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Emission Scenarios and Health Impacts of Air Pollutants in Goa

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ABSTRACT

This paper presents the first emission inventory for the highly urbanized state of Goa in India, which is an important international tourist destination and also accommodates significant industrial activities, including mining. The observed concentrations of the pollutants like PM_{10} and $PM_{2.5}$ show violations at many locations. Sectoral inventories prepared in this study depicts mining (38%), industries (24%), and transport (10% tail-pipe and 15% road dust) as the major contributors to the PM_{10} emissions in the state. Higher emissions intensity is observed in heavily populated and industrialized coastal taluks and mining dominated taluks. Emissions are projected for the future (2030) under two different scenarios (business as usual and alternative) to assess future air quality and impacts. The grid-wise emissions under these future scenarios are fed into an air quality model, to estimate spatial distribution of PM_{10} concentrations in Goa. The model results are validated with actual observations. Thereafter, the grid-wise PM_{10} concentrations are overlaid on the population to compute its health impacts using established dose response functions. The study shows that PM_{10} accounts for 2.6% of mortalities in Goa, which are expected to go up further in a business as usual scenario. Alternative strategies which show reduction in pollution and associated health impacts in the region are evaluated. Based on the alternative scenario, key recommendations are made for air quality improvement in the state.

Keywords: Emission inventory; Air quality modelling; Health impacts; Goa.

INTRODUCTION

Rapid economic development, industrial growth, and mobility demands lead to emissions of air pollutants, which have become an important environmental concern in urban settings. Worldwide, PM (particulate matter) alone causes millions of premature deaths and years of life lost. In India, 0.62 million mortalities are caused due to deteriorating ambient air quality (Lim *et al.*, 2012). The effects of inhaling particulate matter have already been widely studied. These include asthma, lung cancer, cardiovascular disease, respiratory diseases, premature delivery, birth defects, and premature death. Several studies have indicated a close link between ambient PM_{10} concentrations and mortalities. A study conducted by Schwartz *et al.* (2002) suggests no safe threshold level for PM and estimated an increase of 1.5% in daily mortalities with every 10 µg m^{-3} rise in $PM_{2.5}$ concentrations.

The state of Goa, in India, is known worldwide as a tourist destination. The region, which is known for its pristine environment is on the path of rapid urbanization and economic growth. Jamir and De (2013) assessed the GHG emissions for the west coast region (WCR) in India including Goa for the period 1980–2005 and estimated the compounded annual growth rate for GHG emissions in Goa region to be 5.59% for CO_2, which clearly shows rapidly growing energy consumption. Contribution of gasoline consumption to CO_2 emissions shows the highest growth of 8.5% depicting tremendous increase in vehicular activity. Consequently, air quality which was not a priority issue in the region in the past is gradually becoming an important concern. While gaseous pollutants are within the limits, many regions in the state have shown violations of standards of PM_{10} concentrations. There are multiple sources of PM_{10} pollution in Goa- transportation, ports, iron-ore mining, residential sector energy use, industries, road dust re-suspension etc. Natural sources of are not considered in this study but sources like sea spray can contribute significantly to PM_{10} levels in coastal areas like Goa. Goa has not just attracted the tourists (2.3 million domestic and 0.47 million international in 2010) but also migrants from other states. Subsequently, there is growth in demand for mobility, energy, and manufactured products, which in turn has led to increased emissions of pollutants. Other than emissions linked to resident and tourist population, iron-ore mining

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also contributes to deterioration of air quality in the region. Recently, a ban on mining activities was enforced in view of controlling pollution. There are other industries also, which release significant quantities of pollution loads into the atmosphere. Other than these sources, some rural areas of the state still use biomass for cooking which leads to much higher concentration of pollutants indoors and contributes to outdoor air pollution. It is in this context it becomes important to understand the contribution of different emission sources in the state and assess their future trajectories to reduce the deterioration of air quality and health impacts on the resident population.

Emission inventorization is an important step to know the shares of contributing sources in the region. In emission inventories, sectors such as transport, industries, mining, domestic fuel burning at household and commercial level, and road dust re-suspension, etc., are analysed for their contributions in the total emission loads generated in the region over a specific time interval (Utah DEQ, 2012). Construction of emission inventories is important to understand the sources of pollution so as to define priorities and set objectives for pollution management. Global inventories like EDGAR (Emission Database for Global Atmospheric Research) are prepared at the country level for different sectors at a resolution of 0.1°, based on data such as location of energy and manufacturing facilities, road networks, shipping routes, human and animal population density and agricultural land use (EDGAR, 2008). Similarly REAS (Regional Emission Inventory in Asia) emissions use country/region specific emission factors for different pollutants emitted from subdivided source sectors to estimate emissions at state or/and country levels, which are then allocated at a resolution of 0.5 × 0.5 degree (Granier *et al.*, 2011). The emission estimates of global inventories may be different when scaled to city level as compared to an emission inventory based on local data sources of a city. The study by Granier *et al.* (2011) compared global and regional inventories like EDGAR, REAS, etc., for different regions of the world and concluded that different inventories are updated at different intervals and therefore their respective reference activity data and emission factors could be significantly dissimilar. The inventories discussed above although cover Goa as a region, but may just represent Goa in one or two macro grids with broad estimates.

Other than global and regional inventories, there are several studies conducted in India on assessing the emissions and air quality of major Indian cities. These include for cities like Nagpur (Majumdar and Gajghate, 2011), Mumbai (Bhanarkar *et al.*, 2005a), Delhi (Gurjar *et al.*, 2004; Sharma and Pundir, 2008; Ramachandran and Shwetmala, 2009; Sharma *et al.*, 2013), Bangalore (Sharma *et al.*, 2014), and Jamshedpur (Bhanarkar *et al.*, 2005b) in India. However, there are no specific studies to inventorize the emissions of pollutants for the Goa region. Considering the pollutant exposure to the resident and tourist population, it is important to develop a multi-sectoral, multi-pollutant, high resolution emission inventory for the region for air quality assessments and control. This paper uses local information on activity levels (based on secondary and primary sources) in different sectors and develops air pollutant emission inventories for the state of Goa. The inventory is prepared for the baseline year 2010 and projected for future years (2020 and 2030) as well. This is used to predict air quality in future years using air quality models. Based on these, the first ever estimates of health impacts attributed to air pollution in Goa are presented in this study. Eventually, sector-specific strategies are suggested to reduce emissions and improve air quality. This paper assesses air quality in a unique setting dominated by multiple activities like tourism, industries, mining, transport and agriculture impacting the air quality. Other than 1.4 million residents, about 3 million tourists (including 0.47 million international tourists) are exposed to air pollutant levels which violate the prescribed national standards and are well above the WHO guidelines. It is in this context this assessment adds value and provides important directions for improvement in air quality using air quality modelling approach.

MATERIALS AND METHODS

Study Area

Goa, the smallest state of India "Fig. 1", covers an area of 3,702 km^2, lies between the latitudes 14°53'54"N and 15°40'00"N and longitudes 73°40'33"E and 74°20'13"E. The western part of Goa is a coastline of about 101 km and the eastern part is characterized by the Western Ghats, which separate it from the Deccan plateau. The state is highly urbanized with 62% of the population residing in urban areas. Administratively, the state is organized into two districts—North Goa comprising six *talukas* (sub-divisions of a district) with a total area of 1,736 km^2 and South Goa comprising five *talukas* with an area of 1,966 km^2 (Census 2011). Goa, being in the tropical zone and near the Arabian Sea, has a hot and humid climate for most part of the year. The month of May is the hottest, seeing day temperatures of over 35°C (95°F) coupled with high humidity. Most of Goa's annual rainfall is received through the monsoons which last till late September. Goa has a short winter season between mid-December and February marked by nights of around 20°C (68°F) and days of around 29°C (84°F). The air quality in the region is already deteriorated and violates the annual average standard of PM_{10} (60 µg m^{-3}). Due to adverse meteorology (lower wind speeds and mixing heights), the violations are found to be more in winters than in summers. The state accommodates a population of about 1.4 million and attracts about 3 million tourists annually. The state is known for its iron ore mining, and in 2012, in consideration of pollution levels in the region, the Honourable Supreme Court of India imposed a ban on mining activities in Goa. It has now very recently allowed a limited mining of 20 million tonnes yr^{-1}. With ban on mining, air quality in Goa has shown some improvement in 2013 (GSPCB, 2013).

Data Collection

An exhaustive literature review and stakeholder consultations were carried out to understand the activity levels in different sectors like transport, diesel generator sets (DG), industries, mining, and domestic, etc. Data on

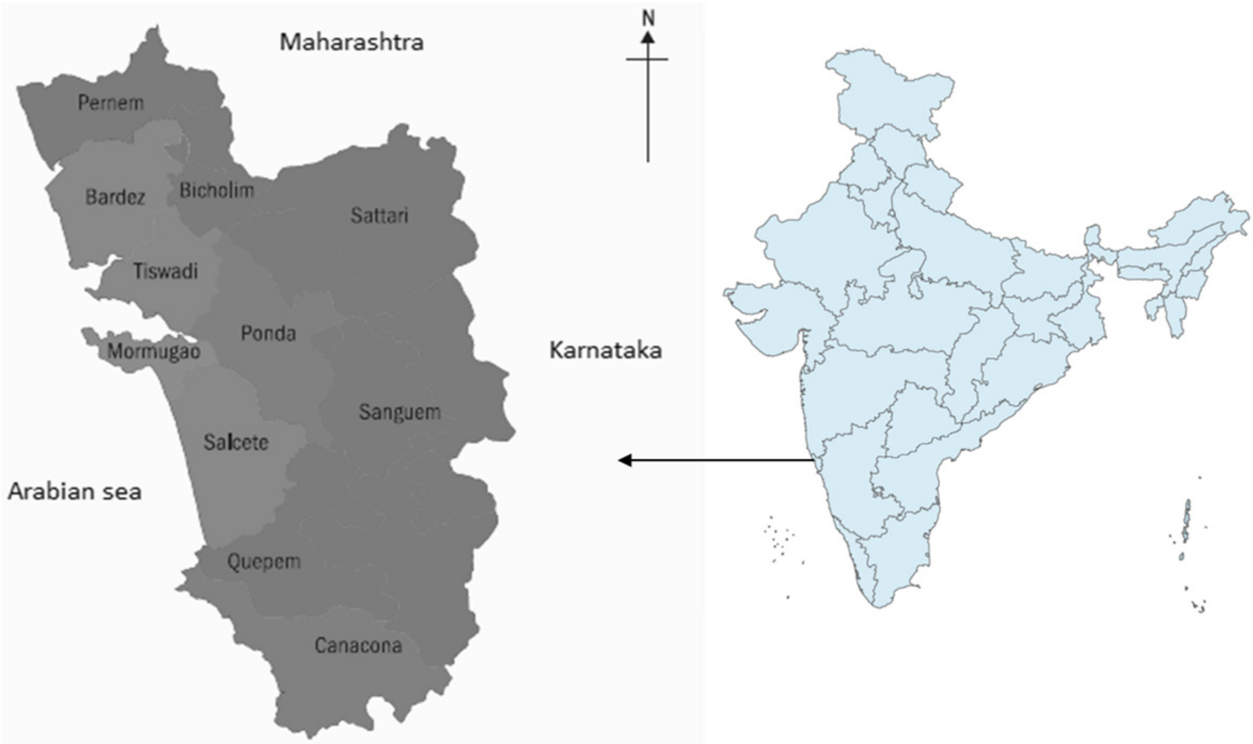

Fig. 1. Taluka map of Goa.

number of registered vehicles, industrial production, mined ore; numbers of DG set installations were collected from local government departments. The number of registered vehicles in the State was collected from the Regional Transport Office (RTO). Information on fuel use and production rates in industry sector was collected from Goa State Pollution Control Board (GSPCB). Information on DG set installations was collected from the Chief Electrical inspectorate. Mining production rates were collected from DoMG, 2012. Other than secondary data sources, primary surveys were carried out to assess the traffic patterns, usage of DG sets, open burning of agricultural residue, and fuel use in bakeries and restaurants. For estimating emissions of road dust resuspension, silt loading samples were collected from different categories of roads in different *talukas* of the State. Before primary surveys, pilot testing of questionnaire was carried out. Spatial analysis using GIS was performed to detect missing or incorrectly mapped emissions across the domain.

Methodology

The broad approach used for emission estimation is shown in Equation 1 (Klimont *et al.*, 2002)

$$Ek = \sum_{l}\sum_{m}\sum_{n} A_{k,l,m.} ef_{k,l,m.} \left(1 - \eta_{l,m,n.}\right) . X_{k,l,m,n} \qquad (1)$$

where:
k, l, m, n are region, sector, fuel or activity type, abatement technology;
E denotes emissions of pollutants (t day^{-1});
A the activity rate;
ef the unabated emission factor(t per unit of activity);
η the removal efficiency(%); and
X the actual application rate of control technology *n* (%) where $\sum X = 1$.

In this study, emission factor approach is used to estimate sector-wise emissions based on activity data, emission factors, and air pollution control technologies employed in the sectors. Bottom-up approach is used to assess the energy consumption in different sectors. The broad framework used in the present study is shown in "Fig. 2". The specific methodologies used and the emission factors used for emission inventorization of different sectors are presented in Table 1. Emissions are estimated for the baseline year 2010 for PM_{10} for all the 11 *talukas* in the State and *taluka*-wise emission intensities are computed. Future projections of emissions were made for two scenarios based on business as usual (BAU) and alternative policies (ALT) for pollution control in different sectors. Sectoral projections for the year 2020 and 2030 were carried out based on the past trends in the sector and present plans and policies of the government. The methodologies used for future emission inventorization was the same as used for the baseline assessment. Details of the projected activity data for various sectors are presented in Chapter 9 of Sharma *et al.* (2015), depicting sectoral growth trajectories for the next twenty years. GIS software is used to allocate the baseline and future emissions at a grid resolution of 3 × 3 km^2. The emission estimates are based on limited set of emission factors relevant for Indian context, and hence, in absence of extensive information on emission factor values for various sources, a proper uncertainty analysis couldn't be carried out for different sources. However, overall estimates of emissions

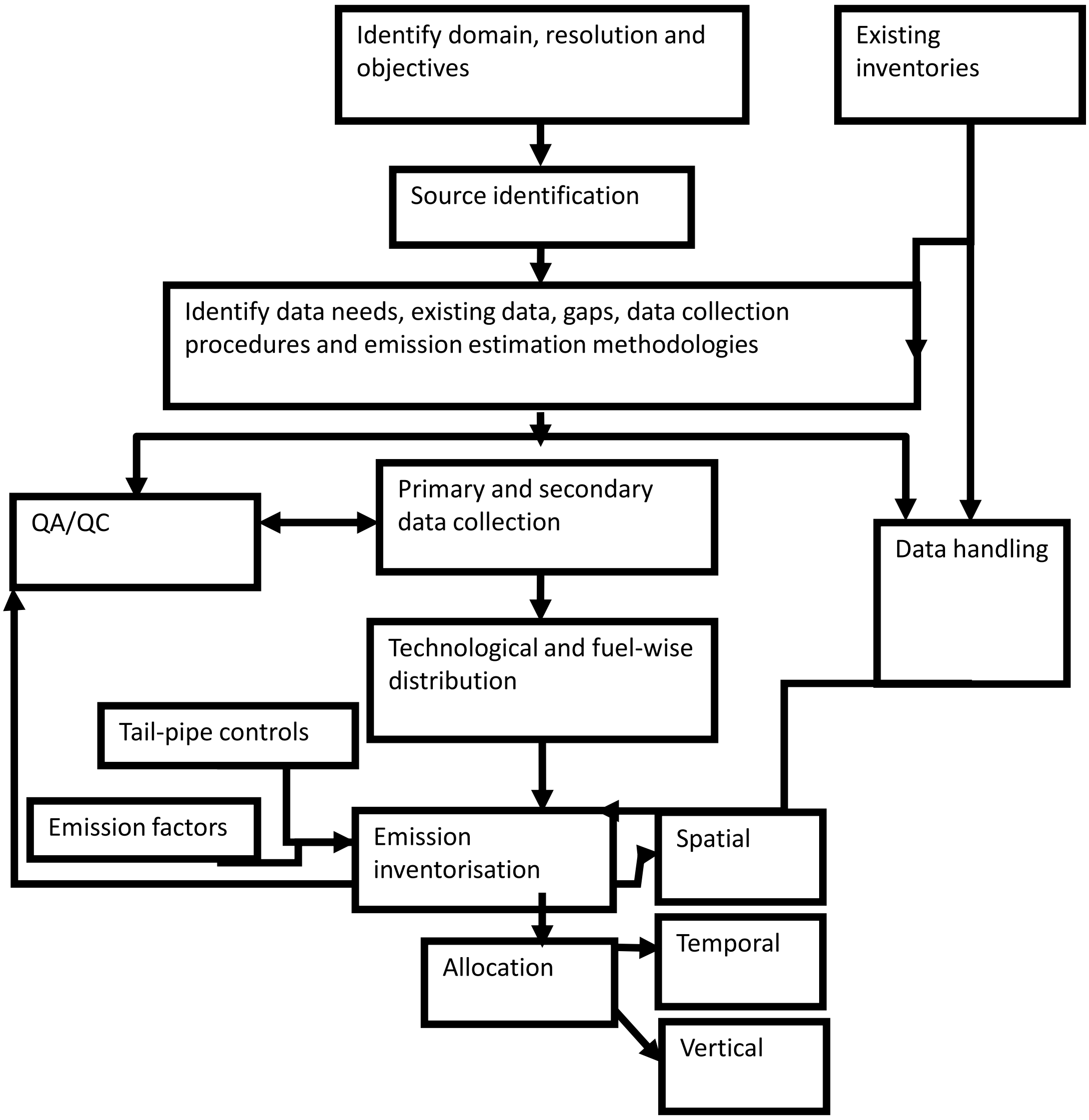

Fig. 2. Overall approach for preparation of emission inventory.

are validated against the state-level estimates of GAINS Asia database (https://gains.iiasa.ac.at).

The grid-wise emissions estimates for the baseline and future scenarios are fed into a Gaussian plume air quality model-ISCST3 (Industrial Source Complex Short Term model) for assessment of air pollutant concentrations in the region. Gaussian plume models predicts the pollutant concentrations at a desired location based on release of emissions from a source and prevailing meteorological (like temperature, wind speeds, mixing height) and terrain conditions. After the release of pollutants from a source, the model disperses pollutants based on the Gaussian distribution, with maximum value of the concentrations at the centre of the plume. The dispersion coefficients are derived based on prevailing meteorological conditions in different seasons. AERMOD software 8.1.0 version is used for carrying out the air quality modelling. ISCST3 model is a steady-state Gaussian plume model used to estimate average concentration of pollutants based on emission, meteorological, and terrain inputs. In the past, several studies have used the ISCST3 model for prediction of pollutant concentrations at various locations in India and the world (Elbir, 2002; Ying *et al.*, 2007; Bandyopadhyay, 2008; Sharma and Chandra, 2008). Climatological data for the study domain is retrieved from IMD (2015) and RAMMET 8.1.0 model is used to prepare meteorological inputs for the ISCST3 model. AERMAP terrain processor within the AERMOD software is used to prepare terrain inputs for the study domain. Terrain datasets for Goa are retrieved from USGS (2015) which are fed into the AERMAP to generate elevation levels for the study domain-emission sources and receptor locations. Mixing heights for winters, summers, and post-monsoon seasons for the Goa region were retrieved from ENVITRANS (2015). ISCST3 model runs are performed for the baseline year 2010 and then modelled PM_{10} concentrations are validated with actual observations at two monitoring locations—Panaji and Marmugao. Actual monitoring data for the two stations is obtained from CPCB (2012). The grid-wise validated PM_{10} concentrations obtained from the air quality model are used to estimate health impacts due to ambient PM_{10} concentrations.

Table 1. Methodologies followed to estimate emissions from various sectors.

S.N	Sector	Approach	Data requirements and Data source	Emission factors (E.F.)
1	Transport	E = Vehicles x (km day^{-1}) × E.F	Number of registered vehicles (category and vintage wise) km travelled per day for all categories of vehicles (primary survey and transport department, RTO office)	ARAI, 2007
2	Industry	E = Actual emission (T d^{-1} or tonnes day^{-1}) E = Industrial fuel consumición × E.F E = Industrial production × E.F	Actual emissions from GSPCB Industrial fuel consumption (furnace oil, diesel, petrol, biomass, LPG), Industrial production, Air Pollution Controls E GSPCB consents	WHO, 1993; CPCB, 2003
3	DG sets	E = No of DG sets × Capacity (kW) × Usage (hr) × E.F	Number of DG sets (Electricity department, sales data, estimates based on survey	AP 42
4	Road dust	E.F = $\{K\,(SL/2)^{0.65}.\,(W/3)^{1.5} - C\}\,(1 - P/4N)$ k = particle size multiplier for particle size, SL = road surface silt loading (g m^{-2}), W = average weight (tonnes) of the vehicles, C = emission factor for vehicle fleet exhaust, brake wear and tyre wear, P = number of "wet" days, N = days in averaging	Silt loading (g m^{-2}) Vehicles data Number of rainy days	AP 42
5	Bakery /hotel/rest.	E = No of bakery/hotels/rest. × fuel (kg day^{-1}) × E.F	Daily fuel consumption in bakery/hotels/rest. (by survey/literature)	USEPA, 2000
6	Domestic emissions	E = Population × % fuel consumption × quantity of fuel used (kg d^{-1}) × E.F.	Population, % household using fuels (LPG, kerosene, wood), quantity of fuel used	USEPA, 2000
7	Mining emissions	*Overall mine* $E = u^{0.4} \cdot a^{0.2}.\{9.7 + 0.01\,p + b/(4 + 0.3b)\}$ *Open pit emission rate* $E = [\{(100 - m)/m\}^{0.1} \cdot \{s/(100 - s)\}^{0.3} \cdot a^{1.6} \cdot \{u/(10 + 125u)\}]$	a = area of pit (km²) m = Moisture content u = wind speed (m s^{-1}) p = mineral production (MT yr^{-1}) b = OB handling (Mm^3 yr^{-1})	Chakraborty *et al.*, 2002
8	Port emissions	$E = k \times 0.0016 \times (U/2.2)^{1.3}/(M/2)^{1.4}$ kg Mg^{-1} k = particle size multiplier, U = mean wind speed, metres per second (m s^{-1}), M = material moisture content (%)	Quantity of coal handled at port (Mormugoa port Trust) Wind speed (Meteorology department) Moisture content	A P42
9	Open burning	E = Waste burnt × E.F.	Waste burnt (Agriculture, farm land and orchard farmer survey)	AP 42; Venkataraman *et al.*, 2006

E is emissions.

World Health Organization (2013) has stated that there is no safe level of exposure or a threshold for PM_{10} below which no adverse health effects occur. WHO (2006) and Samoli *et al.* (2008) has shown that all-cause daily mortalities increase by 0.2–0.6% per 10 µg m^{-3} increase in PM_{10}. These dose response relationships are used to compute mortalities attributed to PM_{10} concentrations in the State under different scenarios (BAU and ALT) (Eq. (2)).

$$\text{Incremental mortalities} = (PM_{10}\text{ concentration dose}) \times \text{DRF} \times \text{All-cause mortality in Goa} \quad (2)$$

where DRF is the dose response function taken as 0.6% increase in all cause mortalities per 10 µg m^{-3} increase in PM_{10} concentrations. While there are studies like Wong *et al*. (2010) and Lu *et al.* (2015) which suggest that gaseous pollutants also contribute to health damages, this study focuses only on PM_{10}, as the concentrations of gaseous pollutants like NO_x and SO_2 in Goa are well within the prescribed standards. Based on the emissions, concentrations, and health impacts under different scenarios, sector specific recommendations have been proposed for air quality improvement in the State.

RESULTS AND DISCUSSIONS

Activity Levels

Activity levels in the State, which have implications over energy consumption and air pollutant emissions are presented in Table 2. Based on past trends, the population of Goa is projected to increase to 1.6 million in 2030 from about 1.45 million in 2010. However, the tourist inflows are projected to double in the same timeframe. Goa shows one of the highest per capita income levels in the country and is expected to double its registered vehicular population in the next 20 years. Industrial production is projected to grow at 6.3% (based on past growth patterns) for next 20 years, although as per the State's industrial policy, only non-polluting new industries are being promoted.

Baseline Emission Inventory (2010)

Baseline emissions of different pollutants estimated using the methodologies and emission factors are presented in Table 3.

Transport Sector

Total registered vehicles in Goa have increased from 0.15 million in 1995 to 0.73 million in 2010. With growing per capita incomes, vehicles per 1000 people have increased to more than 400 in 2008, which is even higher than Delhi. Total vehicular kilometres travelled by different vehicle categories were estimated through parking lot surveys for a sample of more than 2000 vehicles in different *talukas* of the State. Surveys revealed that motor bike, rent bikes, cars, taxis and buses travel about 38 km, 62 km, 48 km, 78 km and 154 km, respectively on a daily basis. There are some steps taken for controlling emissions from the sector. During 2000–2010, entire India along with Goa gradually moved from Euro-I to Euro-III equivalent (known as BS norms) vehicle emissions control norms. Along with improvement in technology of vehicles, the quality of fuel (petrol/diesel) has also improved (reduction of lead, benzene, and sulphur content in the fuels). These measures have resulted in reduction in the emission load from the sector. Vintage of a vehicle is another important contributing factor to the tail-pipe emissions. According to the registered vehicles data, 43% of the vehicles in Goa are of pre-2000 times, when BS norms had not been adopted. Accounting for all these aspects, the emissions are estimated for different categories of vehicles in Goa. PM_{10} emissions are estimated to be 4.7 T day^{-1}. The vehicle category-wise distribution of emissions shows that diesel vehicles account for 69% of PM_{10} emissions, respectively in the sector ("Fig. 3").

Industries

Manufacturing industries in Goa, as per 2010 data, contribute to about 23% of the gross state domestic product in Goa. There are about 20 industrial estates and the major industrial activities in the state are mining, pharmaceutical, chemicals, iron ore, agro, electronics, and ship building. Industrial emissions are estimated based on production, fuel use, and information on control technologies collected from the GSPCB.

Mining industry is an important contributor to the GDP in Goa. Production of iron ore (which is the main product mined) in the year 2010 was 54 million tonnes in 2010. The PM_{10} emissions associated with mining are due to working with bare machinery, dry screening of ores, and drilling operations. On an average, 2.5 to 4 tonnes of mining waste have to be excavated to produce a tonne of iron ore. Other than the mining operations, transportation of ore (movement of machinery/trucks) also leads to significant dust pollution. Chakraborty *et al.* (2002) have developed factors to estimate emission from open cast mines. Data on production of ore, over-burden, wind speed, etc., are used to estimate emissions from the sector. Mining emissions are estimated to be 17.7 T d^{-1} for PM_{10}, which is about 38% of the overall PM_{10} inventory.

Other than mining, industries use fossils fuels for boilers and hot-mix plants, which leads to considerable emissions of air pollutants. Using the emission factors approach described in Table 1, emissions from other industries are estimated to be 11.4 T day^{-1} (24%) for PM_{10}. Distribution of PM_{10} emissions from different categories of industries is shown in "Fig. 4", which shows higher shares of hot-mix plants and metal industries.

Port

Mormugao Port in Goa is one of the oldest ports on the west coast of India. Goan iron ore is exported to many countries including China, South Korea, Italy, and other European countries through this port. In 2009–10, the port handled a traffic of 48.85 million tonnes, which is 9% of the traffic handled by all the twelve major ports of India. About 350–400 loaded trucks and containers come to the port for transporting the freight to and from the port. Fugitive emissions from coal handling activities are estimated using AP-42 emission factors as about 20 kg day^{-1}.

DG Sets

With widening demand–supply gap of power, use of DG sets is on the rise. DG sets are used in houses, apartments, public institutions, commercial centres, and industries as an alternate power source. These units emit at a low height and hence, cause more exposure to the humans. Data of DG sets installed in Goa, show that there is an installed

Table 1. Activity levels in the State (base and future years).

Parameter	2010	2020	2030
Population (million)	1.45	1.541	1.6
Tourist inflows (million)	2.59	3.82	5.06
Vehicles (million)	0.73	1.1	1.5
Industrial (NSDP billion USD)	1.22	2.26	4.19
DG set installed capacity (MW)	250	477	760
Mining (million tons yr^{-1})	54	93	132

Table 2. Sectoral emission loads for PM_{10} (tonnes day^{-1}) in 2010.

S.No	Sector	PM
1	Transport	4.7
2	Industries	11.4
3	Mining	17.7
4	Port	0.02
5	DG sets	0.7
6	Road dust	7.4
7	Domestic	2.9
8	Agri burning	0.8
9	Bakeries	1.4
	Total	47.0

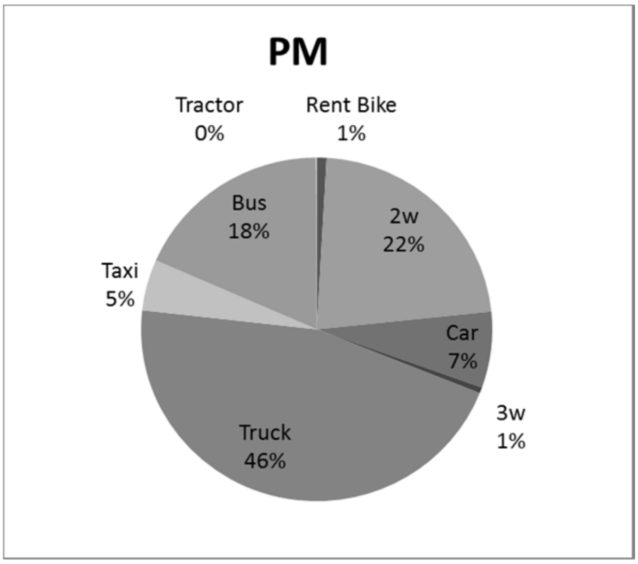

Fig. 3. Category wise distribution of PM_{10} emission loads from road transport sector in Goa.

capacity of about 250 MW in the state. The daily usage of DG sets is ascertained through a primary survey. Emissions are estimated using the emissions factors from AP-42. PM_{10} emissions are estimated to be 0.7 T d^{-1}

Road Dust Re-suspension

Low-quality construction, irregular cleaning, and low maintenance can result in increased silt loading over the roads, which leads to re-suspension of dust during vehicular movements. Mining regions with roads strewn with spilled ore are most prone to this type of dust pollution. Silt loadings were measured on different categories of roads in Goa as per the method prescribed in AP42, and higher loading were observed in mining affected *talukas* of Sanguem and Bicholim and also in the State capital, Panjim, due to increased construction activities. The PM_{10} emissions are estimated as 7.4 T d^{-1}, which contributes significantly (15%) in the overall inventory of PM_{10} in Goa.

Residential Fuel Combustion

According to Census 2011, 21% households in Goa use firewood as fuel, while 73% use LPG. Kerosene is used as the primary fuel in 4% of households. Solid and liquid fuels when burnt in traditional cooking devices like traditional *chulhas* are the major cause of indoor air pollution in rural households. The emissions are estimated to be 2.9 T day^{-1} and 0.8 T day^{-1} for PM_{10} and NO_x, respectively. Residential combustion accounts for 7% of PM_{10} emissions in the State.

Others Sources

Other important sources of air pollution include burning of crop residues in agricultural fields, firewood in bakeries, and other local restaurants. The data on open burning of agricultural residues and wood burning in bakeries is collected from primary surveys. It was revealed that 23% of the residuals are burnt in Goa. Crop productions data along with waste to crop ratios are used to estimate agricultural residue burning. The associated PM_{10} emissions are estimated as 0.8 T d^{-1}.

Total Emissions (2010)

Sectoral share of total emissions loads in Goa is presented in "Fig. 5", which shows that mining (38%), industries (24%) and transport (10% tail-pipe and 15% road dust) are the major contributors to the PM_{10} emissions in the State. Fire-wood burning in households (7%) and agricultural burning of waste residues (2%) also contribute marginally.

Comparison of Emission Estimates with Other Studies

The results of emission inventories in this study are compared with the GAINS Asia database of emissions for Indian states. While GAINS database shows an estimate of about 36 T day^{-1}, our study estimates are slightly higher with 47 T day^{-1} of PM_{10} emissions. The NO_x emissions also show a difference of 19% between the two estimates. However, considering the methodological differences and higher resolutions used in this study, the estimates are in reliable ranges. The differences in the two studies could be attributed to difference in the type of sources included in estimation, e.g., road dust re-suspension has not been included in the GAINS Asia study, which is substantial (7.4 T d^{-1}) in the current study. Emission factors in this study, like for transport sector, are of Indian origin, and hence are more representative of Indian fleet and driving cycles.

Spatial Allocation of Emissions

Emissions from different sectors are spatially allocated using GIS techniques. Transport emissions (tail-pipe and road dust re-suspension) were allocated to the 11 *talukas* based on actual registration of vehicles in the regions. Industrial emissions are allocated based on actual locations of industries in different *talukas* collected from GSPCB. Mining emissions were allocated based on mining capacities in different *talukas*. DG set emissions were allocated based on installed capacities in different *talukas*. Agricultural burning emissions were allocated based on net sown area in different *talukas*. The emissions from bakeries and other commercial fuel use are allocated based on population. *Taluka*-wise distribution of PM_{10} emissions per km^2 area is presented in "Fig. 6", which shows higher emissions intensity in the coastal *taluka* of Marmugoa and mining dominated *taluka* of Bicholim.

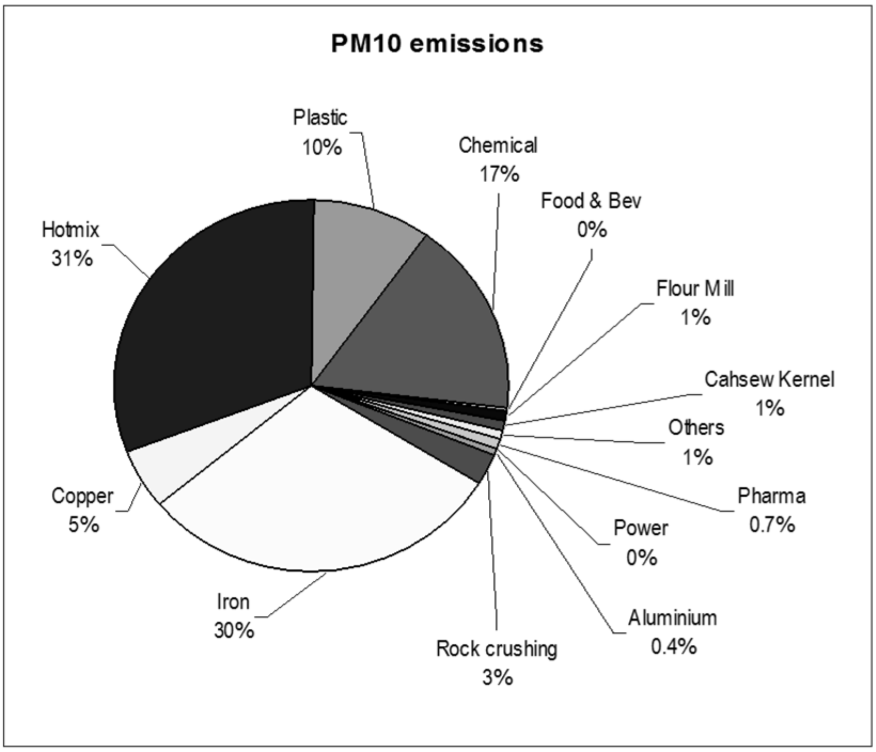

Fig. 4. Industry category wise distribution of PM_{10} emission loads in Goa.

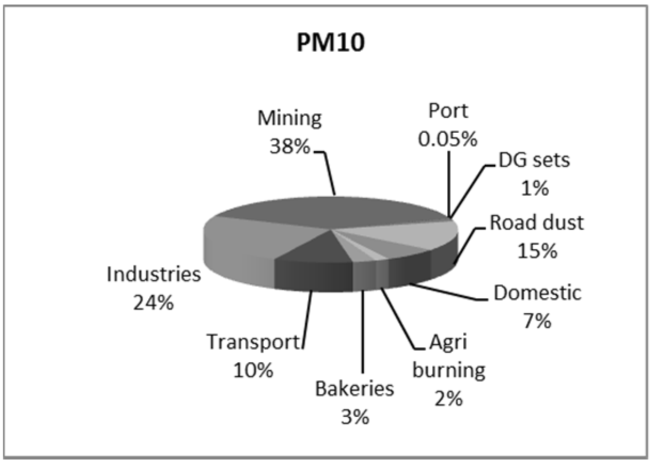

Fig. 5. Share of different sectors in the emission loads for PM_{10} in Goa.

Emission Projection Scenarios

Business as Usual (BAU Scenario)

In the BAU scenario, projections are made for different sectors based on the past trends and current plans and policies of the government. Trend analysis is carried out based on past data of 15 years (1995–2010) of vehicle registrations in Goa. A best fit line (with a $r^2 > 0.95$) is then used to project the growth of different categories of vehicles by the year 2030. Total vehicles in Goa are projected to grow to nearly 1.5 million. However, the emission projections show that the emissions from transport sector will decrease in future on account of introduction of advanced vehicular emission norms (BS-IV/V) and fleet turnover. Hence, despite a steady rise in registered number of vehicles, transport sector emissions indicate a decrease due to expected removal of 20 year old vehicles from the main fleet. The newer vehicles adding to the fleet would be of better technology, following advanced vehicular emission norms (BS-IV/V). Change in vehicle category-wise distribution of PM_{10} during 2010–2030 is shown in "Fig. 7". The share of heavy duty vehicles is expected to reduce in future with removal of older fleet and limited growth in the industrial and mining sector. Despite control of vehicular tail-pipe emissions, the growing number of vehicles will increase the road dust re-suspension emissions significantly. This is assuming of same silt loadings over the roads and increased percentage of heavier fleet (cars) contributing to higher re-suspension.

The industrial output of the State is projected to grow at

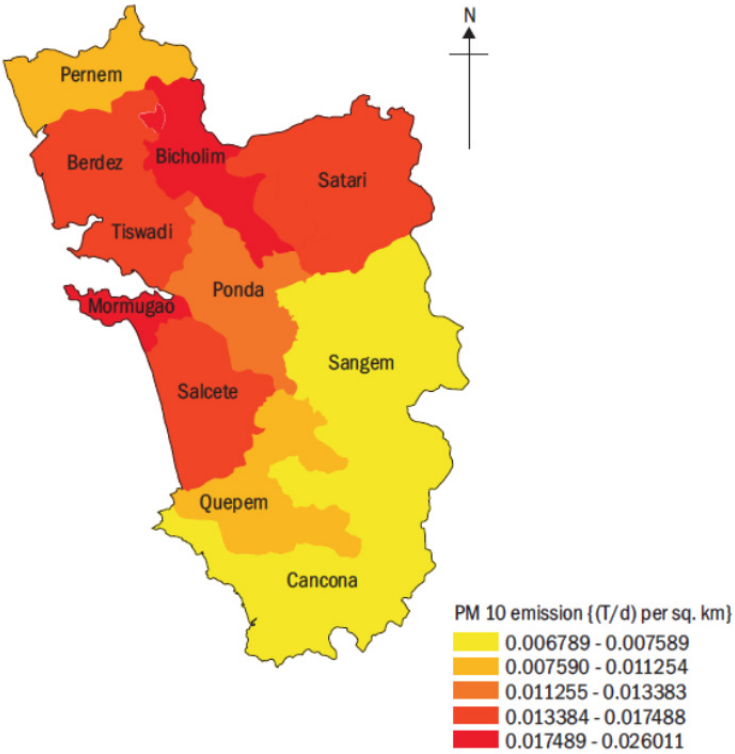

Fig. 6. Taluka-wise distribution of PM_{10} emissions per km^2.

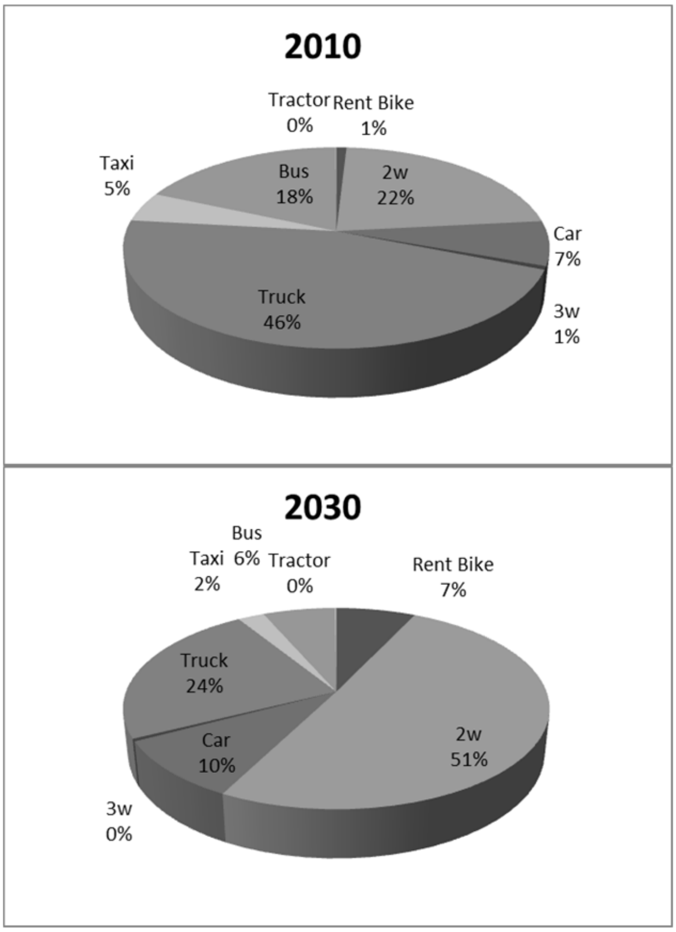

Fig. 7. Changing distribution of PM_{10} emission from road transport sector in Goa during 2010–2030.

a steady rate based on the past trends. However, as per the government's industrial policy, only less polluting industries will be allowed in the State in the future. However, based on expert discussions, there is still a scope of 30% expansion of the existing units. Accordingly, the pollutant emissions from the industrial sector are projected to grow in same proportions, assuming no further controls in a BAU scenario. The mining sector is projected based on past trends of iron-ore production. However, due to the present ban on mining activities in the State and limitation in increase of area allotted for mining, the emissions from the sector are projected to stabilize by 2030.

In the BAU scenario, the population is projected to grow to about 1.6 million in 2030 (Sharma *et al.*, 2015). Despite some increase in population, residential combustion sector emissions are projected to decrease with decreasing dependency on biomass for cooking over the years. Urban population, which is more dependent on LPG for household fuel use is projected to grow from 62% in 2010 to 83% in 2030. Emissions from DG set are projected to grow steadily with the increase in population (both resident and tourist inflows) with the assumption of same electricity demand-supply gap scenario. Agricultural productivity trends are projected to estimate agricultural waste residue and corresponding emissions in the future. With decreasing agricultural produce, the emissions are expected to go down in a BAU scenario.

The overall sectoral growth of emissions is presented in "Fig. 8(a)" for the BAU scenario. In 2030, the share of industries, mining, and road dust re-suspension appears significant in PM_{10} emissions. Road dust re-suspension emerges out of a sector, which needs attention in future.

Alternative Scenario (ALT)

Air quality has already deteriorated in Goa and with further increase in emissions in the BAU scenario, it can worsen. There is a need to mitigate the emissions in various sectors. An alternative scenario is developed considering interventions in different sectors for reduction of PM and NO_x emissions in Goa. The scenario assumes introduction of BS-V emissions norms and fuel quality in the transport sector, 30% penetration of electrostatic precipitators in the industries, restriction of 20 million tonnes annum^{-1} of mining activity, enhanced penetration (100% in urban and 75% in rural regions) of LPG for residential cooking, 25% reduction in silt loadings on the roads and 75% reduction in power cuts and introduction of improved DG sets. In comparison to the BAU scenario, the alternative scenario leads to an overall reduction of 17% and 28% in PM emissions in 2020 and 2030, respectively "Figs. 8(a) and 8(b)".

Air Quality and Health Impact Assessment

Sectoral grid-wise (3 × 3 km^2) emissions under baseline and different future scenarios are fed into the ISCST3 model to predict pollutant concentrations and their impacts on human health in Goa. The modelled PM_{10} concentrations

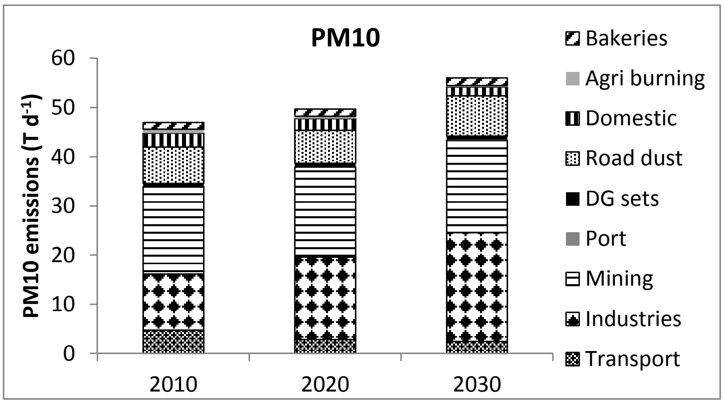

Fig. 8(a). Total emissions loads (T d^{-1}) of PM_{10} in Goa for BAU scenario during 2020 and 2030.

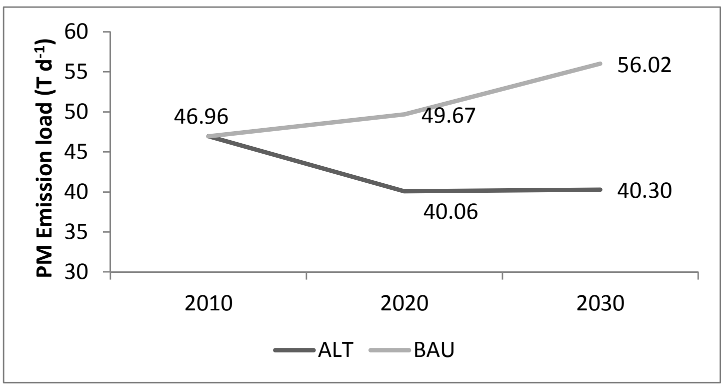

Fig. 8(b). Total emission loads of PM_{10} in Goa in BAU and ALT scenarios during 2020 and 2030.

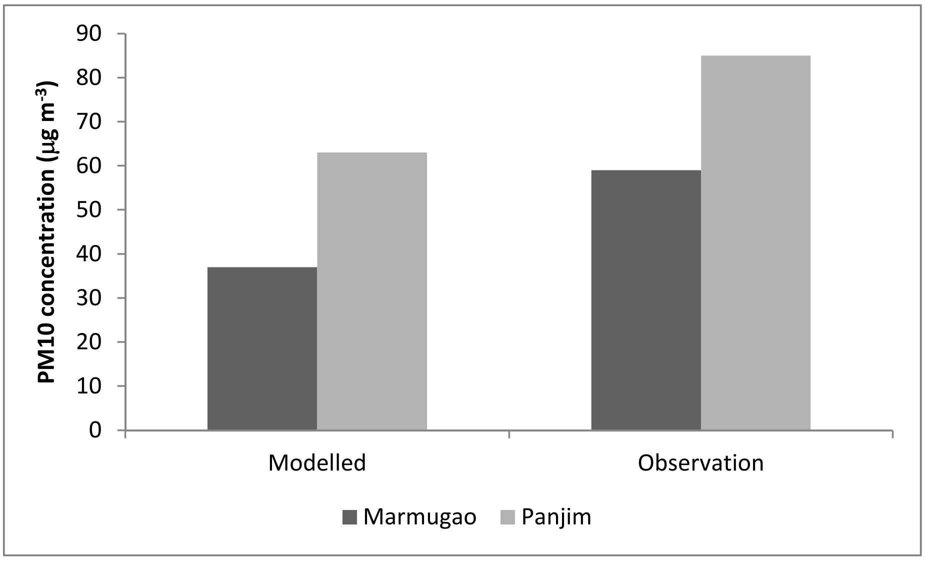

Fig. 9. Comparison of modelled and observed concentrations of PM_{10} at two monitoring stations in Goa.

in 2010 are compared with actual observations at two locations—Panaji and Marmugao. The modelled values are in satisfactory ranges; 63–74% of the actual observations at the two locations "Fig. 9". Modelling results may improve with consideration of natural emissions (wind-blown dust, sea salt, forest fires, etc.), which are beyond the scope of present study.

The validated model is then used to predict PM_{10} concentrations in Goa under different scenarios. "Fig. 10" shows the spatial distribution of modelled annual average concentrations of PM_{10} under different scenarios. In 2010, the concentrations are higher in mining and tourism dominated *taluks* of Bicholim and Tiswadi, respectively. BAU scenario depicts an increase in PM_{10} concentrations and widening of the area showing violations of PM_{10} annual average standard of 60 µg m^{-3}. The percentage of grids with PM_{10} concentrations in excess of WHO guidelines value of 20 µg m^{-3} decreases from 57% in BAU to 52% in ALT scenario in 2030. At Panaji, which is the capital of Goa, the PM_{10} concentrations are expected to decrease from 55 µg m^{-3} in BAU to 41 µg m^{-3} in the ALT scenario.

Using the dose response curves, it is estimated that about 306 mortalities can be attributed to PM_{10} concentrations in the State in 2010. MoHA, 2012 reported 1,165 mortalities (9.8% of the total deaths) due to respiratory illnesses in the State. Our estimates show that 26% of mortalities caused due to respiratory illnesses are attributable to ambient PM_{10} concentrations in Goa. This means that in every 1.2 days, a life is lost on account of air pollution in Goa. Under the BAU scenario, the mortalities could increase to more than 317, and in the alternative scenario it can be reduced to 237 in 2030. These are conservative estimates of health impacts as the analysis does not consider the impacts of air pollutant concentration on tourist population.

CONCLUSION

The baseline assessment of air quality suggests that air quality in general is violating the prescribed standards at many locations in Goa, more specifically in regions of mining, industries, and ports. Considering future growth, the air quality can deteriorate further. This study prepares a detailed emission inventory of different contributing sources in the region. The study shows that mining and other industrial sources are the major contributors to PM_{10} emissions, followed by the transport sector. Prevailing PM_{10} concentrations are estimated to cause more than 306 mortalities each year, which is 2.6% of the all cause mortalities and 26% of mortalities caused due to respiratory illnesses. It is to be mentioned that the study did not focus on exposure levels in the indoor environment and uses dose response functions developed on the basis of ambient air quality only. More accurate exposure assessment can be carried out by taking into account the time spent indoors and outdoors and their respective dose-responses. In a BAU scenario, emissions from road dust re-suspension and industries are likely to increase, while there will be stabilization of emissions from the transport sector, mainly on account of advancement in vehicular emission norms and fleet turnovers. Alternative scenario based on stringent interventions in different sectors show considerable reductions in PM_{10}, and is expected to enhance the air quality to meet prescribed limits. Other than measures assumed in the alternative scenario, other interventions like improving energy efficiency in the existing industrial units, introduction of cleaner technology, strengthening of enforcement mechanism for pollution control, commissioning of effective inspection and maintenance systems, plying restrictions for older polluting commercial vehicles should help in controlling pollution in the region.

The outputs of this study can be used to run the advanced simulation models for improved assessment of air quality in present and future years. Using the inventory, an evaluation of different models can be carried out to test their efficacies in a coastal environment.

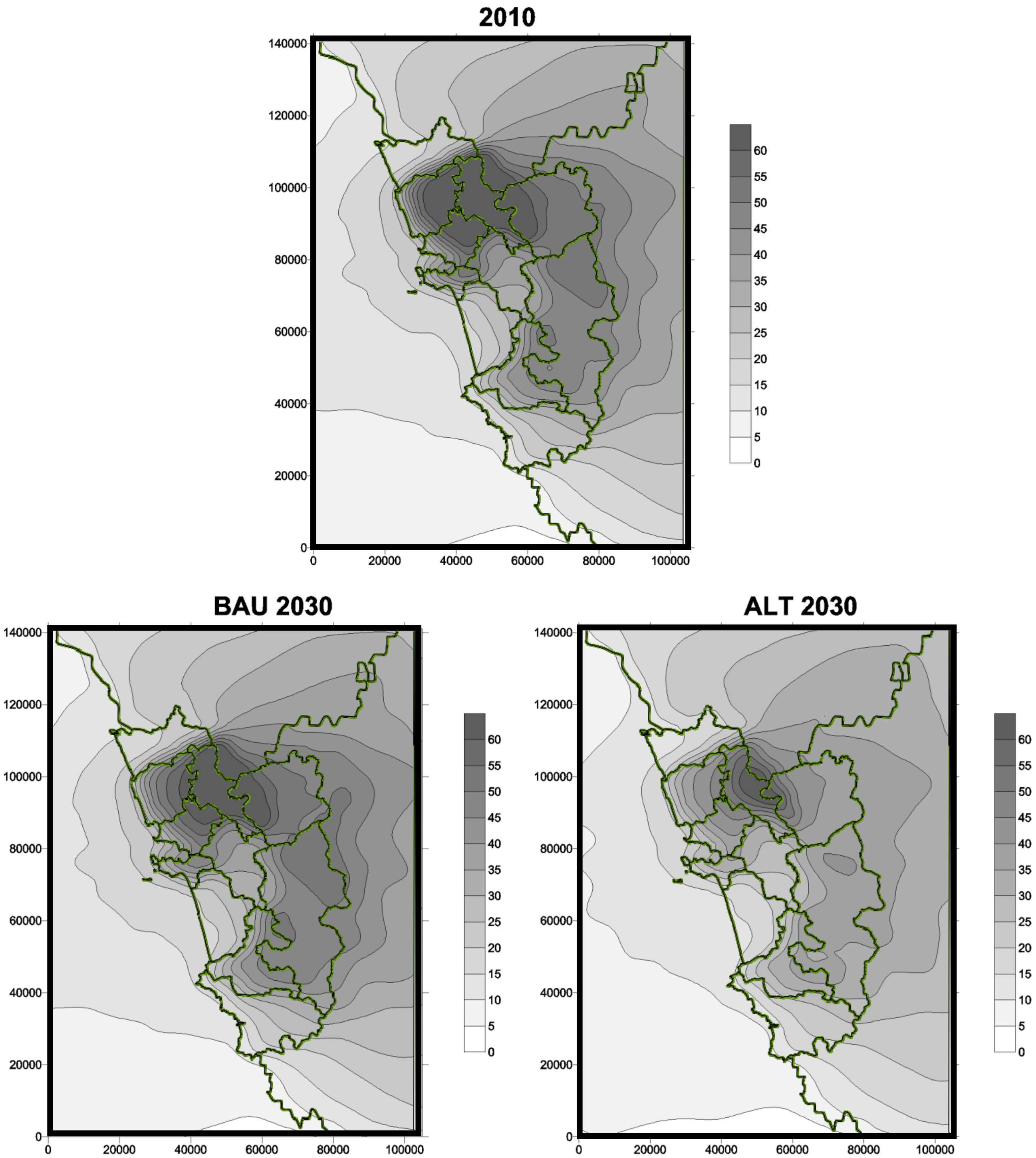

Fig. 10. Isopleths of modelled PM_{10} concentrations (µg m^{-3}) in baseline, BAU, and ALT scenarios.

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