Projecting the air quality, toxic and health impacts of the Rampal coal-fired power plant

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Executive Summary

The proposed 1,320MW Maitree coal-fired power plant at Rampal would be among the largest point sources of air pollution in all of Bangladesh. Its emissions would worsen levels of toxic particles over all of southwestern Bangladesh including the Sundarbans ecosystem and the localities of Khulna, Ashoknagar Kalyangarh, Satkhira, Bagamganj, Basirhat, Narsingdi, Noakhali, Basipur and Komilla. People in Dhaka and Calcutta, particularly children and the elderly, would also be harmed.

Over its operational lifetime, the plant's emissions will increase the risk of stroke, lung cancer, heart and respiratory diseases in adults, as well as respiratory symptoms in children. Even if Bangladesh currently had zero air pollution, the plant alone would cause the premature deaths of 6,000 people, and low birth weights of 24,000 babies. The plant will increase 24-hour average ambient levels of NO2 in nearby localities up to 25% over the current national urban average, and will increase SOx levels up to 50% over the urban average, during days with highest impact from the plant.

The projected health impacts are relatively high for a power plant for this size due to the high population density in the region, and the weak emission limits applied in the project. Emission limits for sulfur dioxide, nitrogen oxides, dust and mercury, as specified in the tender documents, are five to ten times higher than best regulatory practice and technical state-of-the-art emission levels.

The plant could emit high levels of mercury, a potent neurotoxin that damages children's brains and nervous systems. Projected mercury deposition from the Rampal plant could be sufficient to render fish unsafe to eat over an area of approximately 70km2 around the power plant. This highly affected area is entirely in the water catchment of the Sundarbans wetlands. Additionally, 10,000kg of mercury over the life of the plant could end up in either the coal ash pond, which is subject to flooding. This additional mercury poses further risks to the aquatic food chain of the Sundarbans and Bay of Bengal, impacting millions of people who eat those fish.

Avoiding emissions from large industrial sources such as coal-fired power plants will prevent unnecessary public health impacts in Bangladesh and neighboring countries.

Introduction

Public health in Bangladesh is heavily affected by air pollution, with PM2.5 levels in Khulna six times and in Dhaka nine times the World Health Organization guideline. Avoiding or reducing emissions from large industrial sources, such as coal-fired power plants, is one of the interventions with highest effectiveness and feasibility of implementation in addressing the very significant negative health impacts of air pollution.The potential impacts of the pollution emissions from the power plant on air quality, toxic deposition and health were studied using the CALPUFF air pollution modeling system recommended by the U.S. EPA for assessing long range transport of pollutants and their impacts. The health impacts of the modeled air pollutant exposure resulting from the emissions were assessed following World Health Organization recommendations.

The emissions and health and environmental impacts of the plant were assessed for four different scenarios that vary based on the levels of allowed emissions:

1. EIA case: this scenario uses the emission values and pollution control measures given in the July 2013 EIA study for the plant. The plant was granted environmental approval in 2013 despite extremely poor air pollution prevention design described in the EIA, including failure to require a sulfur dioxide-reducing scrubber, called Flue Gas Desulfurization (FGD).
2. Proposed plant: emissions based on specifications in the plant's tender documents, which set out the requirements that companies bid upon to win the contract to build the plant. The tender documents, which were issued in 2015, required an FGD scrubber, but not other key (and currently widely used and accepted) technologies for pollution reduction, such as Selective Catalytic Reduction (SCR) for NOx reduction, specifications to assure that the FGD scrubber efficiency would remove at least 98% of SO2, a baghouse to reduce particulate matter emissions, and activated carbon injection or other dedicated mercury control technique to remove mercury emissions.
3. Indian case: hypothetical scenario in which the plant complies with the much stricter new power plant standards enacted in India in 2015, requiring higher SO2 control performance and the installation of Selective Catalytic Reduction equipment to reduce NOx emissions, with co-benefits for mercury capture. We included this to illustrate how the plant, which will be co-owned, managed and operated with the Government of India's National Thermal Power Corporation, built by state-owned Bharat Heavy Electricals Ltd, and financed by the Export Import Bank of India, would emit much more air pollution than any power plants in India that meet that country's emission standards, and could not be permitted there with the proposed emission limits.
4. State-of-the-art: emissions if the power plant was designed to meet the 'ultra-low' emission standards used for new coal-fired power plants in China, and install dedicated mercury controls, in addition to the FGD and SCR equipment required in scenario 3. This scenario was included to illustrate how the oft-repeated claim that the plant will only use state of the art technologies is false.

Summary of Results

The emissions from the Rampal power plant would elevate the levels of toxic particles, sulfur dioxide (SO2) and nitrogen dioxide (NO2) in the air over entire southwestern Bangladesh, with worst impacts felt a few dozen kilometers to the southwest and a hundred kilometers to the northeast of the plant due to prevailing wind patterns. Exposure to these pollutants increases the risk of diseases such as stroke, lung cancer, heart and respiratory diseases in adults, as well as respiratory symptoms in children. This leads to premature deaths from these causes. Gaseous SO2 and NOx emissions contribute to toxic particle exposure through formation of secondary particles.

Overall, the projected health impacts are relatively high for a power plant for this size, due to the high population density in the impact area and to weak emission limits applied in the project. Emission limits in the tender documents are far from best regulatory practice and technical state-of-the-art emission levels. SO2, NOx, dust and mercury emissions are all 5-10 times as high as emission rates associated with best regulatory practice and best available technology.

In the proposed plant case, the estimated health impacts due to PM2.5 and NO2 exposure are 150 premature deaths per year (95% confidence interval: 100 to 180), or approximately 6,000 deaths during a 40-year operating life. The estimated number of babies born with a low birth weight due to the pollution would be 600 per year. Low birth weight is an important risk factor for newborn babies' health and development. If the much stricter new Indian standards were followed, the predicted number of deaths would fall to 50 per year, avoiding 3,800 premature deaths over a 40-year operating life. In the state-of-the-art emission scenario, premature deaths would fall further to a projected 20 cases per year, resulting in a further 1,300 avoided deaths over a 40-year lifetime.

If the much laxer emission rates given in the EIA instead of the tender documents were followed, the SO2 emission rates would be approximately seven times as high as in the case based on the tender documents, while NOx, dust and mercury emissions would all be approximately 70% higher.

The mercury, fly ash and acid gas emissions from the plant would lead to increased deposition of these toxics around the plant, including into the Sundarbans wetland and into the water catchment from which water flows into the wetland. Projected mercury deposition within 10km of the plant would approximately double the mercury deposition rates compared with regional background. Projected mercury deposition from the Rampal plant could be sufficient to render fish unsafe to eat over an area of approximately 70km2 around the power plant. This highly affected area is entirely in the water catchment of the Sundarbans wetland. This highly affected area is entirely in the water catchment of the Sundarbans wetland. Total mercury deposition into the wetland and catchment area would be an estimated 20kg per year in the proposed plant case, and 60kg in the EIA case, assuming average coal mercury content. There is scant information on the mercury content of the coal to be used; in case high-mercury coal is used, the deposition could be up to 80kg and 230kg per year, respectively. 4-5% of the predicted toxic deposition and 26% of the predicted health impacts occur in India.

Detailed Results: Emissions of major air pollutants

The most important determinants of a power plant's air quality and health impacts are the total amount of emissions and the location of the plant.

In this report, four emission scenarios are assessed: one based on the emission rates given in the Environmental Impact Assessment, one based on the emission rates specified in the tender documents, one based on the much stricter new Indian emission limits for thermal power plants, and one based on meeting the 'ultra-low' emission standards used for new coal-fired power plants in China and using mercury-specific control technology. A plant load factor of 80% is assumed (the EIA uses 100%).

In the EIA, emission rates in g/s are given for SO2, NOx and dust, and these can be used together with the plant load factor to calculate annual emissions. The tender documents and the Indian emission standards specify SO2 and NOx concentration in dry flue gas in mg/Nm3; the total flue gas volume was estimated from CO2 emissions to calculate annual pollutant emissions.

The types of emission control techniques specified in the tender documents can be used to achieve much lower emission levels than those given in the tender. However, the capital and operating cost of the plant increases with stricter emission limits, so the plant operator can be expected to target the lowest control performance that allows the limits to be met. Because meeting the emission limits given in the tender documents in actual operation would require costly inputs and maintenance, installation of emission control devices alone does not ensure that emissions would be in line with design values unless the emission limits are legally enforced.

Table 1. Properties of the power plant used for the study.

	Proposed plant case	**EIA case**	**Indian standards case**	**State-of-the-art case**
Latitude	22.587N			
Longitude	89.551E			
Stack height (m)	275			
Stack Diameter (m)	7.5			
Gas Temperature (℃)	125	80	80	80
Gas velocity (m/s)	25			
SO2, mg/Nm3	200	-	100	35
NOx, mg/Nm3	510	-	100	50
Dust, mg/Nm3	50	50	30	10
SO2, t/yr	5,670	41,325	2,835	992
NOx, t/yr	14,458	24,724	2,835	1417
Dust, t/yr	1,417	1,417	850	283
CO2, Mt/yr	7.96			

These emissions would make the Rampal power plant one of the largest point sources of air pollution in Bangladesh. Currently, the largest fossil-fuel fired power plants are the gas-fired Ashuganj 914MW plant, coal-fired Barapukuria 250MW plant and oil-fired Baghabari 240MW plant, according to the Platts UDI World Electric Power Plants database (January 2017). As the oil and coal-fired plants are one-fifth the size of the Rampal project, and thus are unlikely to produce less emissions even with weaker pollution control techniques. The same holds true for natural gas-fired power plants, which burn a cleaner fuel. The EDGAR emission database (v4.3.1) does not identify any larger industrial sources in 2010.

It is clear from comparison of different emissions cases that emission limits in the Rampal tender documents, while an improvement over the emission rates assumed in the EIA, are far from best regulatory practice and technical state-of-the-art emission levels. For example, the emission limit for SO2 is six times as high as the limit applied to both new and retrofit coal-fired power plants in China, and the NOx limit is ten times as high. The dust limit is five times as high as the limit applied in China and ten times as high as the limit applied the EU.

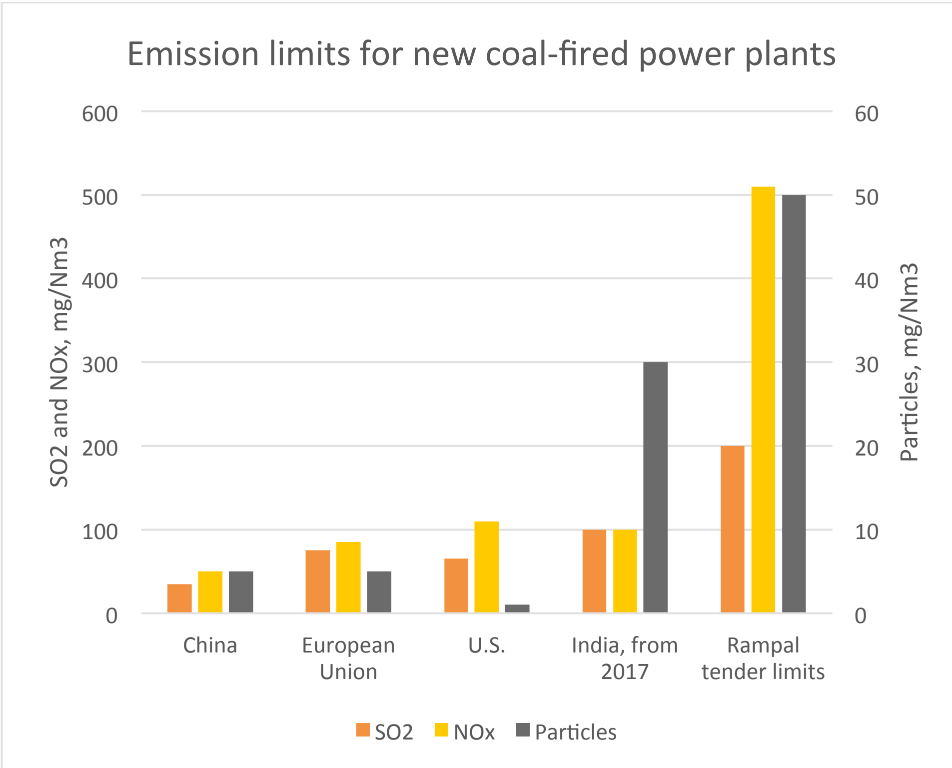

Figure 1. Comparison of the emission limits for air pollutant emissions with examples of best regulatory practice around the world.

These emission and stack data were used as the basis of modeling the plant's air quality impacts using the CALMET-CALPUFF modeling system.

Mercury emissions

Mercury is a potent neurotoxin that can cause severe health problems even at very low doses. Mercury pollution in the environment is a serious risk to children's cognitive and neurological development. (WHO 2017). The most important exposure pathway is through consumption of fish and seafood, especially predatory species due to biomagnification of mercury in food chains. Coal burning is a key source of mercury releases into the environment globally (UNEP 2013); emissions from coal-fired power plants can create significant local hotspots of mercury deposition (see e.g. Sullivan et al 2006).

When coal is burned, the mercury it contains is partitioned between gaseous mercury and mercury contained in the fly ash in the flue gas, with a small fraction retained in bottom ash. Most fly ash is captured by the particle control device, and consequently either reused, typically for cement, or disposed in the coal ash pond, along with bottom ash. Mercury contained in fly ash not captured by particle controls is emitted as particulate mercury. Gaseous mercury in flue gas is in the form of elemental and divalent (reactive) mercury. Wet flue gas desulfurization (wet FGD) which is expected to be installed in the Rampal plant based on the tender documents, is quite effective in capturing divalent mercury from the flue gas stream; this mercury ends up in the scrubber gypsum which is either reused or disposed into the coal ash pond. Selective catalytic reduction (SCR) of NOx (which would occur in the Indian case and state-of-the-art scenarios) has the co-benefit of converting some of the elemental mercury in the flue gas into divalent mercury which is then partially captured by the FGD. Dedicated mercury controls increase mercury capture in either particle controls or the FGD.

The EIA of the Rampal power plant contains no specific information about the mercury content of the coal to be used or the magnitude of the mercury emissions from the plant, a serious omission. To fill in this gap, coal mercury content and mercury emissions are estimated based on the UNEP mercury toolkit (UNEP 2017). The average mercury content of coal from each of the possible source countries, or a midpoint of range when a central value is not available, is used. The average of these central values is used as the base case for the assessment and the low and high global values are used as the range of possible values.

Table 2. Coal mercury content in countries from which coal could be imported for the Rampal power plant, ppm (UNEP 2017).

	Average/midpoint [1]	Low	High	Coal type
Australia	0.215	0.03	0.4	Bituminous
Australia	0.042			Bituminous
Australia median	0.042	0.03	0.40	Bituminous
India	0.140			Power plant average
Indonesia	0.030	0.01	0.05	Sub-bituminous
South Africa	0.310	0.01	1	Bituminous
Average	**0.13**	**0.05**	**0.48**	

Besides the amount of mercury contained in the coal, the capture rate (i.e., the amount of mercury retained in coal combustion residues), strongly affects air emissions. Ranges of capture rates for the different air emission control technology configurations are taken from the UNEP (2017) mercury toolkit, and the midpoint of these ranges are used as the central value. To establish a range of plausible emissions, the low end of coal mercury content and high end of capture rate are applied to calculate the lowest plausible emission rate and vice versa.

Table 3. Mercury capture rates and corresponding mercury air emissions. (ESP = electrostatic precipitator for particle emission control; SCR = Selective Catalytic Reduction, a NOx control technique assumed to be required in the 'Indian standards' case, with side benefits for mercury control.)

	Average/midpoint	Low	High	Unit	Source
Annual coal requirement at full utilization	4.715	4.715	4.715	Mt/yr	Rampal EIA
Capacity factor	80%	80%	80%		assumed
Control efficiency: ESP only	17.5%	25%	10%		UNEP 2017
Control efficiency: ESP+FGD	52.5%	65%	40%		UNEP 2017
Control efficiency: ESP+FGD+SCR	75.0%	90%	20%		UNEP 2017

[1] When a central value is not given in UNEP (2017), the midpoint of the low and high values is used.

Control efficiency: Mercury-specific technique	82.5%	90%	75%		UNEP toolkit
Emissions: ESP only	406.1	141.5	1640.8	kg/yr	calculated
Emissions: ESP+FGD	233.8	66.0	1093.9	kg/yr	calculated
Emissions: ESP+FGD+SCR	123.1	18.9	1458.5	kg/yr	calculated
Emissions: Mercury-specific technique	86.1	18.9	455.8	kg/yr	calculated

While the uncertainties associated with mercury emission rates are very large – roughly a factor of 10 – total mercury emissions are very likely to be significant. In the proposed plant case (ESP+FGD), the most likely emission rate is approximately 230kg/year, and worst case emissions are 1,100kg/year. The range of uncertainty is particularly large in the case of installing an SCR but no mercury-specific controls, due to lack of data and due to very different impact of SCR on mercury capture with different coal types.

It is also important to note that while a higher capture rate of mercury means lower air emissions, the 'captured' mercury does not disappear but ends up in coal combustion waste or scrubber wastewater instead. If all coal combustion waste is dumped into the coal ash pond, the amount of mercury disposed into the coal ash pond, and potentially released into the environment through routine discharges, flooding or failure of the ash pond, or through leakage and seepage, would be projected at 260kg per year in the proposed plant scenario, up from 90kg in the EIA scenario in which Flue Gas Desulfurization is not required. Over an operating life of 40 years, this would amount to 10,000kg in the proposed plant scenario.

Table 4. Projected influx of mercury into coal combustion waste.

	Average/midpoint	Low	High	Unit	Source
ESP only	86.1	18.9	455.8	kg/yr	calculated
ESP+FGD	258.4	75.4	1185.0	kg/yr	calculated
ESP+FGD+SCR	369.2	37.7	1640.8	kg/yr	calculated
Mercury-specific technique	406.1	141.5	1640.8	kg/yr	calculated

Impacts on air quality

The emissions of SO2, NOx and particulate matter from the power plant would affect air quality over a large area. All these pollutants are toxic when inhaled, causing short-term respiratory and other symptoms. Exposure to PM2.5 and NO2 has also been linked to severe long-term health impacts, most importantly increase in the risk of chronic diseases. In the case of PM2.5, these include stroke, lung cancer, heart diseases and chronic respiratory diseases.

The CALMET-CALPUFF atmospheric modeling system used for this report is the U.S. EPA preferred model for assessing long range transport of pollutants and their impacts. The model was chosen for this study because long-range transport of pollution is essential for understanding the potential impacts of the proposed power plant on the Rampal wetland, and both long-range transport and chemical transformation of pollution are essential for projecting the impacts on health (see e.g. Zhou et al 2006).

SO2 and NOx emitted from the power plant lead to the formation of secondary PM2.5 pollution in the atmosphere, a very important impact pathway that is usually neglected in Environmental Impact Assessments and regulatory processes. Similarly, most of the NOx emissions are nitrogen monoxide (NO), which gets oxidized into nitrogen dioxide (NO2) in the atmosphere. Chronic health impacts are mainly linked to NO2 exposure, and NO2 is the parameter monitored by Bangladesh Ministry of Environment and Forests. Importantly, the CALPUFF modeling system is capable of simulating these chemical transformations.

For detailed assessment of compliance with ambient air quality standards in the vicinity of the plant, AERMOD or other more specialized models for short-range impacts should be used and CALPUFF modeling results should not be used to conclude that the plant will not cause violations of specific ambient limits.

The CALMET-CALPUFF system uses detailed atmospheric data, including wind speed, direction, rain, humidity, temperature and turbulence, for every hour of the year, at thousands of locations and 12 vertical levels, to predict the dispersion, chemical transformation and deposition of pollution in the atmosphere. Sources of meteorological data include all publicly available meteorological observations in Bangladesh and neighboring countries, and global meteorological data from satellites and atmospheric models. A full-year simulation for the year 2015 was carried out.

Based on the simulation results, the emissions from the power plant can increase daily average NO2 levels in the most affected locations by up to 5μg/m3, or 25% above annual average levels in urban areas[2], in worst-case conditions. Daily SO2 levels can be elevated by up to 7μg/m3, or 50% above typical levels in worst-case conditions.

A significant part of the total population exposure to pollution and of the resulting health impacts takes place due to long-range transport of the pollution all across Bangladesh, and even across the border to West Bengal in India. Of the modeled PM2.5 exposure, 70% occurs within Bangladesh, 26% in India and 5% in other neighboring countries.

On annual basis, the largest predicted air quality impacts take place to the northeast and southwest of the power plant due to prevailing wind patterns, with Khulna the most affected municipality for NO2 and PM2.5, while Ashoknagar is the most affected by SO2 health impacts. On a daily basis, significant impacts can be felt in all directions some dozens of kilometers away, and up to a hundred kilometers away to the north and the south, depending on atmospheric conditions. Compared with SO2 and NO2 impacts, PM2.5 levels are relatively stronger in the south. Highest PM2.5 concentrations occur when atmospheric conditions lead to both more ground-level pollution and to high rate of secondary particle formation from the gaseous emissions.

[2] Average pollutant levels were calculated from Bangladesh MoEF Monthly Air Quality Monitoring Reports (http://case.doe.gov.bd/index.php?option=com_content&view=article&id=5&Itemid=9).

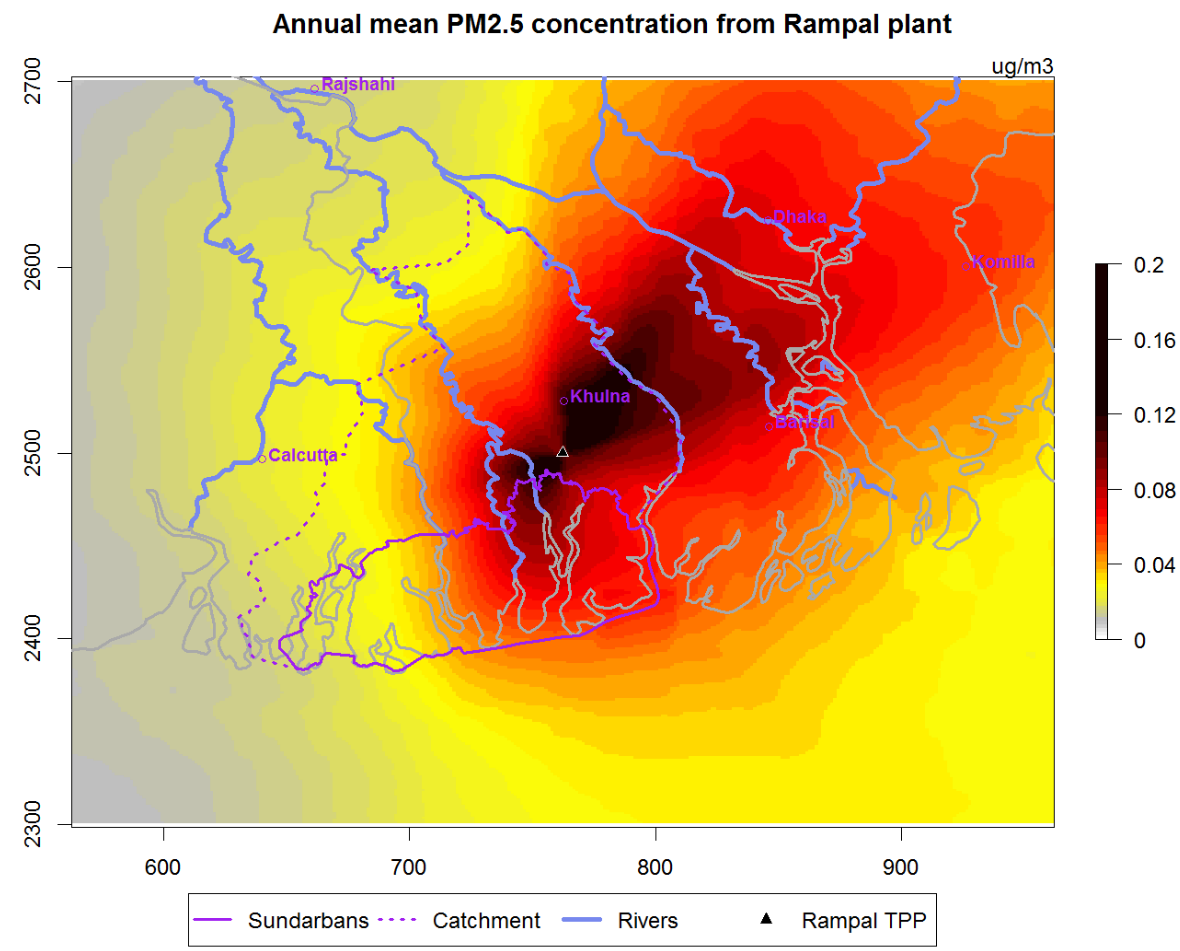

Figure 2. Projected annual average PM2.5 concentrations attributable to emissions from the Rampal coal-fired power plant in the proposed plant case (µg/m3).

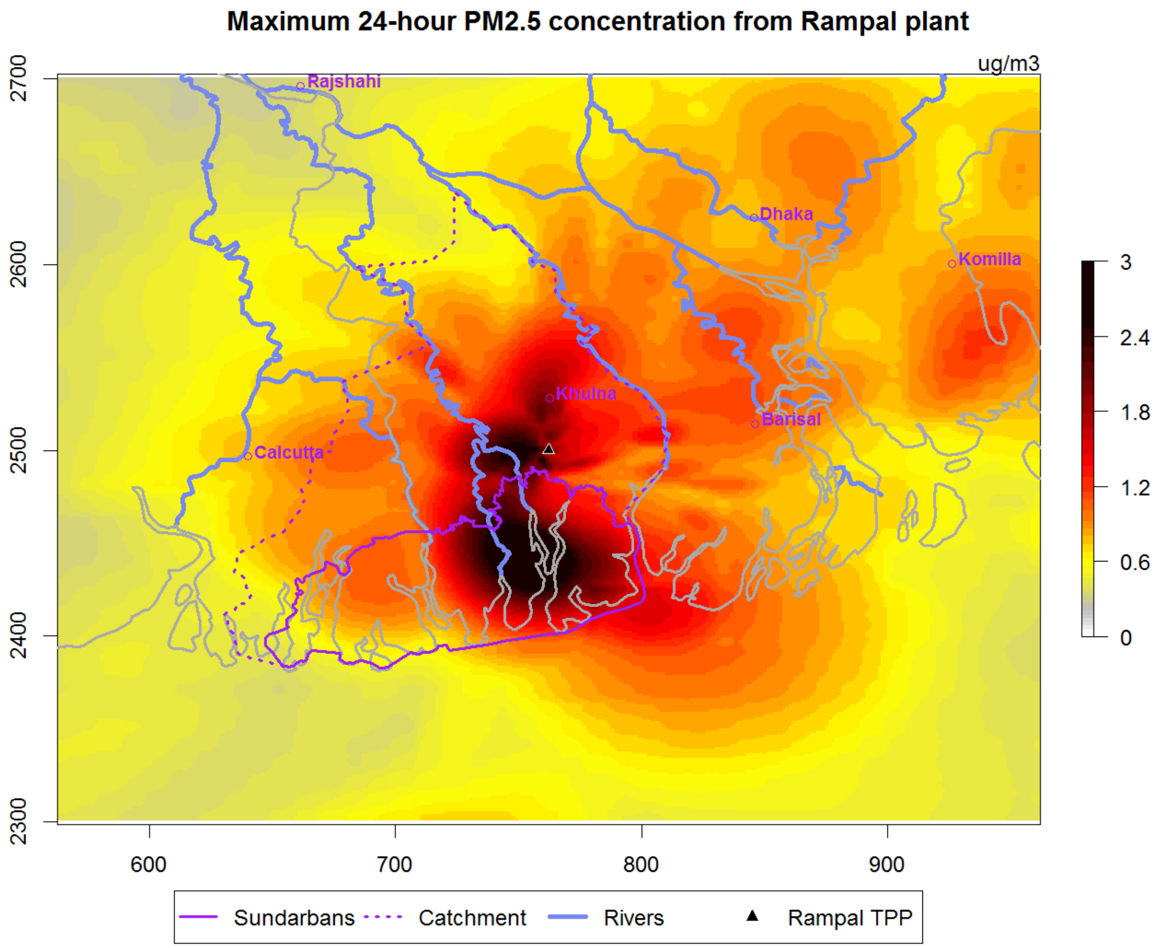

Figure 3. Projected 24-hour maximum PM2.5 concentration attributable to emissions from the Rampal power plant in the proposed plant case (µg/m3)

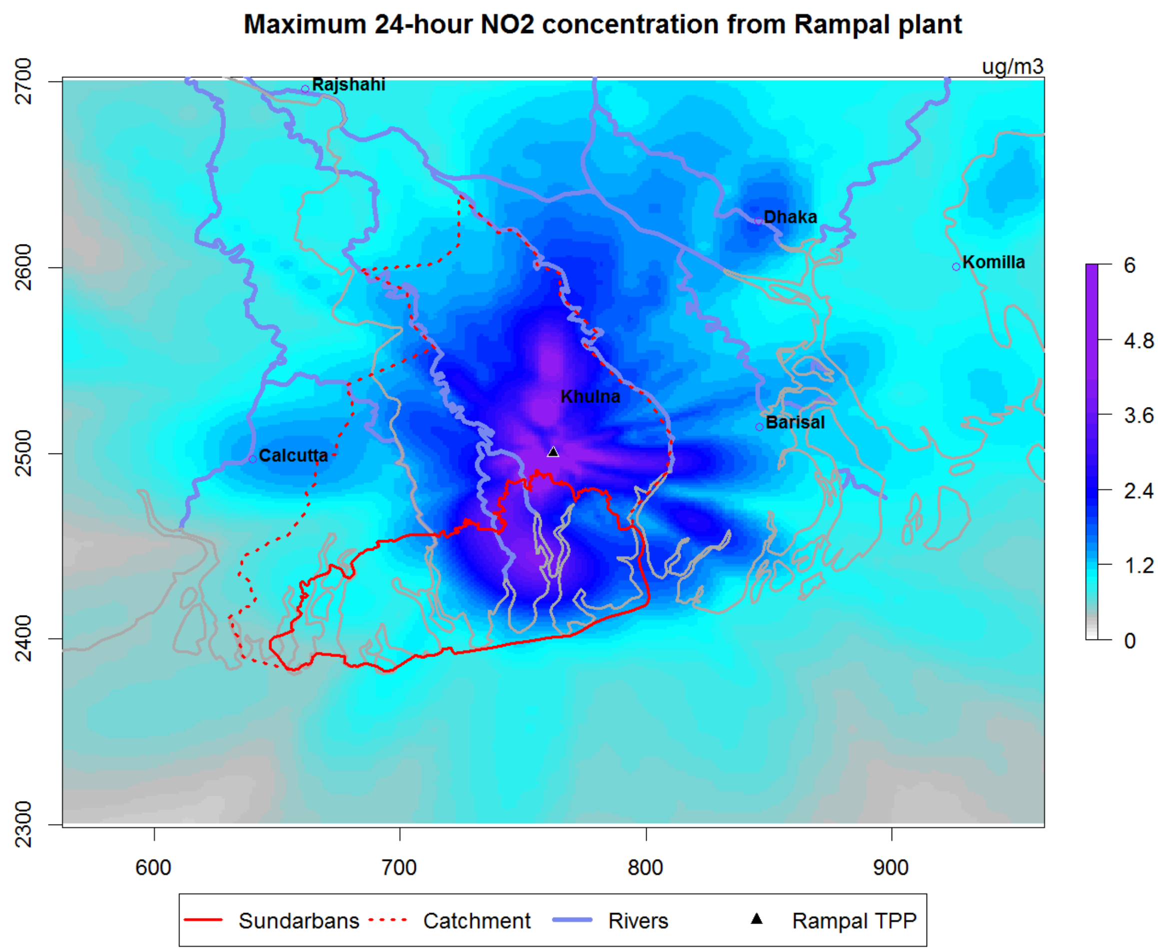

Figure 4. Projected 24-hour maximum NO2 concentration attributable to emissions from the Rampal power plant in the proposed plant case (μg/m3).

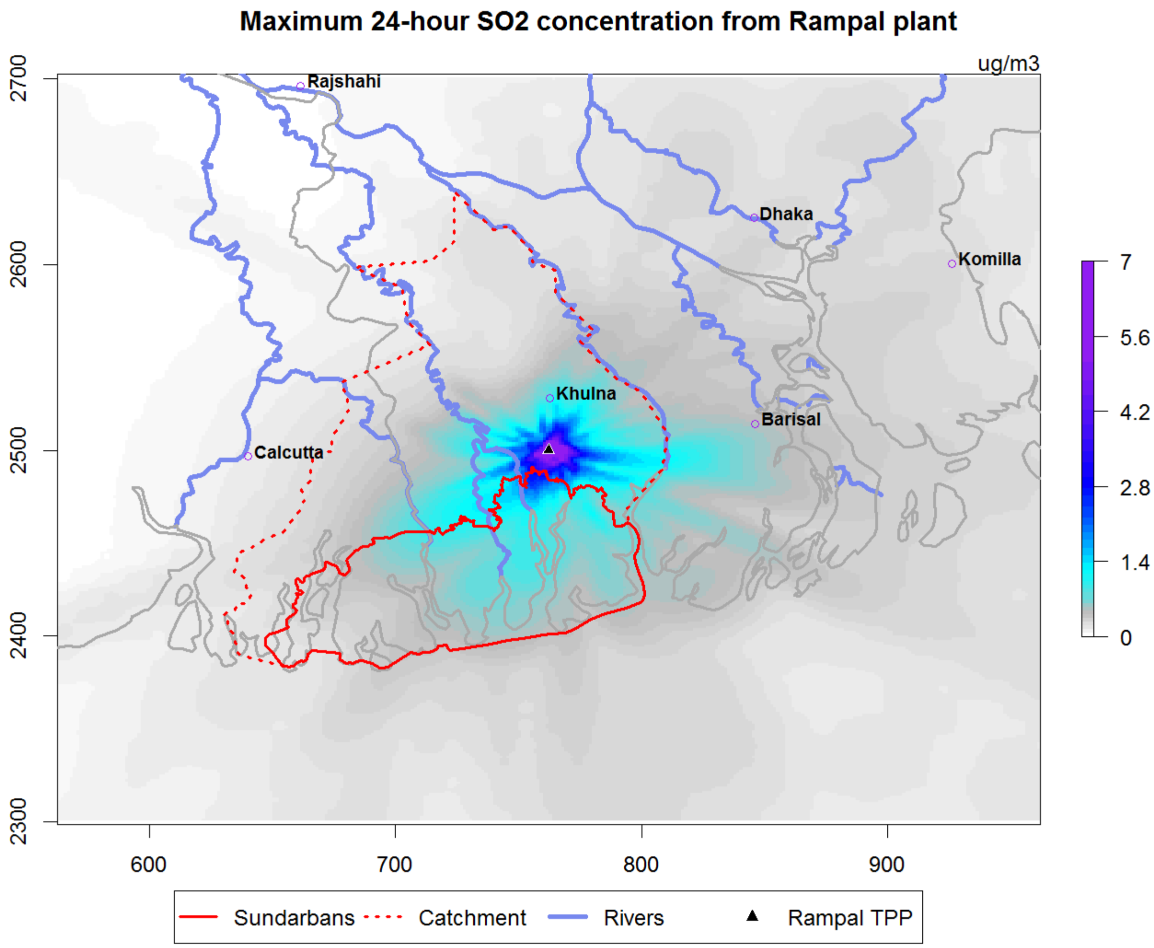

Figure 5. Projected 24-hour maximum SO2 concentration attributable to emissions from the Rampal power plant in the proposed plant case (µg/m3).

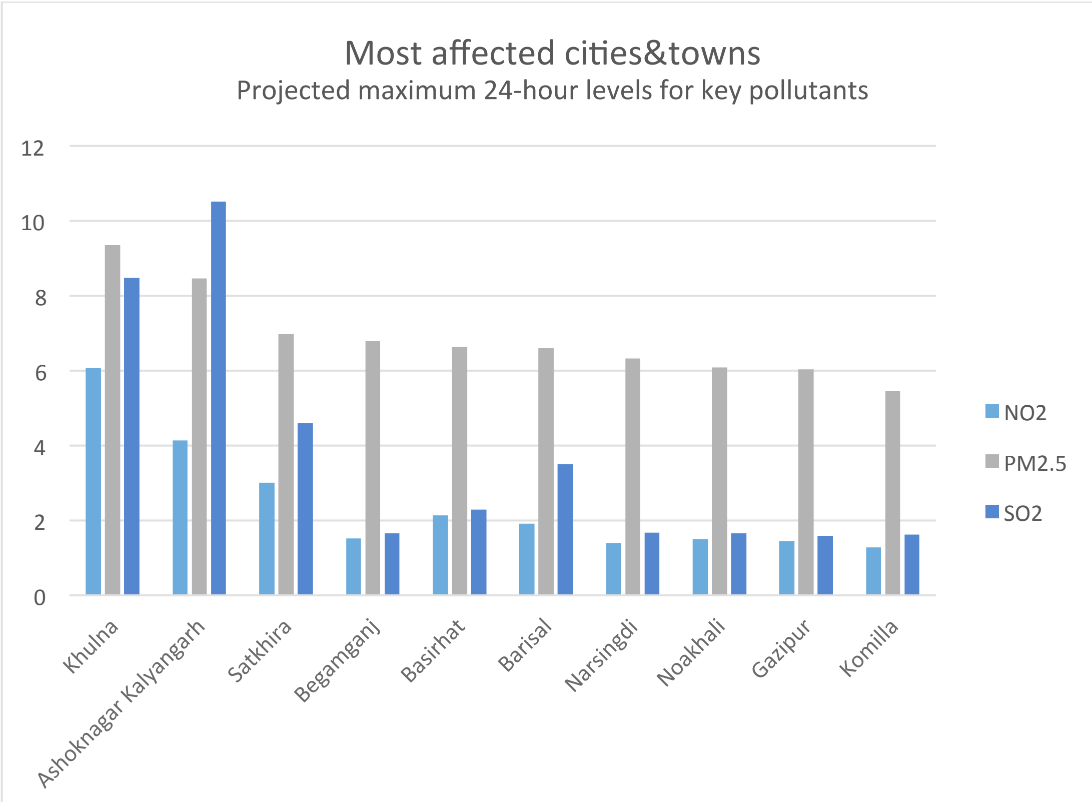

Figure 6. Cities and towns with the highest projected maximum 24-hour concentrations of major pollutants (µg /m3)

Health impacts of air pollution exposure

The air pollutant emissions from the Rampal power plant would result in increases in the ground-level concentrations of harmful pollutants, increasing the exposure of the population to these pollutants. This increase in exposure is linked to a wide range of health risks that can be quantified based on existing epidemiological studies.

It is important to note that the assessment in the EIA that the emissions from the plant alone would not, in the absense of all other pollution sources, lead to violations of ambient air quality standards, does not in any way mean that there won't be health impacts associated with the emissions. First of all, there is most likely no 'safe' threshold for exposure to PM2.5 below which there are no health impacts (WHO 2013). Secondly, the current ambient pollution levels in Bangladesh and surrounding areas are already far above any such threshold. The increase in pollution exposure caused by emissions from the plant will increase associated health risks regardless of whether air quality standards are breached.

The health impacts resulting from the increase in PM2.5 concentrations caused by the power plant were evaluated using the methodology developed for the Global Burden of Disease project, the most comprehensive and authoritative assessment of health risks, including air pollution, globally. To assess the health impacts of NO2 exposure, findings from latest epidemiological studies, synthesized in Mills (2016), were used. Required data for current incidence of different health conditions was obtained from WHO (2014) Global Health Estimates. Low birth weight births were assessed based on the findings of Dadvand et al (2013) on the relationship between low birth weight and PM2.5 pollution, with required baseline incidence rates obtained from World Bank World Development Indicators.

Table 5. Projected annual health impacts attributable to emissions from the studied power plant, cases per year

Pollutant	Outcome	Cause	Proposed plant case	Indian standards case	State-of-the-art case
PM2.5	Premature death	Lower respiratory infections (infants)	8	4	1
		Chronic obstructive pulmonary disease	20	9	3
		Lung cancer	3	1	0
		Stroke	31	14	5
		Ischemic heart disease	33	15	5
		PM2.5 Total	94	42	15
NO2		All causes	52	10	5
Total		Total	146	52	20
		95% confidence interval	*(81 - 204)*	*(29 - 72)*	*(11 - 28)*
PM2.5	Low birth weight births		610	120	60

Table 6. Projected health impacts attributable to emissions from the studied power plant over a 40-year operational lifetime

Pollutant	Outcome	Cause	Proposed plant case	Indian standards case	State-of-the-art case
PM2.5	Premature death	Lower respiratory infections (infants)	320	160	40
		Chronic obstructive pulmonary disease	800	360	120
		Lung cancer	120	40	0
		Stroke	1240	560	200
		Ischemic heart disease	1320	600	200
		PM2.5 Total	3760	1680	600
NO2		All causes	2080	400	200
Total		Total	5840	2080	800
		95% confidence	*(3240- 8160)*	*(1160 - 2880)*	*(440 -*

	interval			*1120)*
PM2.5	Low birth weight births	24400	4800	2400

Toxic deposition

The pollution emissions from coal-fired power plants lead to deposition of toxic mercury and fly ash, as well as acid rain.

Projected mercury deposition within 10km around the plant would approximately double the mercury deposition rates compared with regional background of 250mg/ha/yr, as estimated by Chen et al (2014). Mercury deposition rates as low as 120mg/ha/year can lead to accumulation of unsafe levels of mercury in fish (Swain et al 1992). Projected mercury deposition from the Rampal plant alone exceeds this level over an area of approximately 70km2 around the power plant. This highly affected area is entirely in the water catchment of the Sundarbans wetland. Five percent of the predicted deposition affecting the wetland would occur on the Indian side of the border.

Fifteen percent of mercury emitted from the power plant is projected to be deposited into the Sundarbans wetland and into the water catchment upstream of the wetland in the EIA case and 10% in the proposed plant and 'Indian standards' cases. There is significant uncertainty about the amount of mercury emitted because of lack of data provided by the project proponent, but the best estimates available point to total mercury deposition of 50kg per year in the no FGD case, 20kg per year in the proposed plant (FGD) case and 10kg in the 'Indian standards' case. In the worst case (high mercury coal, low capture rate), deposition into the area could be 230kg in the EIA case and 80kg in the two other cases. With mercury-specific control techniques, projected mercury deposition could be limited to no more than 25kg even in the case of high-mercury coal.

Total fly ash deposition into the wetland and the water catchment is predicted at 170 tonnes per year in the proposed plant and EIA cases, 100 tonnes in the Indian standards case, and 30kg in the state-of-the-art case.

As an indicative estimate, based on USGS analysis of 100 Indian coal samples[3], 170 tonnes of fly ash from Indian coal could be expected to contain around 20-60kg of chromium, 10-20kg of copper, 20-120kg of manganese, 10-50kg of nickel and 5-10kg of lead[4].

Most intense acid deposition would take place in the areas up to 30km to the northeast and northwest of the plant, around Khulna, with most affected areas receiving an estimated 5kg of SO2-equivalent per hectare per year in the tender document case. This deposition could affect agricultural yields or increase input costs for farmers who have to neutralize the deposition. Acid rain also damages property and culturally important buildings. Acid rain would be reduced by more than 80% in the state-of-the-art case, compared with the limit values given in the tender documents.

[3] USGS 2011: World Coal Quality Inventory v1.1. http://energy.usgs.gov/Coal/AssessmentsandData/WorldCoalQualityInventory.aspx

[4] These rough estimates are calculated by assuming an enrichment factor of 1-2 from ash in unburned coal to fly ash emitted from the stack, in line e.g. with the empirical results of Linak et al 2000 http://www.tandfonline.com/doi/pdf/10.1080/10473289.2000.10464171

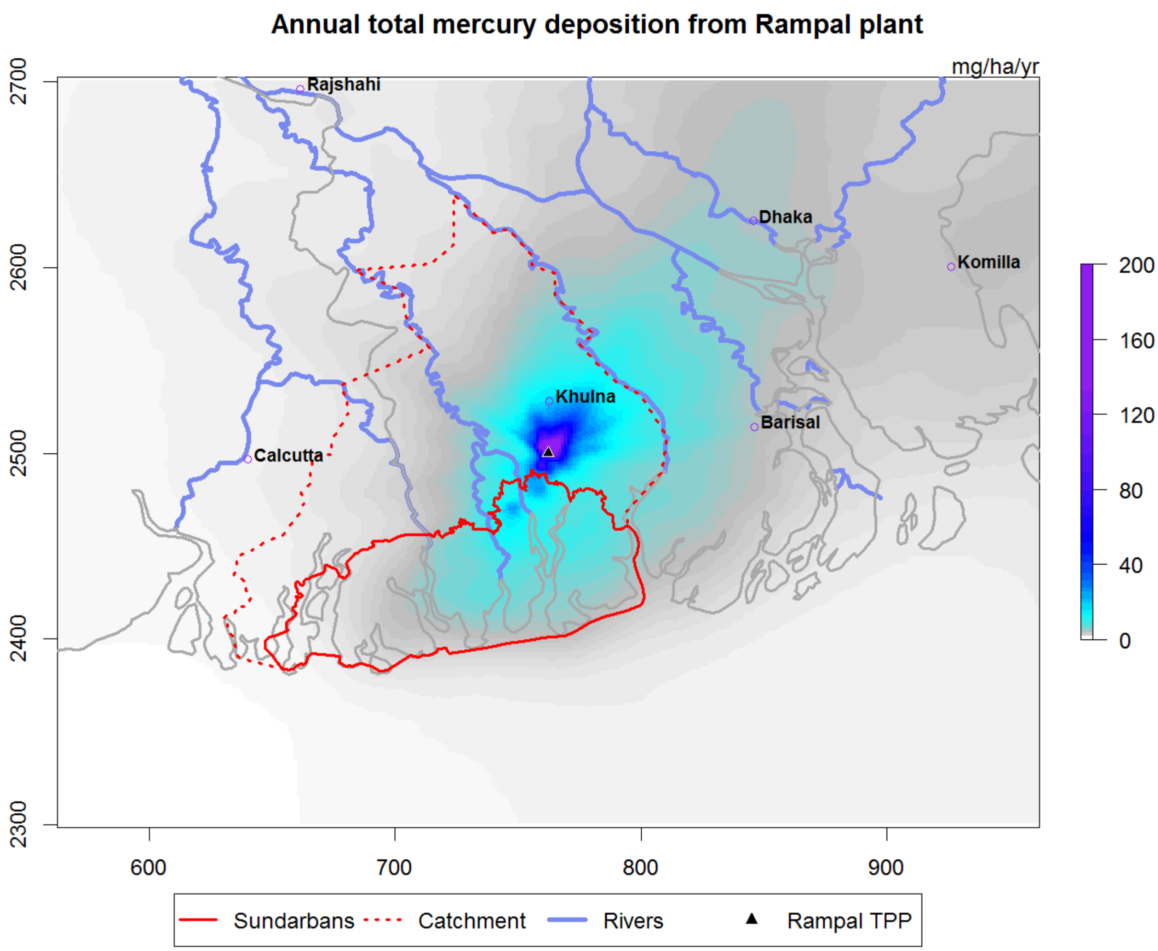

Figure 7. Projected mercury deposition from the Rampal coal-fired power plant in the proposed plant case.

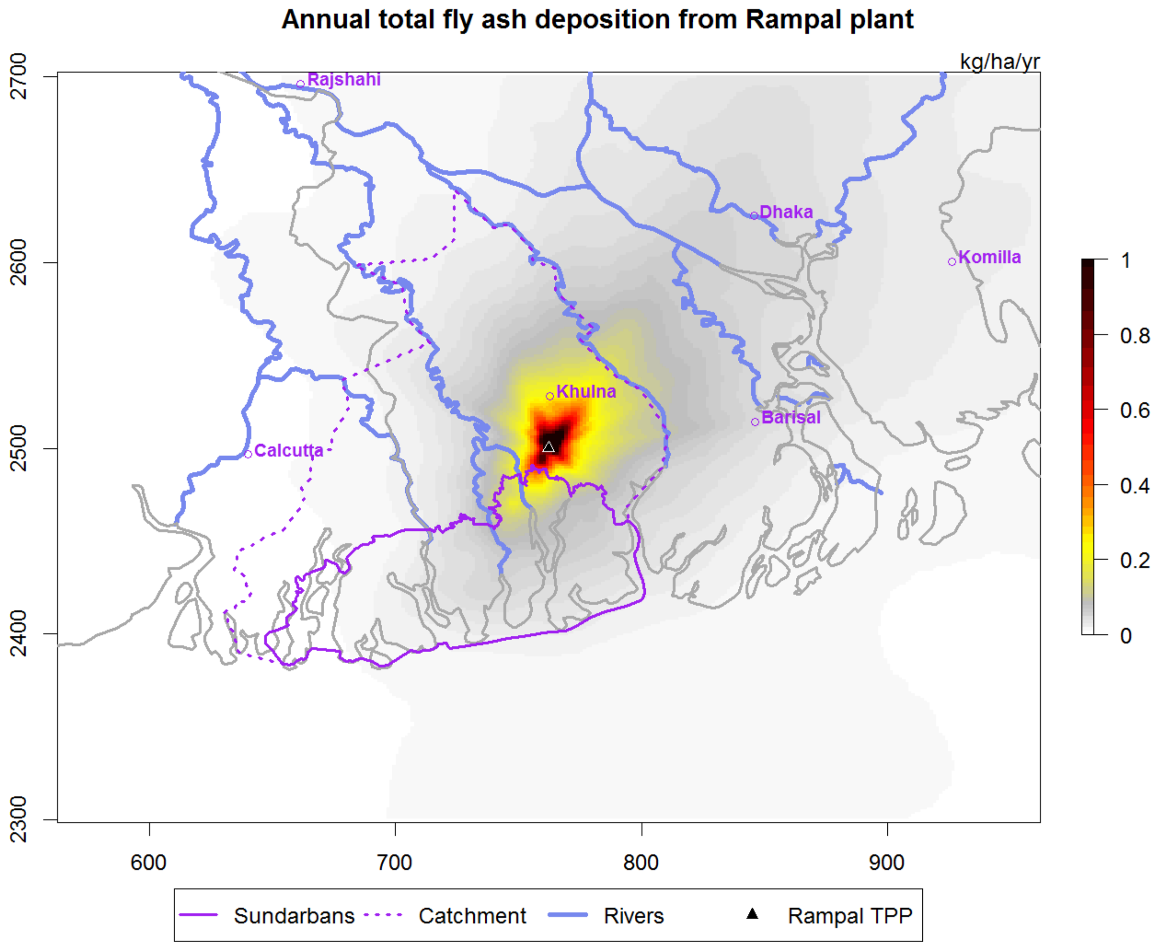

Figure 8. Projected fly ash deposition from the Rampal coal-fired power plant in the proposed plant case.

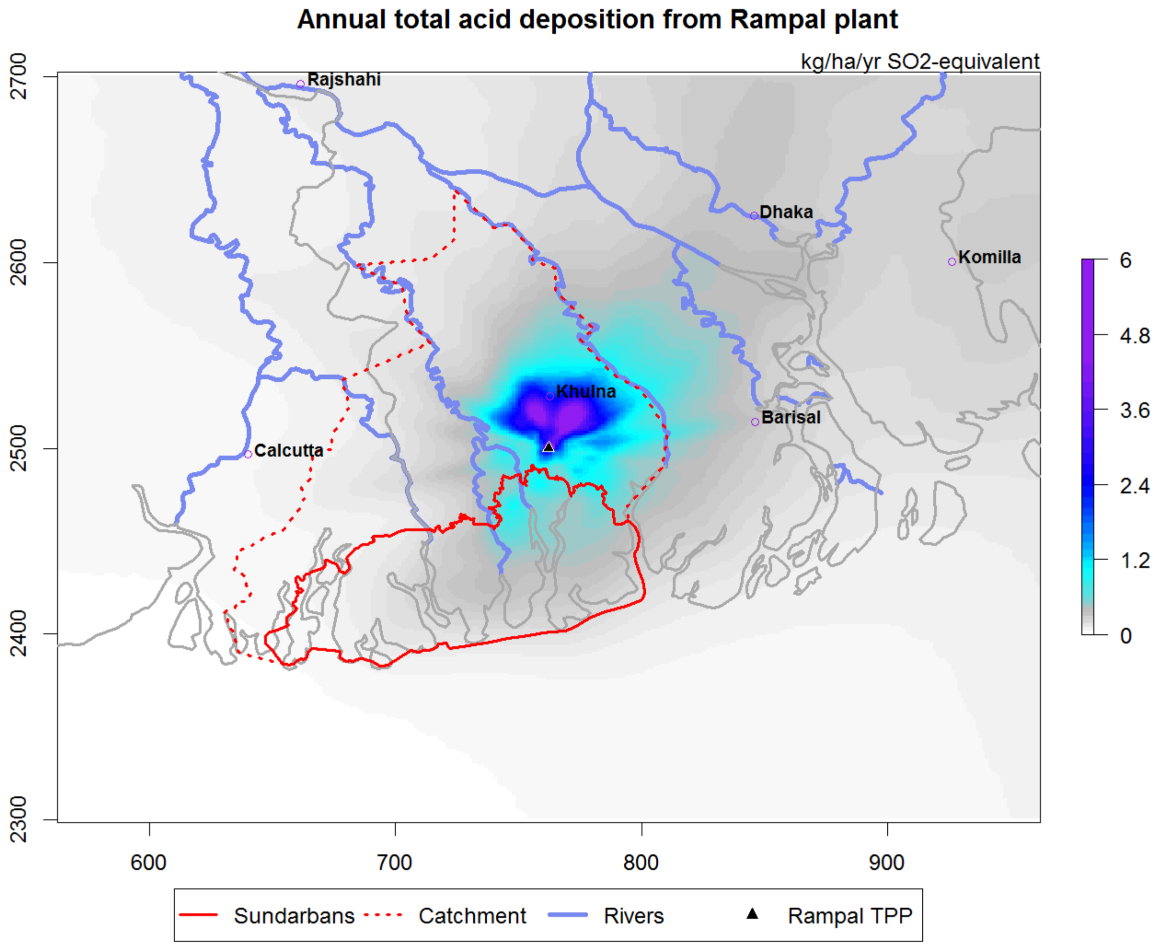

Figure 9. Projected acid deposition (SO2-equivalent) from the Rampal coal-fired power plant in the proposed plant case.

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Appendix: Materials and methods

Atmospheric dispersion modeling for the case studies was carried out using version 7 (June 2015) of the CALPUFF modeling system. CALPUFF is an advanced non-steady-state meteorological and air quality modeling system adopted by the U.S. Environmental Protection Agency (USEPA) in its Guideline on Air Quality Models as the preferred model for assessing long range transport of pollutants and their impacts.

Meteorological data for the simulations comes from two sources: 30 hourly surface meteorological observation stations for which data was available through U.S. NCDC under the World Meteorological Organization agreement on sharing meteorological data, and three-dimensional meteorology generated in the TAPM modeling system, developed by Australia's national science agency CSIRO. TAPM uses as its inputs global weather data from the GASP model of the Australian Bureau of Meteorology, combined with higher-resolution terrain data. TAPM outputs were converted into formats accepted by CALPUFF's meteorological preprocessor, CALMET, using the CALTAPM utility, and the meteorological data were then prepared for CALPUFF execution using CALMET. CALMET generates a set of time-varying micrometeorological parameters (hourly 3-dimensional temperature fields, and hourly gridded stability class, surface friction velocity, mixing height, Monin-Obukhov length, convective velocity scale, air density, short-wave solar radiation, surface relative humidity and temperature, precipitation code, and precipitation rate) for input to CALPUFF.

Terrain height and land-use data were also prepared using the TAPM system and global datasets made available by CSIRO. A set of concentric nested grids with a 50x50 grid size and 30km, 10km and 5km horizontal resolutions and 35 vertical levels, centered on the Craiova region, was used for the TAPM simulations.

A full calendar year CALPUFF simulation was carried out for 2015. The latest version of the model, 7.0, was used and U.S. EPA standard default model settings were used throughout. Deposition parameters for mercury, for which there is no default, were based on U.S. EPA (1997).

To estimate emissions, when emission mass flow rates were not given, flue gas volume was calculated from CO_2 emissions. This calculation is straightforward, as dry standardized flue gas is essentially comprised of CO_2 and ambient air at a specified ratio (6% excess oxygen), with other species such as NO_x and SO_2 making up less than 1/1000 of the volume. The ratio applied in the calculation is 3563.425 Nm^3/tCO_2, calculated from EEA (2008, Table D.1).

30% of emitted fly ash was assumed to be $PM_{2.5}$, and 37.5% PM_{10}, in line with the U.S. EPA AP-42 default value for electrostatic precipitators. Particles larger than 10 microns were modeled with a mean aerodynamic diameter of 15 microns. 95% of NO_x was assumed to be emitted as NO, and 5% as NO_2. A low share of NO_2 reduces predicted air quality and health impacts, as NO must first oxidize into NO_2 before it contributes to NO_2 levels or can oxidize further into nitrate. Reported annual emissions were converted into average emission rates, which were then applied throughout the year.

Local mercury deposition depends strongly on the speciation of mercury – how much of the mercury is emitted in divalent form (Hg^{2+}), elemental gaseous form and bound to particles. The divalent form is most easily deposited locally. Average distribution of the different species without flue gas desulfurization reported by Lee et al. (2006) were used.

The ISORROPIA II chemistry module of the CALPUFF model requires data on background concentrations of species affecting secondary inorganic aerosol formation. Monthly average ozone concentrations for calendar year 2015 were obtained from Bangladesh MoEF Monthly Air Quality Monitoring Reports[5]. Appropriate measured values could not be obtained for ammonia and H2O2 concentrations, so monthly average values for were imported into the model from baseline simulations using the Geos-Chem global atmospheric model (Koplitz et al 2017).

The CALPUFF results were reprocessed using the POSTUTIL utility to repartition different nitrogen species (NO, NO2, NO3 and HNO3) based on background ammonia concentrations.

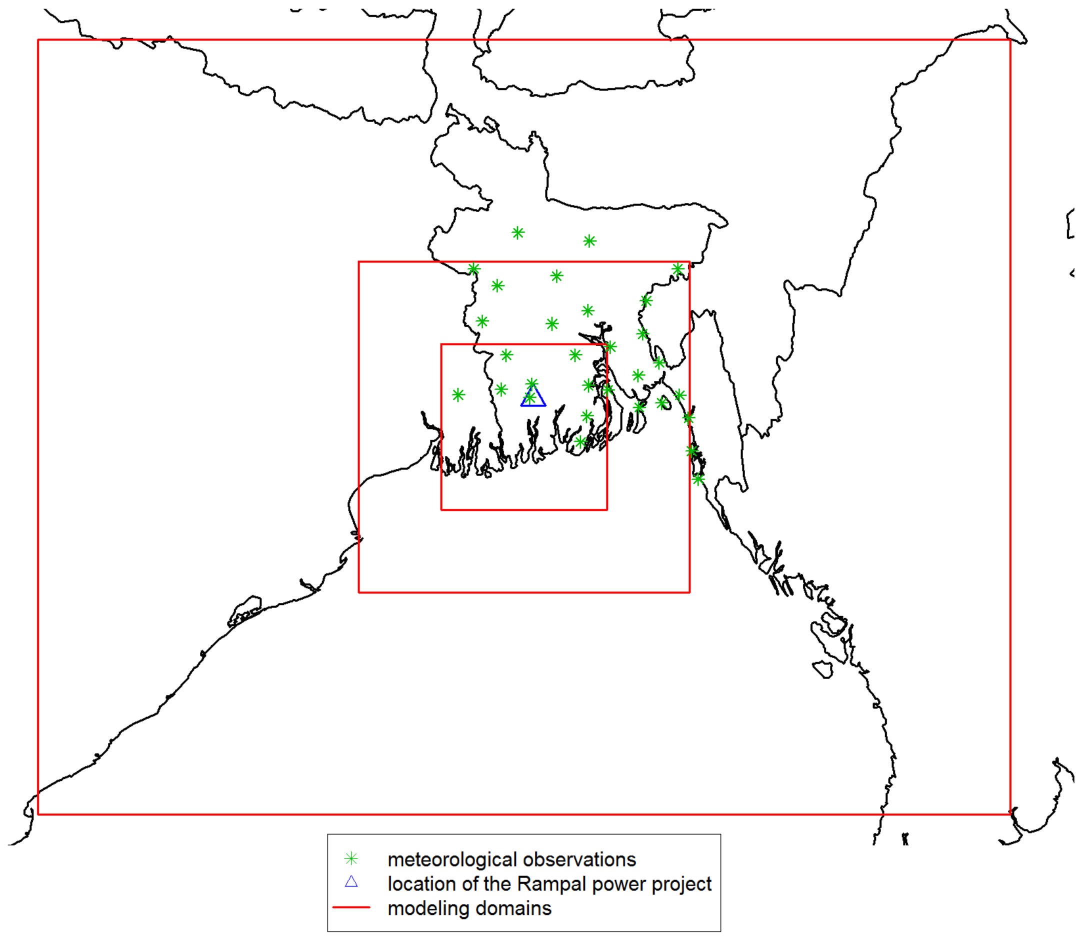

Figure 10. TAPM and Calpuff nested modeling domains, the location of the Rampal power plant and locations of surface meteorological data stations.

Health impacts

The basic foundation for the health impact estimates are numeric scientific studies that show that the risk of chronic diseases such as stroke and lung cancer is increased for people who live in areas with

[5] http://case.doe.gov.bd/index.php?option=com_content&view=article&id=5&Itemid=9

higher PM2.5 levels. We use relationship derived from dozens of such studies to estimate premature deaths attributable to coal pollution, following the methodology of the Global Burden of Disease (GBD) study.

1. Data on current PM2.5 pollution levels across the study are is used to calculate the overall increase in health risks in each location caused by air pollution, compared with living in clean air[6]. For example, at a PM2.5 level of 50 ug/m3, risk of death from lung cancer is estimated to increase by 30%.
2. Current number of deaths from each cause relevant to air pollution health impacts is calculated in every location by combining high-resolution population data, national age structure data, and national data on death rate from each cause per 100,000 people
3. The current number of deaths and the increase in risk of death give the current amount of "excess" or "premature" deaths.
4. The CALPUFF model is used to estimate the PM2.5 concentrations for which the studied sources are responsible for in each location within the study area. These are compared to the overall pollution level in each location to calculate the share the studied sources out of total PM2.5 levels and total health impacts.

More specifically, the implementation of the GBD methodology followed two steps: first, reproduction of the GBD results for total mortality related to PM2.5 for each grid cell, and second, the calculation of the share of these deaths attributable to the Rampal power plant, based on the atmospheric modeling results.

Health impact assessment was implemented in a 2.5x2.5km grid, with atmospheric modeling results interpolated linearly and population data aggregated to the grid. Total premature deaths in a given grid cell are calculated as

Pdtot = PAF * DR * pop * AF, and

PAF = 1 - 1 / RR(Pbase),

in which RR(Pbase) is the cause-specific risk ratio, based on baseline PM2.5 level Pbase in the grid cell and the non-linear concentration-response functions integrated for the GBD project from dozens of epidemiological studies by Burnett et al (2014). PAF is the population attributable fraction, share of deaths from cause c in the relevant age group that are attributable to PM2.5 exposure, DR is the baseline death rate from cause c in the relevant age group, pop is the total population in the grid cell, and age fraction AF is the fraction of population that belongs to the relevant age group (25 years and above for chronic diseases and under 5 years for Acute Respiratory Infections).

For stroke and ischaemic heart disease, the GBD concentration-response functions are age-specific. Appropriate functions for the entire Bangladesh adult population are derived as averages of the age-specific functions weighted by the population share of each age group in Bangladesh.

[6] The GBD methodology assumes a “no-harm” concentration of 6.8µg/m3.

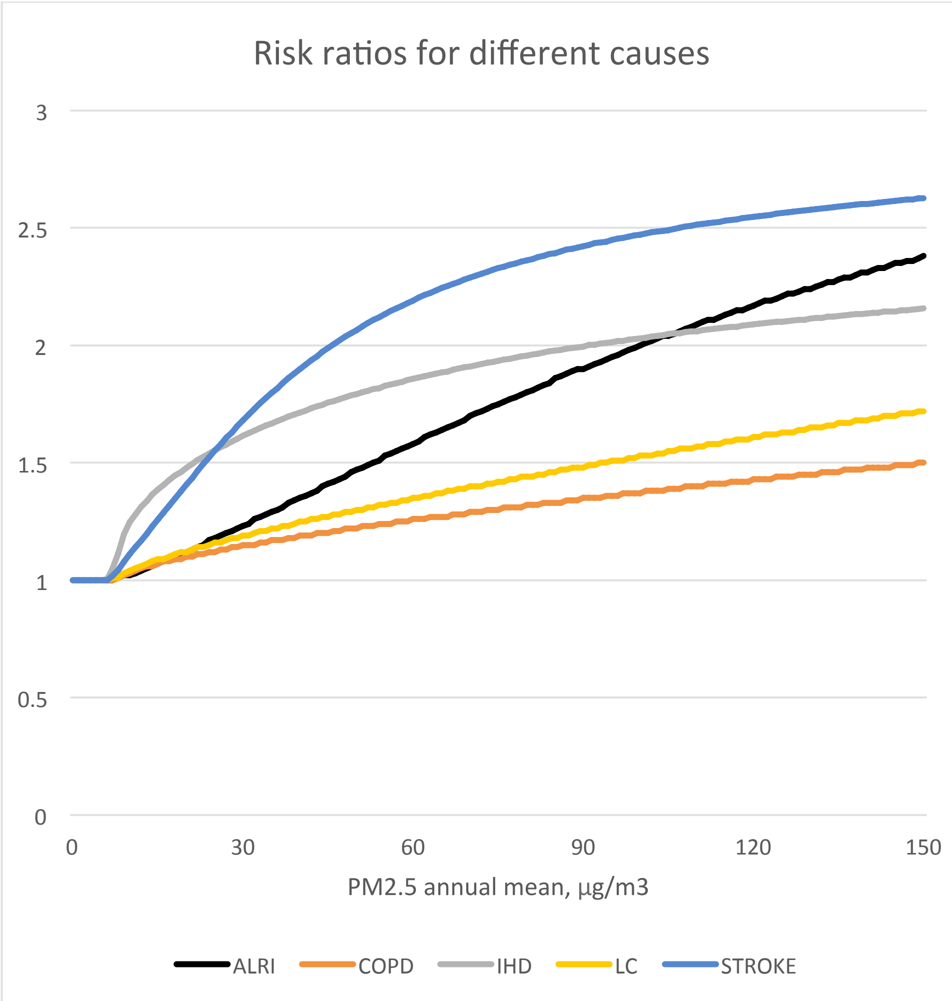

Figure 11. Concentration-response functions developed for the Global Burden of Disease study and applied to assessing the health impacts of the Rampal coal power project.

National average mortality for each country was obtained from WHO (2014) Global Health Estimates database.

To get baseline PM2.5 concentrations we used global gridded PM2.5 data for 2015 derived by combining available ground-level measurements with satellite-based aerosol retrievals and atmospheric model outputs (van Donkelaar et al 2016) for 2015. High-resolution gridded population data for 2015 was obtained from NASA SEDAC (CIESIN, FAO and CIAT 2016).

In the second step, premature deaths attributable to the emissions from the power plant specifically were calculated as

PDcpp = PDtot * Pcpp / Pbase,

where Pcpp is the modeled PM2.5 concentration at the given grid cell that is attributable to emissions from the power plant.

Table 6. Additional risk ratios used for health impact assessment.

Risk ratio for $10 \mu g/m^3$ increase in exposure (Pollutant)	Central	95% CI, low	95% CI, high	Reference
Low birth weight (PM2.5)	1.100	1.030	1.180	Dadwand et al 2013
Deaths, all causes (NO2)	1.0060	1.0033	1.0087	Mills et al 2016