Defining the 'urban critical zone' for global sustainable development

Arkaprabha Sarkar, Vicky Shankar, Vimal Singh, Iain Stewart, Shashank Shekhar and Vinayak Sinha*

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 millennia are rapidly getting modified by the superimposition of the urban components to give rise to a new critical zone system, viz. the urban critical zone. The clogging and bypassing of the natural process pathways and the increasing demands of urban populations for ecosystem services put 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 beyond the presently defined critical zone.

Keywords: Ecosystem services, natural environments, planetary boundary layer, sustainable development, urban critical zone.

URBAN areas have become black holes for ecosystem services in the present global development scenario[1]. Cities are now 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. During the 'Great Acceleration' of the late 20th century[2], this imbalance has been increasing in magnitude. In cities across the world, inevitable tipping points are fast approaching when 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 may come from rethinking the critical zone's influential interdisciplinary paradigm.

In the USA, the National Research Council (NRC) borrowed and reintroduced 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 was redefined at 'freely circulating fresh groundwater', thereby excluding deep connate brines and confined aquifers[4]. To simplify and summarize the existing definitions, the critical zone is defined here 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].

The societal significance of a critical zone is that it hosts intricate interactions between the various biotic and abiotic components within it to maintain life on our planet. All components interact with each other in a complex web of feedback to maintain the system in a state of dynamic equilibrium[7]. Humans live and interact within this system and are a key component. 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 critical zone in urban areas is becoming short-circuited due to increased anthropogenic activities (Figure 1). Consequently, when we consider the definition of the critical zone and try to implement it in urban settings, we observe that there is a need to redefine the term 'critical zone' and ask different questions.

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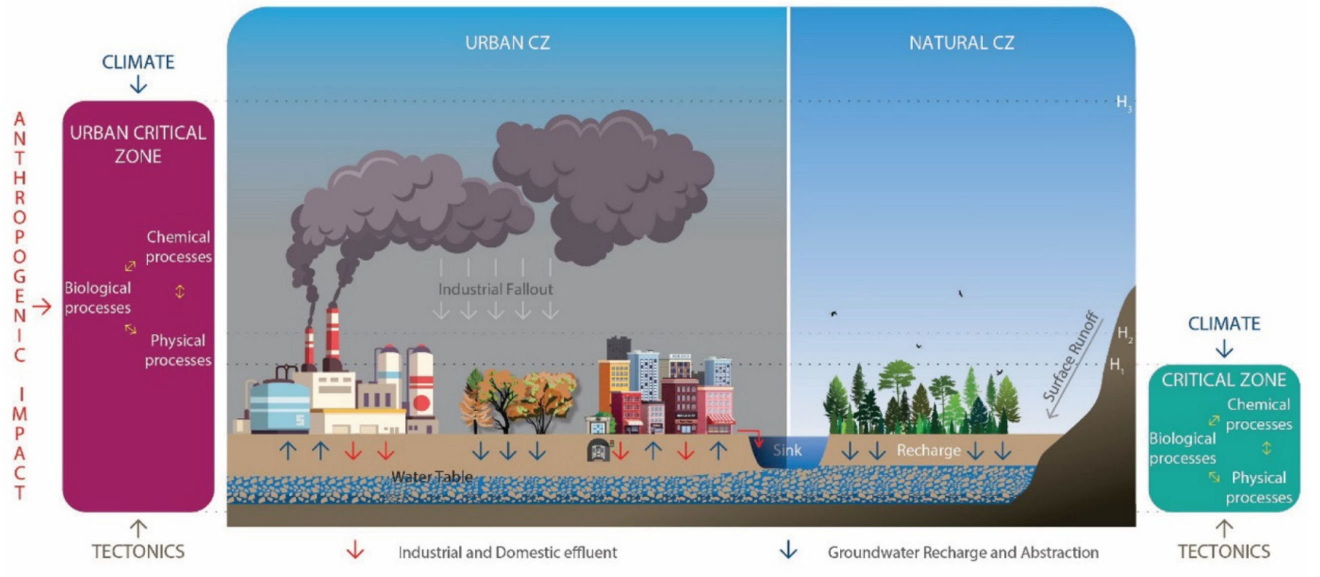

Figure 1. Diagram showing the urban critical zone as a result of modification of components and process pathways of the natural critical zone. Anthropogenic components have short-circuited the processes in the natural critical zone system, resulting into a totally new system. However, the two systems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

Conceptual framework – urban critical zone

The internal topology within the critical zone tends to get more complex with greater anthropogenic impact. As urban growth occurs continuously in a region, it creates a distinct microclimate that changes the dynamics of the wider system – removing some components, adding new ones, and strengthening and weakening existing components. The key question in this context is how different is this urban critical zone from the natural critical zone?

To study the functioning of this short-circuited critical zone, we take the example of Delhi – a megacity of India – and consider some underlying parameters.

Study area

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

Delhi's new unnatural environment

Land and water

Much of Delhi is paved by concrete, slag, asphalt and metaled roads. It is now covered by a cumulative length of 28,506 km of road. Water percolation into the subsurface layers occurs only in areas devoid of pavements. Hence, a significant proportion of the precipitation contributes to the surface run-off. In a well-planned city, surface run-off is restricted to a drainage network (both surface and subsurface). This network drains into the sink (which could be any water body, pond, river, sea or ocean). The urban carapace armours the underlying soil mantle and prevents erosion, but the matter used for its construction – such as gravel, sand, tarmac, macadam and bricks – may erode and generate a sediment flux of different chemical nature. Moreover, swelling industries in the suburban and residential areas release water with physical, chemical and biological contaminants that contribute to a large part of the surface and subsurface run-off.

Decadal census data have shown an exponential rise in the population of Delhi during the past century (Figure 2)[10]. The population growth rate sharply increased from 1951, maintained a constant rate between the 1950s and 1970s, and then started declining in the 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 this demand, the city is expanding vertically and horizontally. Figure 2 shows the temporal change in land use and land cover over the past two decades. There has been a

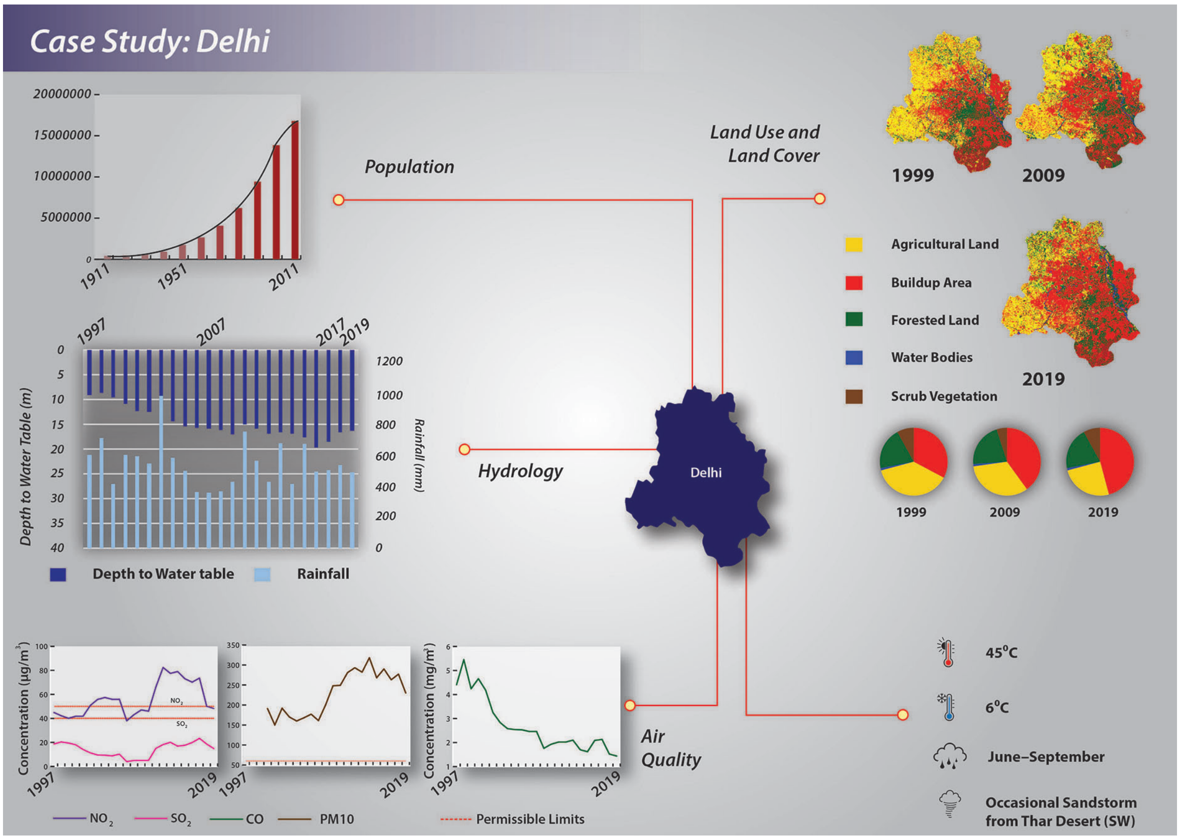

Figure 2. Demography, hydrology, land use and land cover of Delhi, India[10,11].

significant (13%) increase in urban built-up areas at the expense of agricultural land, with little or no change in the forest cover and water bodies.

The demand for water in urban areas is met by the surface water bodies (local rivers and by transfer from far-off rivers like the Ganga and 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, Delhi's yearly average depth to water table has logarithmically declined in the past two decades (Figure 2)[9,11]. The central and southern parts of the city show a 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, in the active floodplain of the Yamuna, parts of its older floodplain and the western parts, the water table is at relatively shallow depths, and seasonal fluctuations in the water level show a marked rise following the monsoon season.

Evapotranspiration contributes to the atmospheric humidity. However, due to low forest cover, the evaporation parameter is much more dominant than the transpiration component. The urban heat island (UHI) effect increases evaporation and alters the natural microclimate[12]. Mohan *et al.*[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, riverside 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 regimes, Delhi's biological ecosystem is changing. Within a small (e.g. 2500 m^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 has resulted 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 the growth of new bacterial strains and inhibiting that of certain native strains. Wetlands are sensitive natural systems that substantially provide ecosystem services to the adjoining natural and urban settings. Singh *et al.*[16] have discussed the effects of urbanization on the degradation

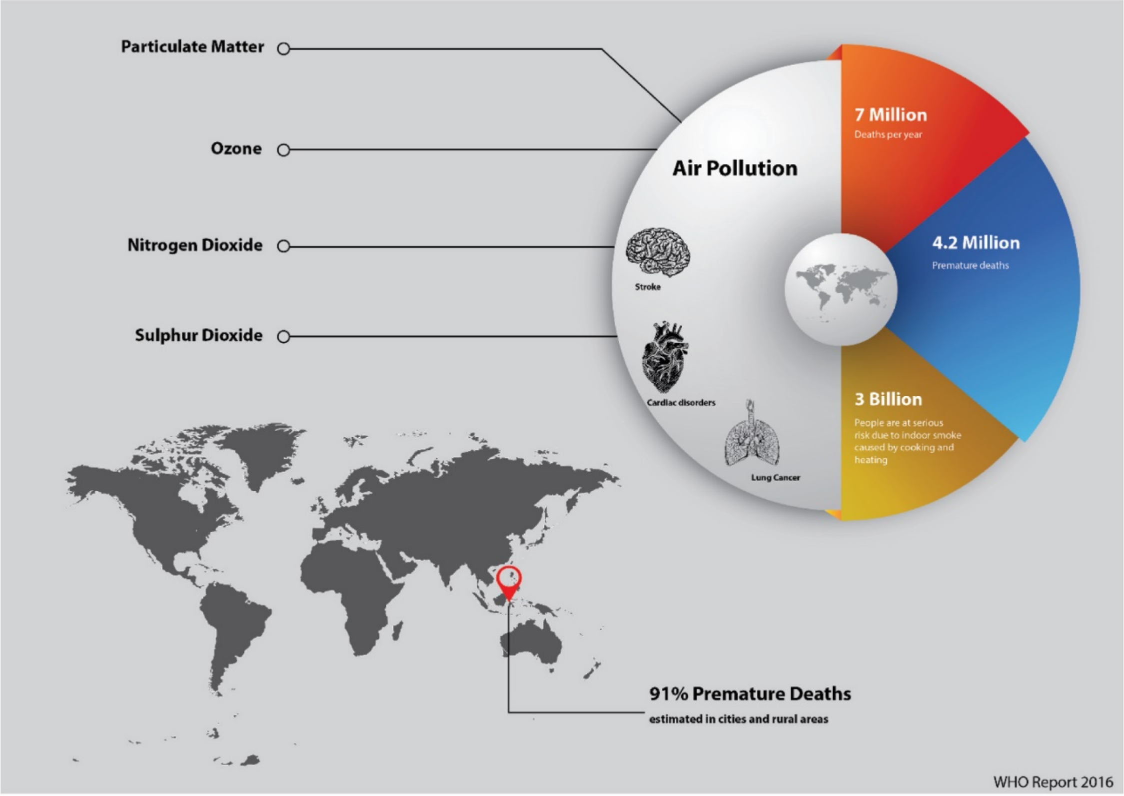

Figure 3. An infographic showing health hazards from atmospheric pollution and global statistics.

of Delhi's wetland ecosystem. Each of these fragments forms micro-ecosystems within the city, which are different from the natural native ecosystem. Urban development is encroaching into the riparian wetlands, shrinking them and disturbing the balance within the system[16].

Ambient air

Across the city, air pollutants are emitted from several 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 atmosphere in the form of both gases and particulate matter often create a toxic haze through both primary emission and secondary pollutants formed within the critical zone. During the 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 cause further widespread disruption in visibility and mobility[18]. Several studies, including reports by the World Health Organization (WHO), have documented an alarming degree of health hazards associated with this phenomenon (Figure 3)[19].

Figure 2 shows SO_2, NO_2, CO and PM_{10} (particulate matter with aerodynamic equivalent diameter less than or equal to 10 µm) trends from 1997 to 2019 based on Central Pollution Control Board (CPCB)[10,20]. These air pollutants are predominantly produced from anthropogenic sources such as industrial and vehicular emissions[21–24]. Chemical compounds (organic and inorganic), metal ions and black carbon constitute particulate matter (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 a pronounced increase in the levels of SO_2, NO_2, between 2010 and 2017 as inferred from the available monitoring station data, after 2017 there seems to have been a decline in their levels along with general decline in CO (Figure 2). In contrast, PM_{10} shows a consistent increase due to the complex mixture of local sources (construction, vehicular traffic, etc.) and episodic external sources (stubble burning, dust storms, etc.)[10,26].

Discussion

Turaga[15] has conceptualized the urban ecosystem as consisting of anthropogenic elements (built-up areas, parks, gardens, water bodies, etc.) and natural ecosystems. Based on this model, we recognize two actively working systems within the urban critical zone – (1) the natural critical zone system native to the region controlled by a local natural setting, and (2) the 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 clogging long-standing process pathways in the natural critical zone and initiating new pathways bypassing the existing ones.

The exponential increase in population demands space for sustenance. Urbanization has taken place at the expense of agricultural lands. 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 of the 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 urbanized section of the city. More than 46% of the land area has a concrete and asphalt cover that impedes the percolation of water. Most places do not have facilities for rainwater harvesting, so the only modes of recharge are rainfall, rivers, canal seepage, irrigation, return flow and water bodies. During the monsoon, the floodwaters of River Yamuna recharge the active floodplain and the adjacent areas, but the discharge of the 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, the occurrence of saline groundwater at shallow levels here restricts local abstraction[9]. Hence, there is less decline in the water table level.

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

Delhi has the highest number of personal vehicles in India[28]. Initiatives and implementation of certain policies during the past two decades have somewhat helped control air quality. Notably: (1) replacement of old buses with new ones 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; (3) restrictions on the use of vehicles older than 15 years and (4) facilitating mass transport with the construction of the 348 km-long metro rail system[29,30]. These changes could be the reason for the steep decline in CO_2 levels, while relocation of industries outside Delhi has probably resulted in decreased SO_2 and NO_2 levels. However, a holistic, integrated analysis of data from the entire the National Capital Region is required to properly 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 states of Haryana and Punjab[26]. Delhi, being at the confluence of winds (desert dust winds from the southwest, Himalayan winds from the north and northeast, and wind from the northwest carrying fine mode PM from stubble burning), experiences stagnation of surface air due to poor ventilation on account of the meteorological phenomenon of subsidence inversion. This is when cold air from higher altitudes in the atmosphere descends over the air close to the surface, thereby trapping the surface emissions in the lower atmosphere[27].

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

We generated a correlation matrix between these parameters to quantitatively study the inter-relationships 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} showed a good correlation with population but did not show correlation with rainfall. Depth to water table showed a negative correlation with rainfall but a stronger positive correlation with population, implying a weak supply system compared to the demand. Despite groundwater reserves getting recharged by rainfall, they were 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 populations 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 the 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 the critical zone – defined by the base of circulating groundwater – fluctuates due to the 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.

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

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 is directly influenced by the surface processes and responds to physical, chemical and thermal forcings. Stull[31] defined this as the planetary boundary layer (PBL). The height of this layer varies between 100 and 2000 m from the surface. Considering the nature of this atmospheric layer, it is evident that it plays a pivotal role in the functioning of any critical zone system in an urban area. Therefore, we define the top limit of the urban critical zone to be ~2000 m from the surface, including 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 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 geophysicists in the study of the critical zone. At present, only a few geoscience courses pay attention to the cities and address these complex, interconnected challenges. 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 300,000–500,000 inhabitants by 2030 (31 in 2018 to 60 in 2030)[32], there is an urgent need to generate workforce trained in the integration of subsurface geology and geoscientific management, which is currently lacking, for resilient and sustainable development.

Conclusion

The urban critical zone is unable to supply the ecosystem services sustainably. In fact, the functioning of the critical zone has been altered, ensuring that the indigenous ecosystem services are proving insufficient and lethal for the sustenance of life. The urban critical zone captures ecosystem services from adjoining natural critical zones, in turn stressing and destabilizing them.

The modified structure and functioning of the urban critical zone manifest the exigency of rethinking the existing limits of the critical zone and defining 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 groundwater reserves.

Cities occupy 2% of the world's land but are home to 55% of the global population, accounting for 70% of the global GDP[33]. They are expanding rapidly and globally. About 60% of the area expected to become urban by 2030 is yet to be built. However, poor strategic planning of this urban expansion hampers 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 an essential inquiry for the future well-being of billions of people.

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

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