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The health and economic impacts of exposure to marine mobile emissions from ships in Durban port, South Africa

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ABSTRACT

South Africa remains an uncharted realm in terms of marine mobile emissions inventory and hence the impact of pollution from ships in coastal cities remains unknown. Such a void creates uncertainties about the extent of population exposure to pollution from ships, the health impact and economic value associated with the changes in policies for the port city of Durban.

This study was aimed at estimating the health and economic impact of marine mobile emissions and the health and economic benefits associated with improvement in air quality within the port city of Durban, which is under eThekwini municipality. The population exposure to particulate matter of less than 2.5 and 10 μm ($PM_{2.5}$ and PM_{10}) and sulphur dioxide (SO_2) from ships calling into Durban port were estimated using the AERMOD air dispersion model. The BenMAP modelling tool was then used to estimate the health impact and economic value of changes in emission of $PM_{2.5}$, PM_{10} and SO_2 from ships visiting Durban port. The reduction in emissions from ships was due to the reduction in the sulphur content of fuel from 3.5% to 0.5% that was implemented by the International Maritime Organisation (IMO) on the 01st of January 2020.

The results showed that $PM_{2.5}$ and PM_{10} emissions reduced by 63% in 2020 compared to 2018, whilst SO_2 emissions reduced by 82% over the same period. The BenMAP results indicated that 49 premature mortalities were avoided in 2020 compared to 2018 since the IMO's forced reduction in sulphur content of fuel by 85% in 2020. These avoided cases on mortality were estimated a monetary value of R228 million using the World Bank's 2016 estimates and R683 million using the USEPA Mean VSL estimate. Such monetary values were respectively equivalent to 0.05% and 0.2% of the eThekwini's GDP, which was estimated at R468 billion in 2016.

1. Introduction

Any concentration of toxic pollutants is associated with increased mortality and morbidity risks and the large health costs resulting from hospitalization, health treatment, and loss of productivity by the population affected by these pollutants (Atkinson et al., 2012; Altieri and Keen, 2019; Mwase et al., 2020). Coastal cities and port cities like Durban, are particularly at high risk as they suffer from pollution from a variety of sources ranging from industrial fumes, chemical factories, oil refineries, vehicular emissions, and exclusively marine mobile emissions (Ramsay and Naidoo, 2012; Altieri and Keen, 2019). Unlike inland cities, the element of marine mobile emissions plays a significant role in the cumulative assessment of urban ambient air quality in coastal cities. This is particularly so in cities like Durban, which has the busiest port in Sub-Saharan Africa (Larnyoh, 2020; Lloyd's List Intelligence, 2020). However, the marine mobile emissions are often overlooked in port cities of developing countries due to lack of data and the capacity to conduct such studies. Also, the marine mobile polluters provide additional complexity in that they are not stationery (Saxe and Larsen, 2004), and therefore difficult to treat them as point sources, line sources, area sources or even volume sources of pollution. Instead, treating ships as a combination of all the source forms mentioned above may be necessary to reveal their true nature as sources of pollution and to measure their impact on societies around coastal cities.

2. IMO enforced changes in fuel sulphur content

Shipping is potentially a significant source of particulates and

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gaseous particles near ports and surrounding coastal areas, including harbour cities (Contini and Merico, 2021). Particularly relevant, is the expected increase in the number of active ships globally and increasing coastal populations, as well as predicted decreases in emissions from land-based sources (e.g. traffic and heating) (Contini and Merico, 2021). Emissions from Port logistics are also relevant, even if emissions from ships are generally larger than harbour-related emissions (Merico et al., 2019). Studies have shown the potential exceedances of ambient NO_2 guidelines near harbour areas (Contini and Merico, 2021).

Most pollution in port result from marine mobile emissions and shore-based sources such as cargo handling equipment (CHE), which include heavy-duty trucks, locomotives, cranes, and tractors operating in the port (USEPA, 2009). The primary source of emissions from marine mobile platforms are diesel engines used for propulsion and those that supply electrical power aboard ships. Major pollutants resulting from marine diesel engines are oxides of nitrogen (NO_x), sulphur dioxides (SO_2), hydrocarbons (HC), and particulate matter (PM) (USEPA, 2009; Han, 2010).

This study mainly focuses on the impact of three priority pollutants namely, sulphur dioxide (SO_2, particulate matter of less than 2.5 μm in diameter ($PM_{2.5}$), and particulate matter of less than 10 μm in diameter (PM_{10}). The $PM_{2.5}$ and PM_{10} contain microscopic solids and liquid droplets that if inhaled, will cause serious health problems (USEPA, 2023a). Both the $PM_{2.5}$ and the PM_{10} have long been associated with cardiopulmonary and lung cancer mortality (Atkinson et al., 2012). These fine particles can enter deep into the lungs and join the blood stream and cause asthma, heart attack, and premature death (USEPA, 2023a). The recent study by Guascito et al. (2023) highlighted that particulate matter is regarded as one of the leading risk factors for human health and is responsible for several million deaths per year globally. This is even though the exact mechanism of toxicity of particulate matter is still not completely understood (Guascito et al., 2023). The SO_2 on the other hand, have been associated with respiratory complications. There is sufficient evidence that prolonged exposure to SO_2 causes emphysema, which is the lung disease comprising of chronic obstructive pulmonary disease that develops overtime and cause gradual damage to lung tissue (World Health Organization (WHO), 2006).

In 2020, the sulphur content of marine fuel was reduced from 3.5% to 0.5% in non-sulphur emission control areas (non-SECA) (Alföldy et al., 2013; USEPA, 2020). The use of low-sulphur content fuels is expected to decrease SO_2 emissions into the future, as well as primary and secondary PM (Tao et al., 2013; Contini et al., 2015; Liu et al., 2018). There are no significant changes predicted for total metals and polycyclic aromatic hydrocarbons (PAHs) in gaseous and particulate phase in PM_{10} (Gregoris et al., 2016). From a regional perspective, NO_2 from ships can enhance the production of O_3 at ground level (Aksoyoglu et al., 2016) even if there is a depletion of O_3 at the local scale related to NO_2 emissions (Ledoux et al., 2018; Merico et al., 2016).

It is therefore expected that the impact of $PM_{2.5}$, PM_{10}, and SO_2 on human health would have significantly reduced since 2020 after the implementation of the new global standards by the International Maritime Organisation (IMO) to limit the sulphur content in marine fuel oil (Barregard et al., 2019; Jonson et al., 2019). This is because SO_2 is a biproduct of burning fossil fuels and other materials that contain sulphur and it is a precursor for particulate matter (Barregard et al., 2019). Barregard et al. (2019) estimated the global reduction of premature mortality by 34% after the fuel sulphur reduction to 0.5% in 2020.

This study was therefore aimed at estimating the Durban population exposure to $PM_{2.5}$, PM_{10} and SO_2 emanating from ships visiting the port and to determine the health and economic benefits associated with the reduction of sulphur content of marine fuel oil in 2020 (Barregard et al., 2019). This exposure to pollutants and the health and economic impacts of marine mobile emissions from the ocean-going vessels (OGVs) visiting the Durban Port were determined using the AERMOD air dispersion model and the BenMAP modelling tools respectively.

The AMS/EPA Regulatory Model (AERMOD) air dispersion model was used to map the concentration and spatial distribution of $PM_{2.5}$, PM_{10} and SO_2. The Benefits Mapping and Analysis Program (BenMAP) modelling tool was used to determine the impact of change of sulphur content of marine fuel oil to human health and to the economy of the affected area (Altieri and Keen, 2019). BenMAP is based on the principle that improvements in ambient air quality will generally lead to a lower risk in adverse health effect by a small amount within a larger population (USEPA, 2023b). Certain areas within Durban, better known as eThekwini municipality, were more adversely affected by the marine mobile emissions from ships operating in Durban port than others, and this was revealed in this study.

3. Method of data input

3.1. Ship activity and emissions data

The emission results were calculated from the data on ship activities compiled by Transnet National Port Authority (TNPA). The detailed approach was used to calculate marine mobile emissions from all ships docking, entering, or leaving the port between 01 January 2018 until 31 December 2018. The same method and ships activity data was used to estimate the changes in emissions after the adjustments of emission factors resulting from the reduction of fuel sulphur content in 2020. formula (1) approved by the Intergovernmental Panel on Climate Change (IPCC) and modified using the propeller law equation (2), was applied on a spreadsheet to calculate emissions from ships calling into Durban port in 2018 and then repeated with reduced emission factors for the same activities in 2020 (Joseph et al., 2009; Yang et al., 2018; Huang et al., 2020).

$$E_i = P_m L_m T_m F_{i,m} + P_a L_a T_a F_{i,a} + P_b L_b T_b F_{i,b} \tag{1}$$

Where.

E_i = emission of each pollutant.
$P_{m,a,b}$ = maximum power output of main, auxiliary and boiler engines.
$L_{m,a,b}$ = load factors for auxiliary and boiler engines.
$T_{m,a,b}$ = time in operation.
$F_{i,m,a,b}$ = emission factors of each engine for each pollutant.

$$P_p = P_{ref} \times \left(\frac{V}{V_{ref}}\right)^3 \times SM \tag{2}$$

Where P_p = propulsion engine operating power (kW).

P_{ref} = vessel's total installed propulsion power (kW)
V = vessel's reported speed (kn)
V_{ref} = vessel's service speed (kn)
SM = sea margin accounting for average weather conditions, assumed to be 1.10 for coastal operations and 1.15 for at-sea operations (unitless)

It was imperative that the same data and same procedure was used for both the 2018 and 2020 scenarios, to determine the impact that the reduction in sulphur content of fuel induced on ship emissions. Unlike other studies that hypothesise the reduction in emissions to propose the change in policy, this study has a more realistic approach in that real changes that were sanctioned by IMO, were indeed implemented on January 01st, 2020 (USEPA, 2020). To reveal the impact of these changes, USEPA (2020) recommended the adjustments of emission factors for the calculation of marine mobile emissions globally.

3.1.1. Adjustment of emission factors for particulate matter (PM_{10} and $PM_{2.5}$)

The calculation of emission factors for PM_{10} for Slow Speed Diesel

(SSD) and Medium Speed Diesel (MSD) Category 3 propulsion engines as well as auxiliary engines and boilers is achieved by making use of the following equation (USEPA, 2020):

$$EF_{PM_{10}} = PM_{base} + (S_{act} \times BSFC \times FSC \times MWR) \quad (3)$$

Where $EF_{PM_{10}}$ = PM_{10} emission factor adjusted for fuel sulphur (g/kWh).

PM_{base} = Base emission factor assuming zero fuel sulphur
=0.1545 g/kWh for distillate fuel (MGO and MDO)
=0.5761 g/kWh for residual fuel (RM and HFO)
S_{act} = actual fuel sulphur level (weight ratio)
=0.001 for most vessel activity within the ECA in 2015 and beyond
=0.027 for all vessel activity outside the ECA before 2020
=0.005 for all vessel activity outside the ECA in 2020 and beyond
$BSFC$ = brake specific fuel consumption (g/kWh)
FSC = fraction of sulphur in fuel that is converted to direct sulphate PM
=0.02247
MWR = molecular weight ratio of sulphate PM to sulphur
=224/32 = 7

IMO sanctioned the reduction of sulphur content in marine fuel oil through Annex VI of the Maritime Pollution Convention (MARPOL), which came into effect in 2005 (Cooper and Gustafsson, 2004; Burgel, 2007; Lloyd's List Intelligence, 2020). This was implemented in cascading levels or tiers commencing from 2011, and then 2020 in non-sulphur emission control areas (non-SECA). This saw the reduction of sulphur content in marine fuel from 3.5% to 0.5% from the 01st of January 2020 in non-sulphur control areas like South Africa as shown in Fig. 1 below (Alföldy et al., 2013; USEPA, 2020). This equates to an 85% reduction in sulphur content of fuel.

The 2018 emission calculation therefore used the actual fuel sulphur level (S_{act}) of 0.027, whereas for the 2020 emission calculation, this figure was adjusted to 0.005 for non-SECA like Durban port as per the USEPA (2020) recommendation of new sulphur regime. The results of this adjustment became apparent when the total $PM_{2.5}$ and PM_{10} emissions reduced by 63.8% (Table 1) and SO_2 emissions reduced by 81.2% (Table 2) in 2020 compared to 2018 emissions. All calculations were made for PM_{10} emissions and the conversion from PM_{10} to $PM_{2.5}$ was made by multiplying the PM_{10} emissions by the factor of 0.92 as the fine particles of $PM_{2.5}$ make up 92% of PM_{10} particles (USEPA, 2020). Tables 1, 2 and 3 respectively show how $PM_{2.5}$, PM_{10} and SO_2 emissions from ships in Durban port changed after the compulsory sulphur content reduction in marine fuel was introduced in 2020 (see Fig. 1).

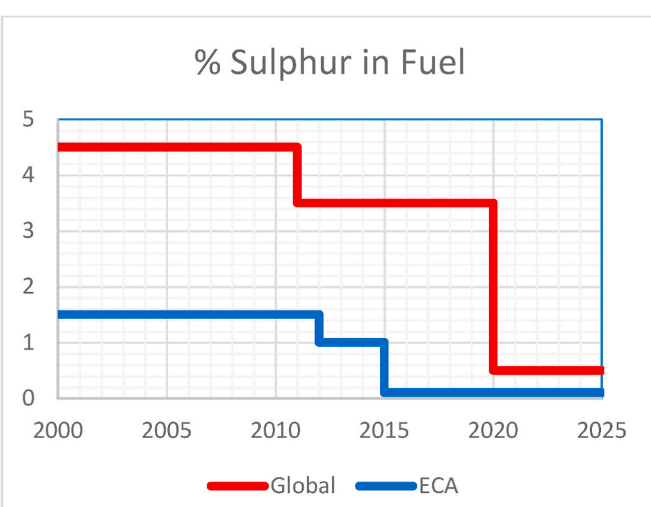

Fig. 1. Percentage reduction in sulphur content of marine fuel (Alföldy et al., 2013).

Table 1
Changes in $PM_{2.5}$ Emissions between 2018 and 2020 due to fuel sulphur content reduction.

	$PM_{2.5}$ Emissions (grams)	
	2018	2020
CONTAINER	17 430 978	6 505 168
BULK CARRIER	11 318 230	4 203 550
TANKER	6 811 066	2 595 896
GENERAL CARGO	1 831 093	727 374
CAR CARRIER	4 309 333	1 468 958
OTHER SHIPS	9 763 484	3 144 953
TOTAL EMISSIONS (grams)	51 464 183	18 645 899
TOTAL EMISSIONS (tonnes)	51.46	18.65
Percentage reduction of $PM_{2.5}$ emissions from 2018 to 2020		63.8%

Table 2
Changes in PM_{10} Emissions between 2018 and 2020 due to fuel sulphur content reduction.

	PM_{10} Emissions (grams)	
	2018	2020
CONTAINER	18 946 715	7 070 835
BULK CARRIER	12 302 424	4 569 076
TANKER	7 403 332	2 821 626
GENERAL CARGO	1 990 319	790 624
CAR CARRIER	4 684 058	1 596 694
OTHER SHIPS	10 612 482	3 418 427
TOTAL EMISSIONS (grams)	55 939 330	20 267 282
TOTAL EMISSIONS (tonnes)	55.94	20.27
Percentage reduction of PM_{10} emissions from 2018 to 2020		63.8%

Table 3
Changes in SO_2 Emissions between 2018 and 2020 due to fuel sulphur content reduction.

	SO_2 Emissions (grams)	
	2018	2020
CONTAINER	191 692 445	35 498 601
BULK CARRIER	118 065 997	21 864 073
TANKER	69 961 614	12 955 854
GENERAL CARGO	18 340 523	3 396 393
CAR CARRIER	47 465 268	9 026 464
OTHER SHIPS	109 927 651	21 580 436
TOTAL EMISSIONS (g)	555 453 499	104 321 822
TOTAL EMISSIONS (t)	555.45	104.32
Percentage reduction of SO_2 emissions from 2018 to 2020		81.2%

3.2. Atmospheric dispersion modelling

To simulate the ground-level impacts of emissions, dispersion modelling was undertaken using the internationally recognized AERMOD modelling software suite. AERMOD is a new generation air dispersion model designed for short-range dispersion of airborne pollutants in steady state plumes that uses hourly sequential meteorological files with pre-processors to generate flow and stability regimes for each hour of the assessment period. The model outputs can be used to produce maps of plume spread with key isopleths for visual interpretation and statistical outputs allowing for compliance reporting purposes (Paine et al., 2003).

The AERMOD atmospheric dispersion modelling system is a steady-state dispersion model designed for short-range (up to 50 km) dispersion of air pollutant emissions from stationary sources. It incorporates air dispersion based on planetary boundary layer turbulence structure and scaling concepts and can treat both surface and elevated sources in both simple and complex terrain settings. The suite includes two pre-processor modules.

- A meteorological data pre-processor (AERMET) that accepts surface meteorological data, upper air soundings, and optionally, data from surface-based stations. It then calculates atmospheric parameters needed by the dispersion model, such as atmospheric turbulence characteristics, mixing heights, friction velocity, Monin-Obukhov length and surface heat flux.
- A terrain pre-processor (AERMAP) to provide the physical relationship between terrain features and the behaviour of air pollution plumes using digital elevation data (DEM). It generates surface characteristics and elevation data for each grid receptor location (Paine et al., 2003).

The U.S. EPA AERMOD model has been extensively studied and validated. Studies have typically demonstrated good correlation with real-world values (Paine et al., 2003).

3.3. Population and mortality data

The eThekwini population density data and the mortality rate for 2018 was obtained from Statistics South Africa database. Only natural mortality was used, which was a fraction of the total mortality making approximately 60% (Statistics South Africa, 2023). Statistics South Africa compiles the causes of death statistics in accordance with the World Health Organization (WHO) regulations, which uses codes to indicate the causes of death using the tenth revision of the International Classification of Diseases and Related Health Problems (ICD-10). The statistics regarding the causes of death indicated that 10% of deaths in South Africa were due to respiratory diseases (Altieri and Keen, 2019; Statistics South Africa, 2023) and particulate matter and sulphur dioxide have long been associated with respiratory diseases, cardiopulmonary and lung cancer mortality (Atkinson et al., 2012).

The population-weighted exposure to air pollution from ships was estimated from emissions inventory and spatial distribution model results. The results from the population-weighted exposure were then combined with the mortality rates and exposure-response functions to estimate emissions related reduction in mortalities (Barregard et al., 2019).

The 2018 population of eThekwini district was estimated to be approximately 3 442 361 (Macrotrends, 2023; Statistics South Africa, 2023). The Department of Home Affairs registered the total number of deaths in 2018 at 454 014 people in South Africa with 27 742 occurring in eThekwini district. Of the recorded eThekwini district mortalities, 4138 were associated with heart diseases, 1244 were cerebrovascular, 1071 were ischaemic heart diseases, 7390 were circulatory diseases and 1837 were due to respiratory diseases (Table 4). Since the loss of life data is only registered at the district level and not at ward level, the loss of life data was therefore aggregated across the municipality and interpolation made for each ward.

3.4. Benefit Mapping and analysis (BenMAP) data

The population and mortality data of eThekwini district municipality for 2018, extracted from Statistics South Africa (2012), was applied to Benefits Mapping and Analysis Program (BenMAP) modelling tool to quantify the health impact and economic benefit of reducing the emission of fine particles of matter and sulphur dioxide from ships visiting Durban port. BenMAP utilizes a concentration-response function to estimate the health benefit and perform the cost-benefit analysis associated with the change in the quality of air (Altieri and Keen, 2019). BenMAP considers the population data, morbidity and mortality data, the ambient concentration of pollutants and data from epidemiological studies that provide concentration-response (C–R) functions. It then estimates the benefits from the improvement of human health based on reduction in relative mortality risk (Altieri and Keen, 2019; USEPA, 2023).

In general, the health effects and the economic impact of fine particles and sulphur dioxide can be represented in a hierarchical form as depicted in Fig. 2, with the resulting morbidity and mortality affecting various proportions of the population in any given area.

Fig. 2 shows that lung function decrement, inflammation, and asthma attacks usually appear at the bottom of the severity pyramid and affect a larger proportion of the population. However, those at the tip end of the pyramid like hospitals and heart attacks are more severe and affect fewer people within a population (USEPA, 2023). The focus was therefore, on the last stage of the pyramid, i.e. mortality, which affect the small portion of the population and the middle section of the pyramid that determines the economic factor resulting from school and work absence due to illness from pollution and cost of hospitalization.

The process used in estimating the impact of air pollution followed the steps below (Fig. 3).

1. Modelled air quality changes
2. Population
3. Baseline incident rate
4. Effects estimate (USEPA, 2023)

The BenMAP computes the economic benefit, in value, of changes in the quality of air using both the "Cost of Illness" and "Willingness to Pay" metrices. The Cost of Illness relates to the expenses incurred by an individual emanating from hospitalization and incapacitation due to air pollution-related illnesses. It includes mainly the medical costs and the loss of income from absenteeism or loss of work (USEPA, 2023). The final step of the BenMAP modelling was the application of the

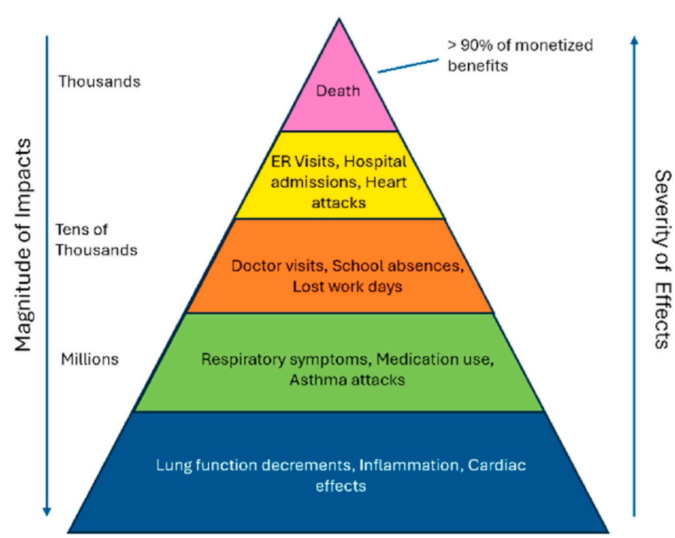

Fig. 2. A pyramid of effects from air pollution (USEPA, 2023).

Table 4
Mortality and Causes of Deaths in eThekwini in 2018 (Statistics South Africa, 2021)

Area	Deaths by Other forms of Heart Diseases	Deaths by Cerebrovascular Diseases	Deaths by Ischaemic Heart Diseases	Deaths by Circulatory Diseases	Deaths by Respiratory Diseases	Death by other Causes	Total Deaths
eThekwini	4138	1244	1071	7390	1837	12 062	27 742

Fig. 3. A Process of Estimating the Health Impact of Air Pollution using BenMAP Tool (USEPA, 2023).

epidemiological data from the Stats SA to estimate the health impact and the economic value of air pollution changes due to the reduction in sulphur content of fuel in 2020 (USEPA, 2020; USEPA, 2023a).

4. The health impact analysis

Rabl et al. (2011) and Hammitt et al. (2020) recognized that exposure to air pollution is not easily identifiable as the cause of individual death and the number of deaths due to exposure is not easily determined by mortality data alone. One can therefore not determine the loss of life expectancy by ordinary method for other causes of death like chronic illness. For instance, if air pollution deaths occurred soon after the exposure, the corresponding life expectancy loss could be determined by observing the increase in mortality rate immediately after the peak in pollution rate (Rabl et al., 2011). There is therefore always an overlap corresponding to the mortality results of time series studies. This requires an extended window of observation to allow for all contributions of time series coefficient to the total. This calls for mortality and air pollution data to be collected over a long time (at least five years) to determine the severity of impact of air pollution and loss of life expectancy (Rabl et al., 2011).

The simpler method to avoid such lengthy processes was to utilize a computer software model like BenMAP, which contains a function that uses mortality risk coefficients from various epidemiological studies to determine the premature mortalities resulting from exposure to specific pollutants like particulate matter and sulphur dioxide. The excess mortality was estimated using the exposure-response (ER) function (Barregard et al., 2019). BenMAP calculates the health impact associated with changes in air pollution using the health impact functions as shown in *equation (4)* below (USEPA, 2023a).

$$\Delta y = y_0\left(1 - e^{-\beta \Delta PM}\right) * pop \tag{4}$$

Where Δy = health impact

y_0 = baseline incidence
β = effect estimates
ΔPM = pollutant change
pop = population (Altieri and Keen, 2019; Alpfjord Wylde et al., 2023; USEPA, 2023a).

The first step was to determine the change in air quality due to reduction in emissions of SO_2 $PM_{2.5}$, and PM_{10} and how this influenced the related mortalities. BenMAP can use either monitoring data or modelled data for the health impact analysis and valuation (USEPA, 2023). In this case, the modelled air quality data was derived from the AERMOD air dispersion model tool, and the maximum concentration determined for each ward. When the air pollution data was inserted onto BenMAP for health impact analysis, BenMAP assumed that the maximum concentration of pollutants occurred at the centre of the grid cell, which in this case was the centres of each ward within the eThekwini municipality area. However, as a worst-case scenario, the estimated mean exposure to the pollutants was evenly distributed across the entire ward.

To estimate how the changes in SO_2, $PM_{2.5}$, and PM_{10} concentrations affected the mortality incidences, the dose-response functions derived from various health impact studies were utilized. In this case, the epidemiological studies by Krewski et al. (2009) and Wichmann and Voyi (2012) were used in BenMAP as the health impact functions. The number of deaths avoided were then obtained by multiplying the change incidence with the population of an area of interest (USEPA, 2023). The population exposure was dependent on the relationship between population density received from the Stats SA database and air pollution levels extracted from the AERMOD results. Although the incidence data was grouped in accordance with gender and age, the population data file did not make any distinctions based on gender, age, and ethnicity (Statistics South Africa, 2021; Wazimap, 2023). There was therefore no distinction between gender, age, and ethnicity in the affected population and the incidence data used for analysis.

The total mortality and specific causes of deaths in 2018 (Table 4) were extracted from Statistics South Africa (20118). The population exposure (in $\mu g/m^3$ x persons) and the mean exposure to each pollutant per person is depended on a relationship between population density and air pollution levels (Barregard et al., 2019). The same population figures were assumed for both 2018 and 2020 so that the analysis will be compatible (Barregard et al., 2019; Alpfjord Wylde et al., 2023). The concentration of pollutants of SO_2, $PM_{2.5}$, and PM_{10} were estimated using AERMOD modelling tool and then combined with population data using BenMAP to determine the population-weighted exposure to ambient pollution in 2018 and 2020 (USEPA, 2023b). The estimated reduction in population exposure and the subsequent reduction in premature deaths due to reduction in $PM_{2.5}$, PM_{10} and SO_2 emissions from ships since 2020 were then determined.

5. The economic impact analysis

According to Hammitt et al. (2020), "the economic value of reducing the mortality risk by eliminating air pollution is equal to the sum over a population, of each individual's value of their risk reduction in individuals less than 60 years of age". Hammitt et al. (2020) explained how to estimate the monetary value of reducing the health risk associated with air pollution using *equation (5)*.

$$V = \sum_{t=60}^{90} v(t)r(t)S(t)\rho^{t-a} \tag{5}$$

Where: V = monetary value.

v(t) = average value per unit risk reduction of reducing hazard at age t by r(t).

S(t) = probability of surviving to t

ρ = discount factor (equal to 1/[1 + discount rate]) (Hammitt et al., 2020).

Altieri and Keen (2019) estimated 14 000 avoided premature fatalities if more stringent NAAQS guidelines for fine particulate matter were met in South Africa in 2012. This was associated with a monetary value of $14 billion per annum, which was equivalent to the 2.2% of GDP in 2012. This happened even though the debate on the appropriate method to perform the valuation associated with premature mortality risks from pollution was ongoing (Altieri and Keen, 2019). To make things worse, developing countries have limited information on ways to estimate these figures and develop ways to reduce the impact using the value of statistical life (Altieri and Keen, 2019). A method was therefore adopted to calculate the value of statistical life (VSL) in South Africa using the values determined by USEPA (2023) for the USA estimates, and converted to the scenario for the year of interest, using the following formula:

$$VSL_{S.\ Africa,2018} = VSL_{US.1990} * \left(\frac{Y_{S.\ Africa,2018}}{Y_{US.1990}}\right)^{\varepsilon} * PPP_{1990} * \frac{CPI_{S.\ Africa\ 2018}}{CPI_{S.\ Africa\ 1990}} \tag{6}$$

Where:

$VSL_{S.\ Africa,2018}$ is the VSL value for South Africa in 2018 in Rands.

$VSL_{US.1990}$ is the VSL value for USA in 1990 in US Dollars.

Y is the per capita GDP of the specified country in the specified year, expressed in constant international (PPP-adjusted) dollars.

ε is the income elasticity of the VSL; BenMAP-CE default = 0.4

PPP_{1990} is the Purchasing Power Parity index in 1990 in units of South African rand per international dollar.

CPI is the consumer price index in the specified country in the specified year.

The VSL for South Africa in 2018 was therefore estimated at R 14 362 533 after obtaining all the required values from Statistics South Africa (2019) and making calculations using *equation (6)*. The results are given in Table 5 (Statistics South Africa, 2012; Statistics South Africa, 2019; OECD, 2023).

The resulting VSL values were then applied in the BenMAP tool to estimate the economic impact of SO_2, $PM_{2.5}$, and PM_{10} emissions and the cost of morbidity and premature mortality associated with exposure to ambient air pollution from ships in Durban port (Altieri and Keen, 2019).

6. Results

6.1. Population density and air pollution levels

The exposure of population to ships pollution in eThekwini (Durban City) area are depended on the relationship between air pollution levels and population density (Barregard et al., 2019). The eThekwini district is an area of 2558.9 square kilometres with a population density of 1446.8 people per square kilometre (Wazimap, 2023). The city is divided into one hundred and eleven (111) wards (Municipal Demarcation Board, 2020; eThekwini Municipality, 2023), each with varying population. Fig. 4 shows the results from the BenMAP population density mapping by ward.

BenMAP does not estimate personal exposure to pollutants, but it calculates the average pollutants concentration within which people are exposed to, in each grid. Such average values are used to work out the health impact functions (USEPA, 2023). The highest levels of concentration were within the port basin where ships dock and along the transit routes and these concentrations decreased rapidly with distance from the port. This trend holds true for both 2018 and 2020 emissions with the maximum Daily $PM_{2.5}$ values standing at 16.5 μg/m^3 in 2018 and 6.10 μg/m^3 in 2020 (Fig. 5). This meant a 63% reduction in the highest concentration of pollutant of $PM_{2.5}$ in 2020 compared to 2018. The PM_{10} also reduced by 63% from the highest Daily Mean concentration of 17.9 μg/m^3 in 2018 to 6.63 μg/m^3 in 2020 (Fig. 6). The SO_2 achieved a reduction of 81.6% from the highest Daily Mean concentration of 219.5 μg/m^3 in 2018 to 40.3 μg/m^3 2020 (Fig. 7).

It must be noted that before the fuel sulphur content was reduced in 2020, the highest daily concentration of SO_2 of 219.5 μg/m^3 from ships in Durban port exceeded the national ambient air quality standard by 94.5 μg/m^3, which is 75% more than the permitted SO_2 limit of 125 μg/m^3 (Fig. 7). However, after the forced changes, there were no exceedances as the highest SO_2 concentration steadied at 40.3 μg/m^3.

Table 5
VSL for South Africa in 2018 (USEPA, 2023).

PARAMETER	VALUE
$VSL_{S.Africa.2018}$	**R14 362 533**
$VSL_{US.1990}$	$4 800 000
$Y_{S.Africa.2018}$	$7049
$Y_{US.1990}$	$36 312
PPP_{1990}	1.27
$CPI_{S.Africa.2018}$	107.8
$CPI_{S.Africa.1990}$	23.75
ε	0.4

The pollution in areas that are within the eThekwini municipality boundary but farther away from the port were not mapped as the concentration and spatial distribution of these pollutants were below a specified threshold and thus regarded as negligible. However, BenMAP used the user-specific interpolation to average the concentration of these pollutants in remote areas and uniformly mapped their spatial distribution.

After mapping the concentration and the spatial dispersal of pollutants (Figs. 5, 6, and 7) and inserting the results on AERMOD, it was discovered that five wards experienced higher concentration of pollutants from ships than other wards and these included the Waterfront area (Ward 26), the City Central (Ward 28), Salisbury Island to Clairwood (Ward 32), Glenwood to UMbilo (Ward 33) and the Bluff (Ward 66). These wards are shown in Fig. 8 and are all surrounding the Durban port basin.

The population density of the most affected areas within the eThekwini municipality is provided in Table 6 (City Population, 2023; Wazimap, 2023). However, it must be noted that these population densities only represent permanent residents of these wards and not workers and commuters in and out of the port and the surrounding central business district (CBD), which may double or even triple the population of these wards at certain times.

6.2. Health impact assessment results

The health impact assessment from changes in emissions was done by wards. Each ward was assumed to represent a grid-cell (Keen and Altieri, 2016). The results show that wards that are closest to the port benefitted the most from the reduced emissions since 2020 as they experienced higher concentration of pollutants (Fig. 9).

Krewski et al. (2009) health impact function has the mortality endpoint for ischemic heart disease and lung cancer and has the health impact function for $PM_{2.5}$ only. However, the lung cancer mortality endpoint was not used in this study since Statistics South Africa (2012) did not report the statistics for lung cancer. Wichmann and Voyi (2012) health impact function has the mortality endpoint for Cerebrovascular and Cardiovascular and can estimate the impact of PM_{10}, SO_2, and NO_2. However, the health function for NO_2 was not utilized since there were no changes in the emissions of NO_2 following the reduction of sulphur content of fuel in 2020.

The reduction in mortalities from the reduced $PM_{2.5}$ emissions were therefore analysed using the Krewski et al. (2009) health impact function, whilst the reduction in mortalities from the reduced PM_{10} and SO_2 emissions were analysed using the Wichmann and Voyi (2012) health impact function (see Fig. 9). The three mortality endpoints considered were ischemic heart disease, cerebrovascular, and cardiovascular mortality endpoints. The ischemic heart disease and cerebrovascular mortality endpoints for all age groups are reported at municipal level by the Statistics South Africa (2012), however, the cardiovascular was only reported at a provincial level and only for the perinatal age group (0–2years). Such deficit created challenges in analyzing the health impact of SO_2 as the Wichmann and Voyi (2012) health impact function specifies cardiovascular as its endpoint for SO_2 pollutant. The values from Death by other heart diseases from Statistics South Africa (2012) were therefore chosen as the endpoint for Wichmann and Voyi (2012) health impact function. Fig. 9 shows the BenMAP results of the reduction in premature mortality due to reduced $PM_{2.5}$, PM_{10}, and SO_2 emissions from ships in 2020.

BenMAP produced the results in Table 7, as the reduction in excess mortality due to reduction in ship emissions in 2020. The total avoided mortalities were obtained by adding the results from individual wards. The changes in excess mortalities were then simplified as follows; Five

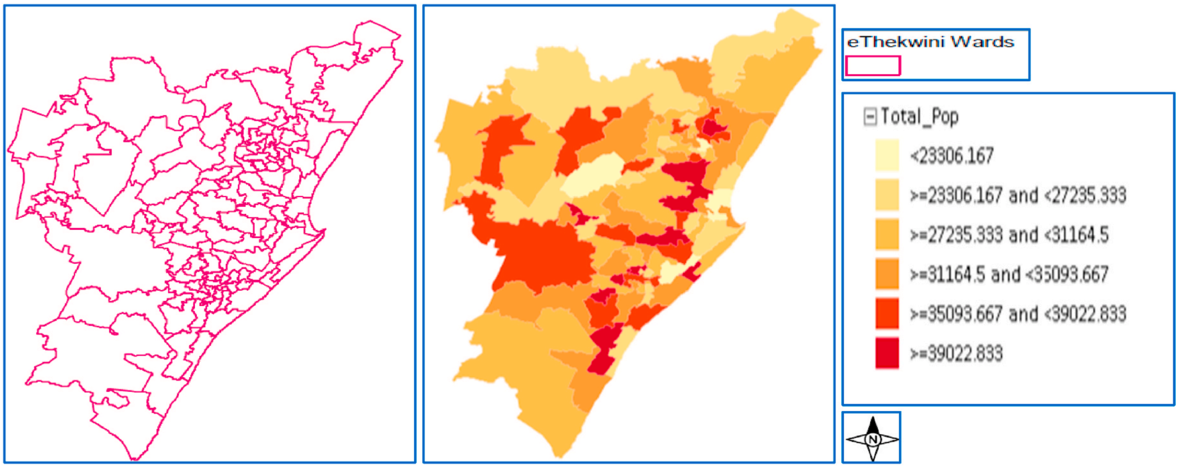

Fig. 4. Population density of eThekwini Municipality Wards (BenMAP, 2023).

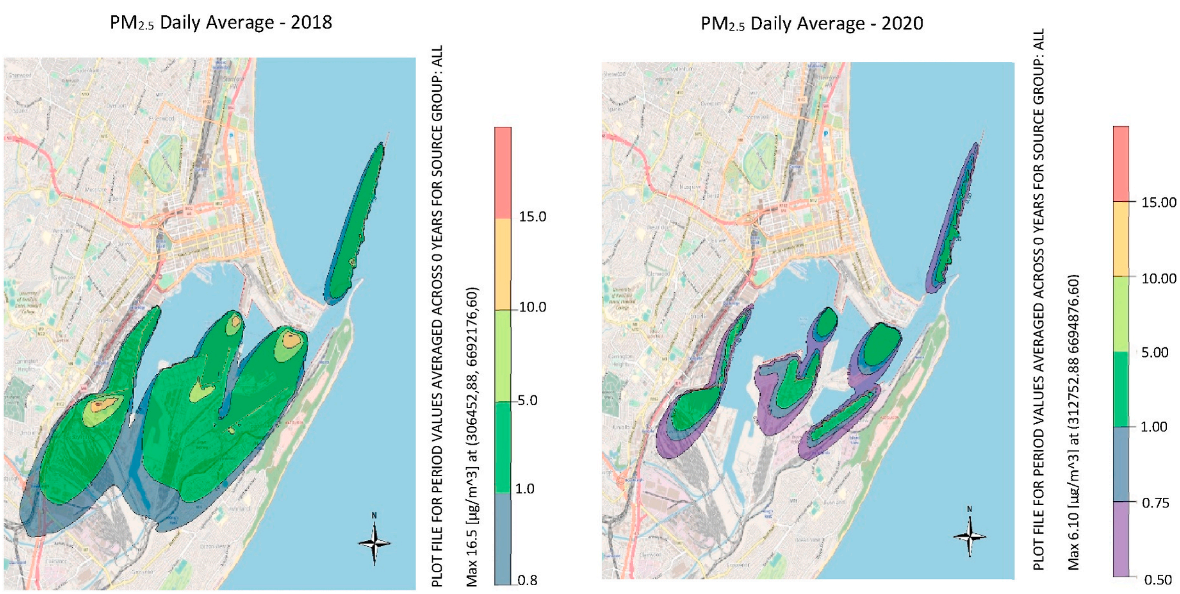

Fig. 5. Mean Daily concentration and spatial distribution of $PM_{2.5}$ in 2018 vs 2020.

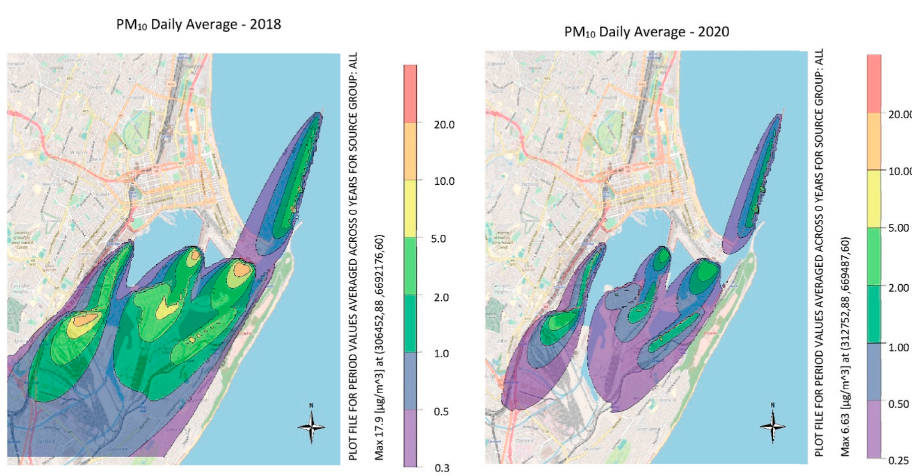

Fig. 6. Mean Daily concentration and spatial distribution of PM_{10} in 2018 vs 2020.

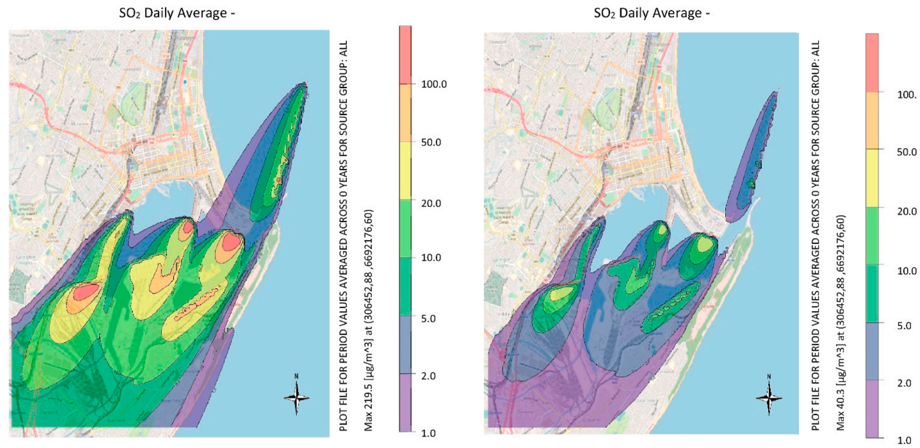

Fig. 7. Mean Daily concentration and spatial distribution of SO_2 in 2018 vs 2020.

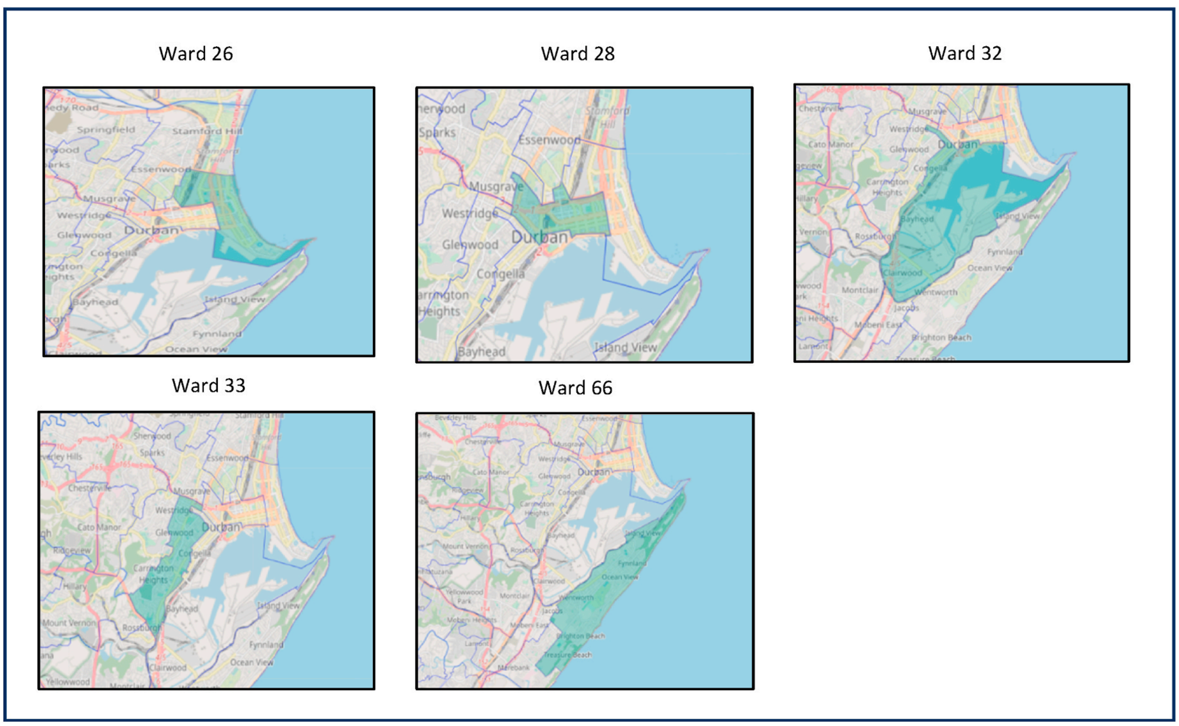

Fig. 8. Areas mostly impacted by ships emissions within eThekwini municipality (Wazimap, 2023).

Table 6
Population Density of the most impacted areas: Census 2016; City Population, 2023; Wazimap, 2023).

Description of Areas included	Area	Population 2011	Area Size (km2)	People per km2
Waterfront	WARD 26	34 601	7.2	4801.9
City Central	WARD 28	23 169	3.4	6789.1
Salisbury Island to Clairwood	WARD 32	25 109	26.3	954.4
Glenwood to UMbilo	WARD 33	28 944	7.3	3989.6
The Bluff	WARD 66	30 854	18.5	1666.1

(5) mortalities were avoided due to the reduction in $PM_{2.5}$ emissions; One (1) avoided mortality from the reduction in PM_{10} emissions; and Forty-three (43) avoided mortalities resulted from the reduction in SO_2 (Table 7). The higher figure from the SO_2 results can be associated with the higher SO_2 daily concentration that exceeded the national ambient air quality standards, and the higher mortality incidences reported under the death by other heart diseases from Statistics South Africa (2012), which is related to cardiovascular diseases.

It must be noted that the health impact functions used were extracted from Krewski et al. (2009) and Wichmann and Voyi (2012) but the results are from this study (Table 7). Both Krewski et al. (2009) and Wichmann and Voyi (2012) health impact functions are applicable to South African context (Altieri and Keen, 2019).

Based on the scale and the spatial extent of this study, the results indicated that the avoided mortalities resulting from the reduction in sulphur content of fuel were minimal, particularly the $PM_{2.5}$ and PM_{10} results. These results only reflected the impact of ships that entered the

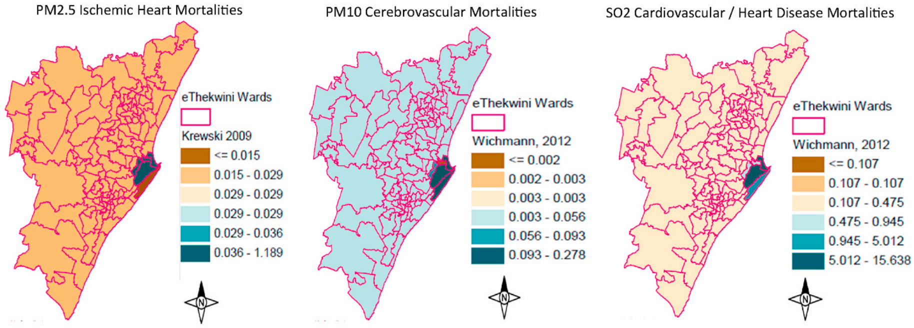

Fig. 9. Reduction in excess mortality due to reduction in $PM_{2.5}$, PM_{10}, and SO_2 emissions in 2020.

Table 7
Reduction in all-cause mortalities associated with reduction in sulphur content of fuel (BenMAP).

Health Impact Functions	Mortalities avoided by reducing $PM_{2.5}$ emissions in 2020	Mortalities avoided by reducing PM_{10} emissions in 2020	Mortalities avoided by reducing SO_2 emissions in 2020
Krewski et al. (2009)	5		
Wichmann, J. and Voyi, K. (2012)		1	43

Note: The results were rounded for reporting purposes.

port and considered their operation at berth, within the basin, up to 3 nautical miles to seaward from the harbour mouth.

6.3. Valuation Results

The BenMAP tool allows one to aggregate the incidence results from two or more air quality grids and health impact functions and to place the economic value on combined results (USEPA, 2023b). This is done by creating an aggregate, pooling, and valuation configuration file containing various air quality scenarios and the health impact functions to aggregate the estimated change in incidence and provide valuation of the results. Valuation means placing financial cost on projected health incidence. Monetizing the benefit of reducing air pollution encompasses the society's willingness to pay or the cost of illness, and BenMAP has a valuation function for this (USEPA, 2023b).

The two sources for valuation adjustments used were the USEPA Mean VSL system, and the World Bank (2016) estimate system. Hence there are two valuations for each pollutant of $PM_{2.5}$, PM_{10}, and SO_2. The results showed that the reduction in mortality risk from $PM_{2.5}$ had an estimated value of R70 million using USEPA Mean VSL system and R24 Million using the World Bank (2016) estimate (Fig. 10).

The reduction in mortality risk from PM_{10} had an estimated value of R13 million using USEPA Mean VSL system and R4 Million using the World Bank (2016) estimate (Fig. 11).

The reduction in mortality risk from SO_2 had an estimated value of R600 million using USEPA Mean VSL system and R200 Million using the World Bank (2016) estimate (Fig. 12).

The total monetary cost associated with the $PM_{2.5}$, PM_{10}, and SO_2 burden was obtained by adding the results of all pollutants using the USEPA Mean VSL estimate, and the World Bank (2016) estimate systems, separately. The reduction in mortality risk associated with the reduction in sulphur content of fuel was thus estimated at the total cost of R683 million using the USEPA Mean VSL estimate and R228 million using the World Bank (2016) estimate. These were equivalent to 0.2% and 0.05% of the eThekwini GDP of R468 billion in 2016 respectively.

7. Limitations

Health outcomes estimated depend on the accuracy in emission calculations. Any errors or limitations in emission estimates would be carried to the health estimate calculations (Remais et al., 2014). In this study, the first limitation was the uncertainty on emissions since only ships berthed inside the port and those manoeuvring within the port limits up to 3 nautical miles outside the port were considered. Ships on an innocent passage along the coastline and those anchored at a distance away from the port were not considered. Such ships may have an impact on emissions reaching the city and may add to premature mortality in the city. Such limitation may underestimate the impact of ships emission on the city's population. It is difficult to estimate the number of ships transiting close to the port without entering or those at anchor, however, showed an estimate of about $^3/_8$ between ships in transit or at anchor and ships in port at any given time. This could result in almost 40% error in estimated emissions. Nonetheless, this error may be minimized by the fact that emissions from ships at anchor or on innocent passage occur in

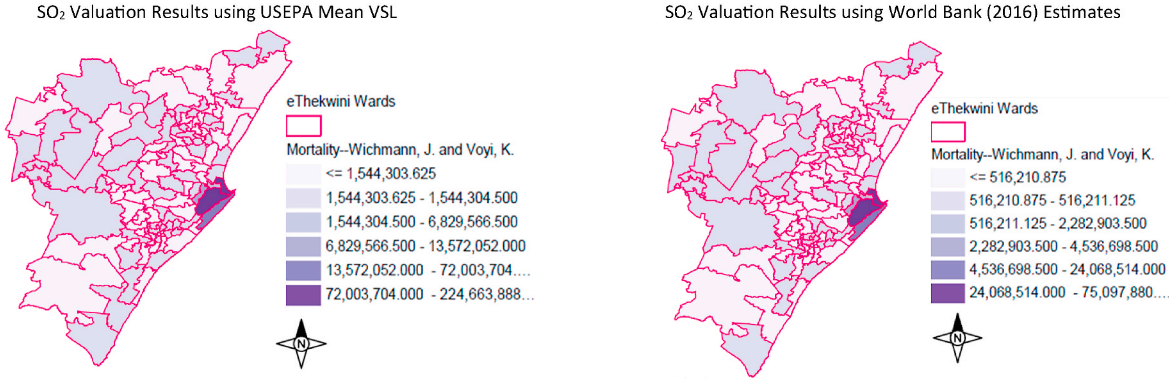

Fig. 10. Valuation Results for $PM_{2.5}$ from both USEPA Mean VSL and World Health Organization (WHO), (2006).

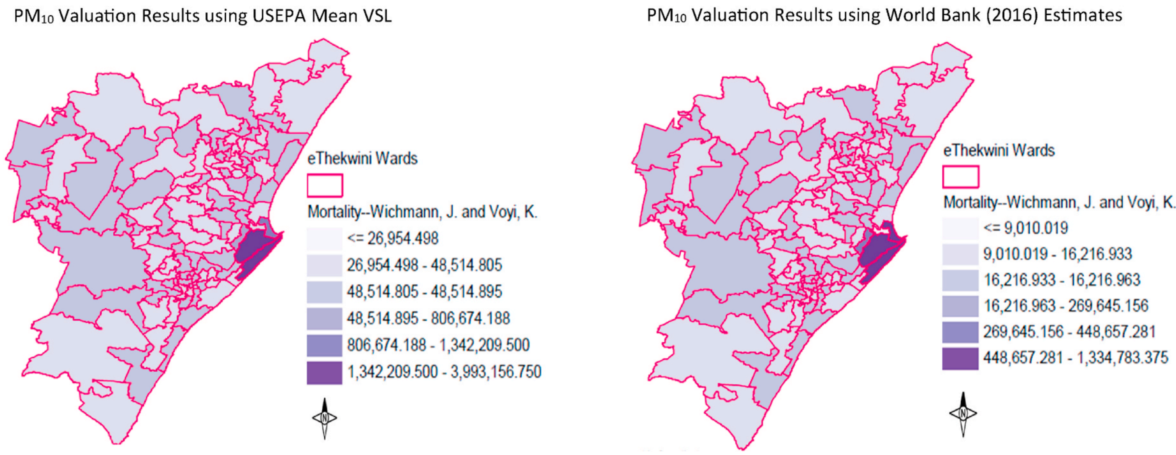

Fig. 11. Valuation Results for PM_{10} from both USEPA Mean VSL and World Health Organization (WHO), (2006).

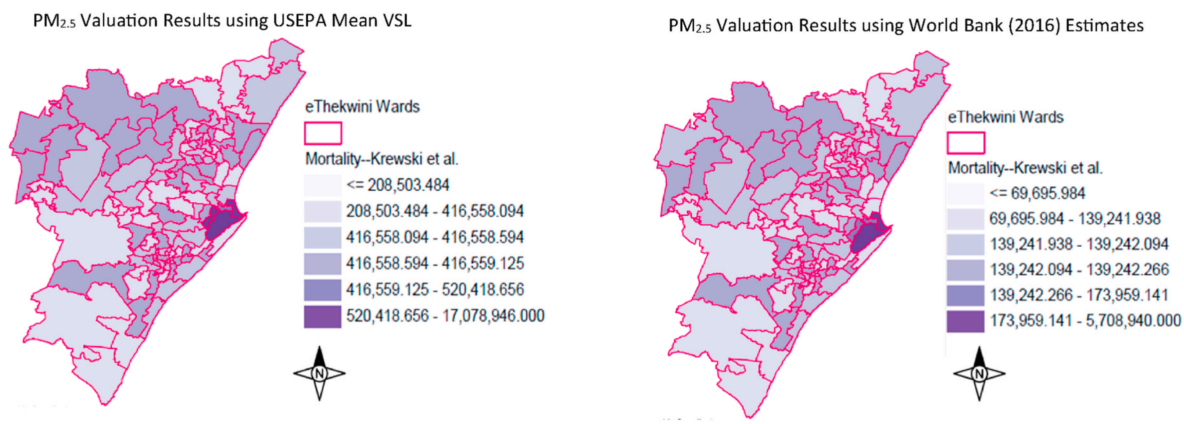

Fig. 12. Valuation Results for SO_2 from both USEPA Mean VSL and World Health Organization (WHO), (2006).

areas with low or no population and since the air quality grid is created via an inverse distance squared-weighted interpolation, any pollutant concentration in areas farthest away from the source, will contribute very little to the overall mortality burden (Altieri and Keen, 2019).

Another limitation is associated with the uncertainty in health risk associated with specific concentration change. South Africa has limited data on premature mortalities caused by exposure to certain pollutants to create the health impact functions for modeling and therefore relies on studies in Europe and America and global exposure mortality model (Altieri and Keen, 2019). This was demonstrated in Altieri and Keen (2019) study of the impact of particulate matter in South Africa where there were no specific studies in South Africa to generate the concentration-response function for $PM_{2.5}$ using local population. Instead, the Krewski et al. (2009) study in the USA was utilized to create the health impact function for $PM_{2.5}$ (Altieri and Keen, 2019) and the same was done in this study. Nevertheless, the health impact functions for PM_{10} and SO_2 were extracted from a South African study of Wichmann and Voyi (2012).

Lastly, the formation of secondary aerosols was not simulated. However, these processes are more relevant at larger scales and the model domain in this study was only 10 km × 10 km.

8. Discussion and conclusion

The reduction in sulphur content of marine fuel from 3.5% to 0.5% in 2020 resulted in reduction of ship emissions by 63.8% for both $PM_{2.5}$ and PM_{10}, and 81.2% for SO_2. This reduction in ship emissions from Durban port resulted in the estimated number of premature mortalities avoided in 2020 compared to 2018. The combined results indicate that 49 premature mortalities were avoided because of mandatory reduction in sulphur content of fuel in 2020.

The economic impact of this reduction in fuel sulphur content was estimated at the total cost of R228 million using the World Bank (2016) estimate and R683 million using the USEPA Mean VSL estimate over a period of one year. This respectively accounted for 0.05% and 0.2% of eThekwini's GDP that was estimated at R468 billion in 2016 (eThekwini Municipality, 2023b).

Therefore, the reduction in sulphur content of fuel from 3.5% to 0.5% in non-sulphur emission control areas (non-SECA) significantly reduced ship emissions and led to a substantial reduction in premature mortalities and the associated monetary costs in Durban.

CRediT authorship contribution statement

Nkosinathi M. Manqele: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Raeesa Moolla:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis. **Lisa Frost Ramsay:** Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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