Defining the ‘Urban Critical Zone’ for global sustainable development

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Abstract

With urbanization, cities are becoming new landscapes, significantly altering the properties, processes and pathways of previous natural environments. The natural critical zones that have existed for many millenia are rapidly getting modified by superimposition of the urban components to give rise to a new critical zone system – the Urban Critical Zone. The clogging and bypassing of the natural process pathways, and the increasing demands of urban populations for ecosystem services are putting the native critical zone and the adjoining zones under stress. To elucidate this point, we present a case study on Delhi, the capital city of India, to demonstrate how the urban critical zone is unsustainable. We exemplify the increasing demand and supply gap of basic ecosystem services, such as clean air and water that are essential to sustain life. In doing so, we redefine the limits of the critical zone in urban areas, recognizing that significant parts of cities are going beyond the extent of the presently defined critical zone.

Keywords: Critical Zone, Urban Critical Zone, Planetary Boundary Layer

Introduction

Urban areas have become black holes for ecosystem services in the present global development scenario[1]. Cities are incapable of managing their own unparalleled growth demands. As a result, most of the ecosystem services are borrowed from adjoining regions which are relatively pristine.

The accelerating demands of rising metropolitan populations are putting these broader natural ecosystems under stress. This one-way exploitation of resources to supply for urban growth is creating an imbalance in nature and during the course of the 'Great Acceleration'[2] of the late 20th Century, that imbalance has been increasing in its magnitude. In cities across the world, inevitable tipping points are fast approaching when the supply from the surrounding natural support system will be insufficient to meet the urban demands. A fresh framework to address this looming socio-ecological challenge is needed, and a useful perspective for that may come from a re-thinking of the influential interdisciplinary paradigm of ‘the critical zone’.

In the USA, National Research Council (NRC) borrowed and re-introduced the term “Critical Zone” defining it as “the heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air and living organisms regulate the natural habitat and determine availability of life sustaining resources”[3]. This definition was subsequently modified and the lower limit re-defined at “freely circulating fresh groundwater”, thereby excluding deep connate brines and confined aquifers[4]. To simplify and summarize existing definitions, the Critical Zone is here defined as the thin outer skin of the living planet that forms an interface for interaction between the atmosphere, lithosphere, hydrosphere and biosphere extending from the base of circulating groundwater to the top of vegetation canopy[5,6].

Societal significance of the Critical Zone is that it hosts intricate interactions between the various biotic and abiotic components within it to maintain life on the planet. All components interact with each other in a complex web of feedbacks to maintain the system in a state of dynamic equilibrium[7]. Humans live and interact within this system and are a key component of the system. However, because the original motivation was to elucidate the intricate workings of natural systems, most of our understanding of the Critical Zone so far, comes from the terrains that are largely in pristine condition. A vital mission, therefore, is to develop an appreciation for understanding how the natural CZ in urban areas is becoming short-circuited due to increased anthropogenic activities (fig 1). As a consequence, when we look at the definition of the Critical Zone and try to implement it in urban settings, we observe that there is a need, not only to redefine the term critical zone, but also to ask different set of questions.

Conceptual Framework – Urban Critical Zone

The internal topology within the Critical Zone tends to get more complex with the amplification of the anthropogenic impact. As urban growth takes hold in a region and continues at pace, it creates a distinct microclimate that changes the dynamics of the wider system – removing some components, adding new ones, and strengthening and weakening of existing components. The key question that arises in this context is, how different is this "Urban Critical Zone" from the Natural Critical Zone?

In order to investigate the functioning of this short-circuited critical zone, we explore the example of Delhi –a mega-city of India and look at some underlying parameters.

Study Area

Delhi is an inland metropolitan city away from the direct influence of sea and mountains. The resulting climate of the region is arid to semi-arid, with the city experiencing average highest temperature of 39°C during the summers and average lowest temperature of 6°C during the winters[8]. Rainfall is mainly confined to the southwest monsoon months from June to September, with a little rainfall during the rest of the year[8,9]. The area also witnesses occasional dust storms from the Thar desert that is located southwest of Delhi. Geographically, located at the confluence of the Precambrian Aravalli ranges, the Thar desert and the Indo-Gangetic plain, the region is locally drained by the River Yamuna, which passes through the city. The city is built on Quaternary aeolian sediments from Thar desert and alluvium from the Yamuna river, which in turn overlie the quartzite basement of the Precambrian Aravalli Group[9].

Delhi's new 'un-natural' environment

Land and Water

Much of Delhi is paved by concrete, slag, asphalt and metaled roads. It is now covered by cumulative length of 28506 km of roads. Water percolation into the subsurface layers takes place only in specific areas which are devoid of pavements. Hence, a significant proportion of the precipitation contributes to the surface runoff. In a well-planned city, surface runoff is restricted to a drainage network (both surface and subsurface). This network drains into the *sink* (which could be any water body, a pond, river, sea, or ocean). The urban carapace armours the underlying soil mantle and prevents erosion, but the particulate matter used along with them – such as gravel, sand, tarmac, macadam, and bricks – may erode and generate a sediment flux of a different chemical nature. Moreover, swelling industries in the suburban areas and the residential areas release water with physical, chemical and biological contaminants that contribute to ever large part of the surface and subsurface run off.

Decadal census data show an exponential rise of the city's population during the past century (fig. 2)[10]. The population growth rate sharply increased from 1951, maintained a constant rate between 1950s to 1970s, then it started declining from 1980s before dropping abruptly in 2011. Despite the recent slowdown of population growth, the vastly increased urban population presents a growing demand (and competition) for space. To meet that demand, the city is expanding vertically and horizontally. Fig. 2 shows the temporal change in land use and land cover over the past two decades. There has been a significant (13%) increase of urban built-up area at the expense of agricultural land, with little or no change in the forest cover and water bodies.

The demand for water in urban area is met by the surface water bodies (local rivers and by transfer from far off rivers like the Ganga and the Sutlej) and abstraction from groundwater resources[9]. Hence, residential and industrial areas become zones of heavy groundwater depletion. The imbalance in the water budget results in a rapid and consistent lowering of the water table. As a result, the yearly average depth to water table in Delhi has logarithmically declined in the past two decades (fig. 2)[9,11]. The central and southern parts of the city show consistent lowering of the water table indicating greater abstraction of groundwater with insufficient recharge. The degree of lowering decreases away from the central area. By contrast, the active floodplain of Yamuna, parts of its older floodplain and the western parts have water table relatively at shallow depths and the seasonal fluctuation in the water level shows marked rise following the monsoon season.

Evapotranspiration contributes to the atmospheric humidity. But due to low forest cover, the evaporation parameter is much more dominant than transpiration component. The Urban Heat Island (UHI) effect[12] increases evaporation and alters the natural microclimate. Mohan et al. (2012)[13] classified Delhi into three settings – (1) dense and commercial built-up areas having high UHI effect; (2) medium or less built-up areas having moderate UHI effect, and (3) open, river side areas and green belts with low UHI effect. The maximum daily values of UHI make Delhi comparable to other megacities, such as, London, Beijing and Tokyo.

With the changes in microclimate and water regime, Delhi's biological ecosystem is changing. Within a small (e.g. 2500m^2) area, a large diversity of flora can flourish - ferns, cycads, palms and deciduous species – many of which are not native to the particular setting. Instead, the new urban flora reflects anthropogenic demands. Urban planners have replaced the natural flora with selected exotic species to suit the aesthetics[14]. This results in the formation of fragments of ecological refuges for avifauna within the urban system[15]. Moreover, to facilitate the growth of alien/incompatible species, the physical parameters have to be altered, principally by introducing chemical and biological additives (pesticides such as DDT, medical grade antibiotics etc.). Such biochemical alteration further modifies the microbial activity within the soil, facilitating growth of new bacterial strains and inhibiting the growth of certain native strains. Wetlands are sensitive natural systems that substantially provide ecosystem services to the adjoining natural and urbansettings. Singh et al. (2013)[16] discussed the effects of urbanization on the degradation of Delhi's wetland ecosystem. Each of these fragments form micro-ecosystems within the city which is different from the natural native ecosystem. Urban development is encroaching into the riparian wetlands, shrinking them and disturbing the balance within the system (Singh et al. [16]).

Ambient Air

Across the city, air pollutants are emitted from myriad anthropogenic sources such as exhaust emissions on roads, open burning of biomass, biofuel and municipal waste in landfills and industrial effluents from chimneys designed to discharge at several metre-tall stack heights (e.g. coal-fired power plants). Despite regulatory mechanisms, regulation of many of these sources is inadequate and the chemical emissions released into the air in the form of both gases and particulate matter often create a toxic haze through both primary emission and secondary pollutants formed with the critical zone. During transition from summer monsoon to winter, a 'pollution dome' often forms, regionally aided by calm anticyclonic conditions[17]. This smog which is rich in particulate matter and toxic gaseous organics can influence the fog cycle and causes further widespread disruption in visibility and mobility[18]. Several studies, including reports by the World

Health Organisation (WHO), have documented an alarming degree of health hazards associated with this phenomenon (fig. 3)[19].

Figure 2 shows SO_2, NO_2, CO and particulate matter (PM-10) trends from 1997 to 2019 based on CPCB data[10,20], These air pollutant gases are predominantly produced from anthropogenic sources such as industrial and vehicular emissions[21,22,3,24]. Chemical compounds (organic and inorganic), metal ions, and black carbon constitute particulate matter finer than 10µm (PM-10)[25]. PM-10 has a wide range of sources varying from fossil fuel burning to masonry constructions, wildfires, landfills, dispersed pollen etc. Despite an increase in the levels between 2007 and 2012, the levels of SO_2 and NO_2 and more recently CO in Delhi limited spatially available data from monitoring stations show that there is a decreasing tendency in these gases during the last decade, (fig. 2). In contrast, PM-10 shows consistent increase[10] due to the complex mixture of local sources (construction, vehicular traffic etc.) and episodic external sources (stubble burning, dust storms etc.)[26].

Discussion

Turaga (2015)[15] has conceptualized the 'urban ecosystem' as consisting anthropogenic elements (built-up area, parks, gardens, water bodies etc.) and the natural ecosystems. Based on this model, we recognize two actively working systems within the urban critical zone – (1) natural critical zone system native to the region controlled by the local natural setting, and (2) urban system consisting of anthropogenic components and processes. The urban system has been superimposed on the natural critical zone system, thereby, forming distinct fragments with each having its own network of processes, albeit interlinked with one another. This superposition of the urban system is responsible for the clogging of long-standing process pathways in the natural critical zone and inducing new pathways bypassing the existing ones.

The exponential increase in population demands space for sustenance. Urbanization has taken place at the expense of agricultural land. Furthermore, the urban concentration (i.e., the percentage of the total urban population of a country that resides in the largest/metropolitan cities) has increased in the developed part of the city. All other factors are directly or indirectly influenced by population numbers.

The increasing depth to water table suggests heavy abstraction of groundwater to meet the rising demand of the population, but without sufficient recharge. Groundwater depletion is at its maximum in the highly urbanised section of the city. More than 46% of the land area has a concrete and asphalt cover that impedes percolation of water. Most places do not have facilities of rainwater harvesting, so the only modes of recharge are rainfall, rivers, canal seepage, irrigation, return flow, and water bodies. During the monsoon floods, the floodwaters of the River Yamuna, recharge the active floodplain and the adjacent areas, but the discharge of Yamuna is controlled by a barrage located upstream of Delhi. The western half of the floodplain is mostly agricultural land where the exposed soil cover allows infiltration. However, here the occurrence of saline groundwater at shallow levels[9] restricts local abstraction and hence, there is lesser decline in the water table levels.

Fig 2 shows that depth to water table decreases during high rainfall and vice versa. Thus, besides the potential of the aquifer, the local depth to water table is a function of rainfall, available area for percolation and the local abstraction. But the question remains whether this natural recharge by rainfall is sufficient to meet the urban demand. Moreover, the impact of future anthropogenic demands is uncertain, most notably in the light of development of underground metro network which might adversely impact the shallow subsurface water pathways, an issue that will require detailed investigation and data from specific sites.

Delhi has the highest number of personal vehicles in India[28]. Initiatives and implementation of certain policies in the past two decades have helped in controlling air quality to some extent, notably: (1) replacement of old buses with new buses that run with improved technology to cut down CO_2 emissions; (2) switching of fuel of all public transport vehicles from petrol and diesel to compressed natural gas (CNG); (3) restrictions on use of vehicles older than 15 years; and (4) facilitating mass transport with construction of the 348-km-long Metro rail system[29,30]. These changes could be the reason for steep decline CO_2 levels, whilst relocation of industries outside Delhi has probably resulted in decreased SO_2 and NO_2 levels . However, a holistic, integrated analysis of data from entire National Capital Region (NCR) will be required to really understand the changes in the levels of the aforementioned atmospheric pollutants.

Delhi has a natural dust flux hazard from the Thar Desert. Further, to meet the demand for space, vertical and horizontal expansion of the city involves masonry construction – one of the chief sources of PM-10. A significant fraction of PM-10 during winters comes from stubble burning in the adjoining areas of Haryana and Punjab[26]. Delhi being a place of confluence of winds (desert dust winds from South-west, Himalayan winds from North and North East and wind from North-west carrying PM-10 from stubble burning) occasionally experiences stagnation of surface air with poor ventilation due to the meteorological phenomena of subsidence inversion. This is when cold dense air from aloft descends over surface air trapping surface emissions.

Since rainfall has a big role in controlling the air quality, especially the acidic gases, we examined a possible relationship between rainfall and the gaseous pollutants (fig. 2). But the results do not show any strong correlation. Rainfall as a modulator of air quality is a very dynamic process that occurs over short time periods, ranging from few hours to few days. As rainfall in Delhi is temporally heterogeneous and is focused during three months of the year, the control of rainfall on air quality needs to be considered on annual scale.

We calculated a correlation matrix between these parameters to quantitatively investigate the interrelationships between the parameters and understand the city's demand and supply gap of various ecosystem services (Table 1).

The level of acidic gases and PM-10 shows a good correlation with population. They are not correlated to rainfall. All of the air pollutants are independent of rainfall. Depth to water table shows a negative correlation with rainfall, but a stronger positive correlation with population, implying a weak supply system compared to the demand. And despite groundwater reserves getting recharged by rainfall, they are insufficient to meet the demands.

Limits of the Urban Critical Zone

A significant part of the city extends beyond the limits of the presently defined critical zone. The population residing in skyscrapers and high-rise apartment blocks interact with the critical zone even though they are technically positioned out of it according to the present definition of the upper limit of critical zone. Most of the ecosystem services offered by the critical zone of the peri-urban territory are harnessed by the urban residents. The lower limit of critical zone - defined by the base of circulating groundwater - fluctuates due to mobilization of deeper stagnant water activated by heavy abstraction of the groundwater reserves. The withdrawal/abstraction also lowers the water table at rates higher than replenishment.

Thus, both above and below the ground, the urban critical zone extends beyond the defined limits of the natural critical zone. So, what should be the limit of the urban critical zone? The lowest part of the troposphere in contact with the Earth's surface directly gets influenced by the surface processes and responds to physical, chemical and thermal forcings. Stull (1988)[31] defined this layer as the Planetary Boundary Layer (PBL). The height of this layer varies between 100 to 2000m from the surface. If we consider the nature of this atmospheric layer, it is evident that this layer plays the pivotal role in the functioning of any critical zone system in the urban area. Therefore, we define the top limit of the Urban Critical Zone to be ~ 2000 m from the surface including the PBL within the critical zone. Similarly, the lower limit can be extended to the base of the first aquifer which is currently being exploited and may include deeper level groundwater reserves.

Extending the limits of the Urban Critical Zone will ensure to bring the expanse of anthropogenic activities, both above and below the surface within the urban critical zone. It will also demand a greater role of atmospheric scientists and the geophysicists in the study of the critical zone. At present, there are very few geoscience courses that pay attention to the cities and address these complex, interconnected challenges. But as the cities continue to expand, with an expected increase in the number of megacities (cities with more than 10 million population) to 43 (it was 33 in 2018) and nearly two fold expected increase in the number of cities with 300,000 to 500,000 inhabitants by 2030 (31 in 2018 to 60 in 2030)[32], there is an urgency to generate man power trained in the integration of geological basement and the geoscientific management, which is currently lacking, for the resilient and sustainable development.

Conclusion

The urban critical zone is unable to supply the ecosystem servicessustainably. In fact, the functioning of the critical zone has been altered and has moved in a direction that ensures the indigenous ecosystem services are proving not only insufficient, but also lethal for the sustenance of life. The urban critical zone captures ecosystem services from adjoining natural critical zones, in turn stressing and destabilising them.

The modified structure and functioning of the urban critical zone manifest the exigency of rethinking the existing limits of the critical zone and define new limits that include all processes of this altered system. We propose extending the upper limits to 2000 m to include the planetary boundary layer within the critical zone and the lower limits to the base of the first aquifer being exploited, to include deeper levels of the groundwater reserves.

Cities occupy 2% of the world's land, but are home to 55% of the global population and account for 70% of global GDP[33]. They are expanding rapidly, and globally. 60% of the area expected to be urban by 2030 is yet to be built. However, poor strategic planning of this urban expansion hampers the delivery for their sustainable development. With climate change putting ever more pressure on the ecosystem services that underpin the world's fastest growing cities, the geoscience of the urban critical zone is essential inquiry for the future wellbeing of billions of people.

We see an urgent need to initiate studies on urban critical zone in order to understand this system and balance between natural critical zone. This is a multidisciplinary project and requires efforts from experts from geo, physical, life s, atmospheric, ecological sciences and medical sciences. It is this balance that can pave way for the global sustainable development.

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Table 1: Matrix showing coefficient correlation between various parameters.

	SO_2	***NO_2***	***CO***	***PM_{10}***	***Rainfall***	***Population***	***Depth to groundwater***
SO_2	1						
NO_2	0.661	1					
CO	-0.066	-0.444	1				
PM_{10}	0.585	0.708	-0.653	1			
Rain	0.074	0.033	0.171	-0.087	1		
Population	0.541	0.453	-0.765	0.728	-0.171	1	
Depth to groundwater	0.309	0.543	-0.789	0.677	-0.468	0.784	1

LEGEND					
🟦	🟦	🟨	🟧	🟧	🟩
Strong Negative	**Good Negative**	**Independent**	**Good Positive**	**Strong Positive**	**No Physical Relation**

List of Figures

Figure 1: A diagram showing urban critical zone as a result of modification of components and process pathways of the natural critical zone. Anthropogenic components have short circuited the processes in the natural critical zone system and have evolved into a totally new system. However, the two systems continue to interact with each other.

Figure 2: Demography, hydrology, land use and land cover of Delhi[10,11].

Figure 3: An infographic showing health hazards from atmospheric pollution and global statistics[27].

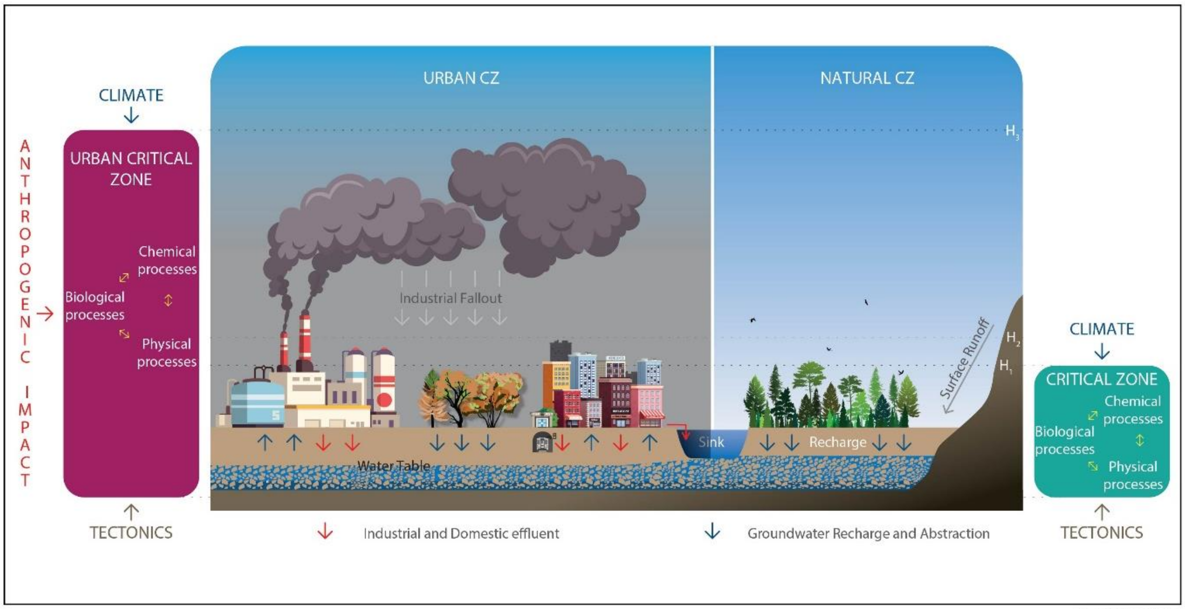

Image: N.G. Dastidar

Figure 1

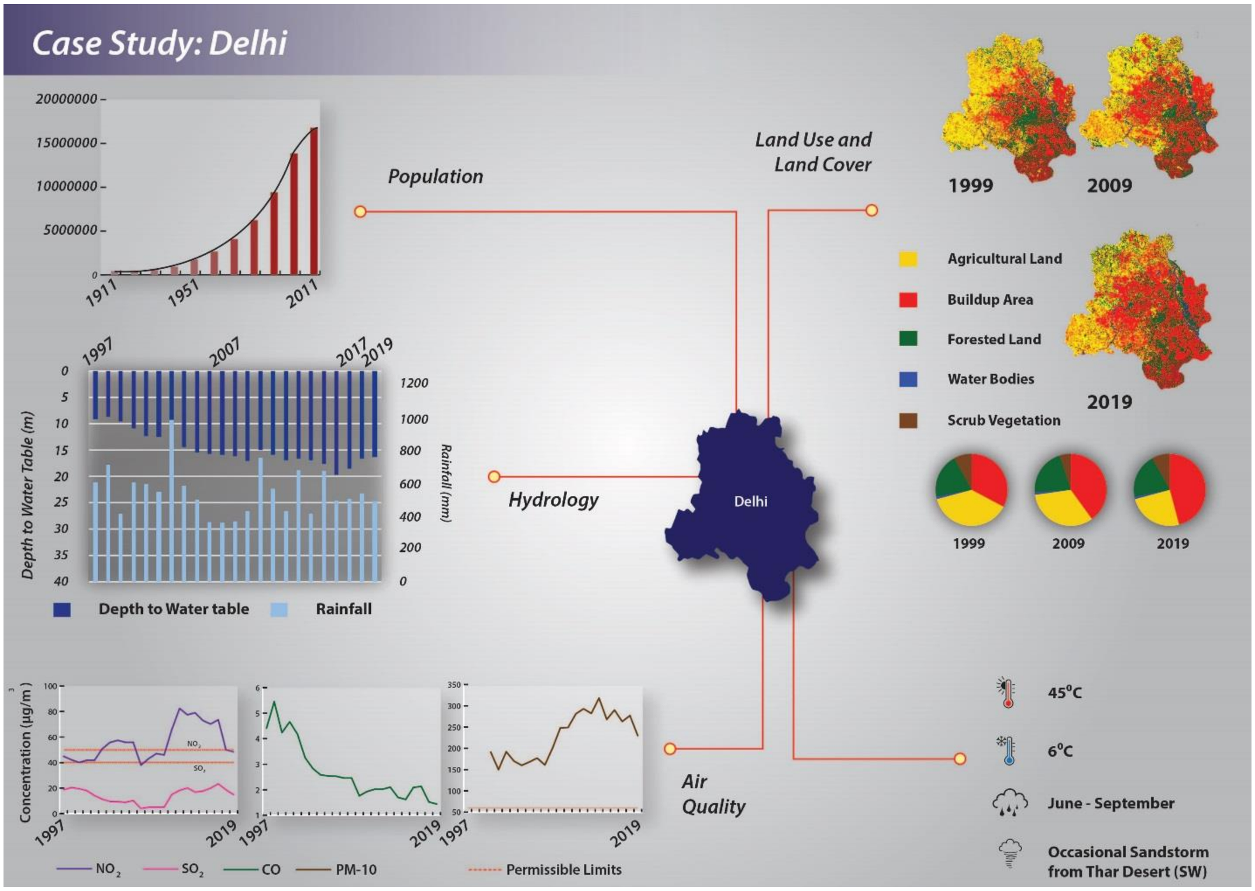
Case Study: Delhi
20000000
15000000
10000000
5000000
0
1911
1951
2011
Population
Land Use and Land Cover
1999
2009
2019
🟨 Agricultural Land
🟥 Buildup Area
🟩 Forested Land
🟦 Water Bodies
🟫 Scrub Vegetation
1999
2009
2019
1997
2007
2017
2019
Depth to Water Table (m)
0
5
10
15
20
25
30
35
40
1200
1000
800
600
400
200
0
Rainfall (mm)
Depth to Water table
Rainfall
Hydrology
Delhi
Concentration (µg/m³)
100
80
60
40
20
0
NO₂
SO₂
1997
2019
6
5
4
3
2
1
1997
2019
350
300
250
200
150
100
50
1997
2019
NO₂
SO₂
CO
PM-10
Permissible Limits
Air Quality
45°C
6°C
June - September
Occasional Sandstorm from Thar Desert (SW)

Figure 2

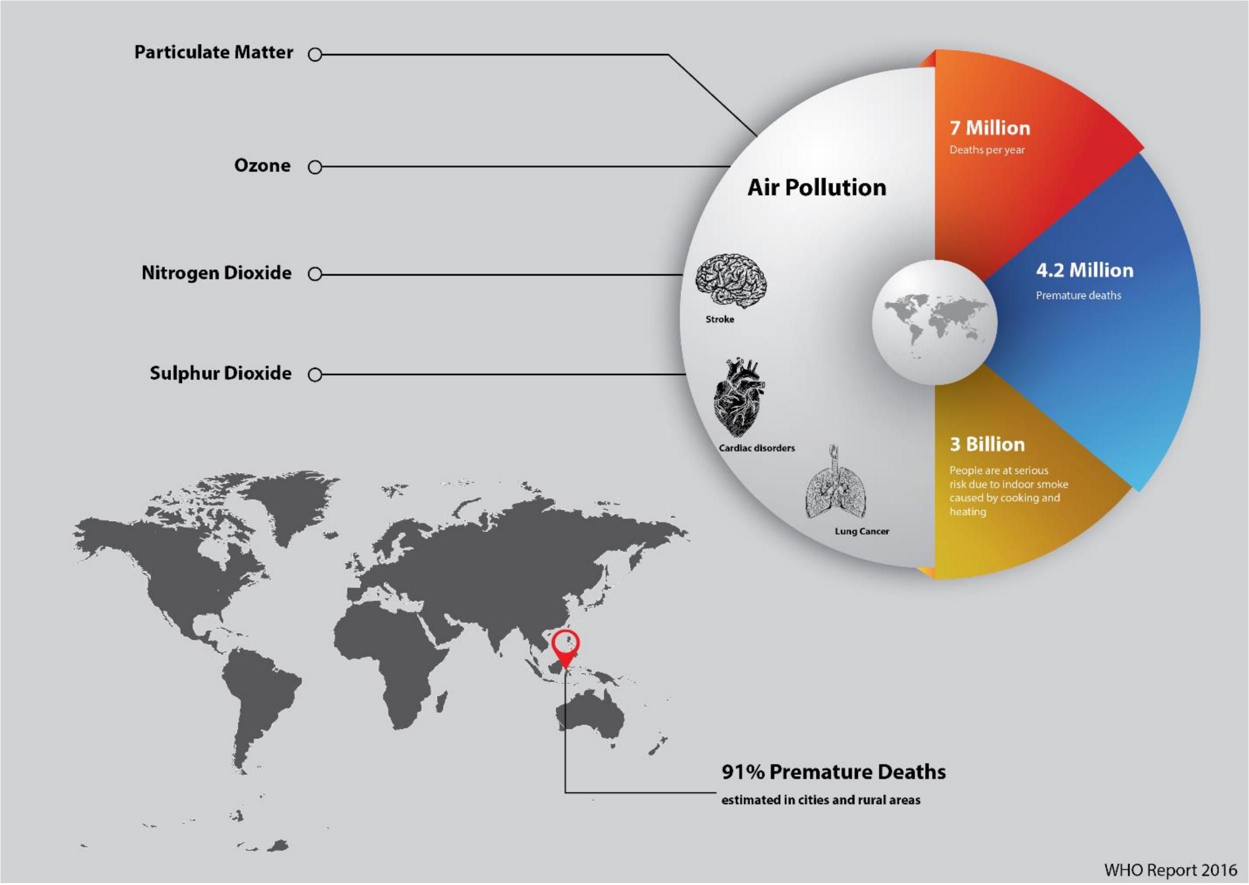
Particulate Matter
Ozone
Nitrogen Dioxide
Sulphur Dioxide
Air Pollution
Stroke
Cardiac disorders
Lung Cancer
7 Million
Deaths per year
4.2 Million
Premature deaths
3 Billion
People are at serious risk due to indoor smoke caused by cooking and heating
91% Premature Deaths
estimated in cities and rural areas
WHO Report 2016

Figure 3