Impacts of air pollution on human health and natural ecosystems quantified.
- Inter-state contributions to pollution levels determined.
- Benefits of reduced flaring activity and increased flaring efficiency demonstrated.

## ARTICLE INFO

*Article history:*
Received 8 February 2015
Received in revised form
30 July 2015
Accepted 3 August 2015
Available online 7 August 2015

*Keywords:*
Gas flares
Remote sensing
Dispersion modelling
Health impacts
Environmental impacts
Niger delta

## 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.



## 1. Introduction

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

As there was little local awareness of the environmental impacts of gas flaring in the 1960s and because flaring technology was in its infancy, flaring efficiencies were low relative to modern day standards (Leahey et al., 2001; OGP, 2000) with large volumes of gas flared at flow stations (where oil from different wells is initially gathered) and in refineries on an almost continuous basis (Marais et al., 2014). Although it is generally assumed that flares attain high flaring efficiency, producing only non-toxic carbon dioxide ($CO_2$) and water, in reality, combustion is incomplete and harmful by-products such as sulphur dioxide ($SO_2$), nitrogen oxides (NOx), hydrogen sulphide ($H_2S$), volatile organic compounds (VOC), total hydrocarbons, heavy metals and particulates are released into the environment (Johnson and Coderre, 2012; Abdulkareem, 2005a). Generally, flares are thought to operate at an average efficiency of 68% ± 7% (Leahey et al., 2001).

* Corresponding author.
*E-mail address:* obicd@yahoo.com (O.C.D. Anejionu).

http://dx.doi.org/10.1016/j.atmosenv.2015.08.006
1352-2310/

**Fig. 1.** Open ground flare at Rumuekpe, Rivers State, surrounded by farmland (Ezeamalu, 2014).

The dangers posed by prolonged and continuous flaring have been a source of concern to the inhabitants of the Niger Delta. Reported impacts include increased concentrations of airborne pollutants, reduced agricultural yields, acidification of soils and rainwater, decreased plant flowering and fruiting, corrosion of metal roofs, heat stress, deformities in children, decreased lung function and damage, and skin problems (Ismail and Umukoro, 2012). These impacts have prompted numerous studies as documented by Anejionu (2014).

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

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

The objectives are as follows:

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

## 2. Study area

The Niger Delta is at the centre of oil and gas exploration in Nigeria. In addition, it provides the natural habitat for a wide variety of endemic coastal and estuarine fauna and flora, supporting over 60% of the total species in Nigeria (Anejionu et al., 2015b). It is therefore ranked as one of the highest conservation priorities in West Africa (IUCN, 1994). The region is very humid with average ambient temperatures ranging from 21 °C to 35 °C. It generally experiences light south-westerly winds ranging from 1.6 m/s to 5.4 m/s for most of the year, due to its proximity to the Atlantic Ocean; although during the few dry months of Harmattan (late November to early February), some north-easterly winds are recorded (Marais et al., 2014; Odu, 1994).

## 3. Methodology

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

### 3.1. Modelling system description

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

### 3.2. Data

#### 3.2.1. Flare volume flow rate

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

#### 3.2.2. Meteorological data

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

#### 3.2.3. Emission factors

There are practical challenges in obtaining accurate estimates of