Tackling Climate Change: Integrated Planning of Mumbai's Eastern Waterfront

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The Intergovernmental Panel on Climate Change (IPCC) AR-6 report from the United Nations spelled out how urbanization has pushed up intense rainfall in cities across South Asia using several scientific pieces of evidence generated on Indian cities. The report builds on an analysis by NASA predicting that several Asian cities on or near the coastline would have to withstand significant sea level rise by 2100.

The Eastern Waterfront of Mumbai city is a property mainly under the Mumbai Port Authority (MPA), a large holding for the Indian Navy and other Government activities. This area is predominantly used as a port and has been opened for new development in recent months. As the city grows, this land will play a vital role in the future development of the city. Based on the current first estimates made by the National Aeronautics and Space Administration (NASA) and Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado studies, this area indicates fast deterioration by the liquefaction of soil. Therefore, there is a dire need to study the area in greater detail and create a comprehensive understanding of the impact of sea level rise before new infrastructure is developed that brings more vulnerable people to this site. This paper presents an expanding innovative solutions design exercise and supports a study focusing on the issue and a mitigation strategy through green infrastructure solutions. It will involve the expertise of the University of Notre Dame, the University of Colorado, NASA, and Xylem Water Solutions & Water Technologies.

The area's urban development will house a few hundred people once developed to reduce the impact of coastal flooding and sea level rise.

1. INTRODUCTION

The United Nations has discussed the prerogative that we must work on climate change more responsibly. One of the critical areas impacting climate change is the construction sector, which has at least 39% of the responsibility regarding the greenhouse gas emitted on this planet.[1] Of those total emissions, building operations are responsible for 28% annually, while building materials and construction (typically referred to as embodied carbon) are responsible for an additional 11% annually.[2] The percentage recorded in this case does not contain the already existing towns and cities; it is just building energy emissions and consumption without the impact of overall city infrastructure.

While more awareness has been brought to discussions on the construction industry's impact on climate change, more needs to be discussed on the urban effects on climate. Cities are a vital contributor to climate change, as urban activities are significant sources of greenhouse gas emissions. For example, the two sectors of transportation and buildings, both impacted by the urban planning of cities, are responsible for 75% of global CO2 emissions.[3]

Beyond our built world, the climate change impacts are visible in the rising levels of glacial ice melt, sea level rise, water scarcity, storms, hurricanes, floods, and wildfires. These issues, with the increasing size of cities and reduced natural ecosystems and biodiversity areas, are impacting the built world and vice versa.

The impact of climate change is real and will make millions of people living in coastal cities homeless. The Intergovernmental Panel on Climate Change (IPCC) AR-6 report from the United Nations spelled out how urbanization has pushed up intense rainfall in cities across South Asia using several scientific pieces of evidence generated on Indian cities.[4] The report builds on an analysis by NASA predicting that several Asian cities on or near the coastline would have to withstand significant sea level rise by 2100.[5]

The UN predicts a population explosion in Asia, with a rise in the world population up to 9.7 billion by 2050 reaching a peak of 11 billion by 2100.[6] Given these predictions, cities with large densities like Tokyo, Delhi, Shanghai, and Mumbai will face significant issues when planning visionary city expansions to accommodate larger densities of people without losing the quality of place and interaction. For example, the estimated

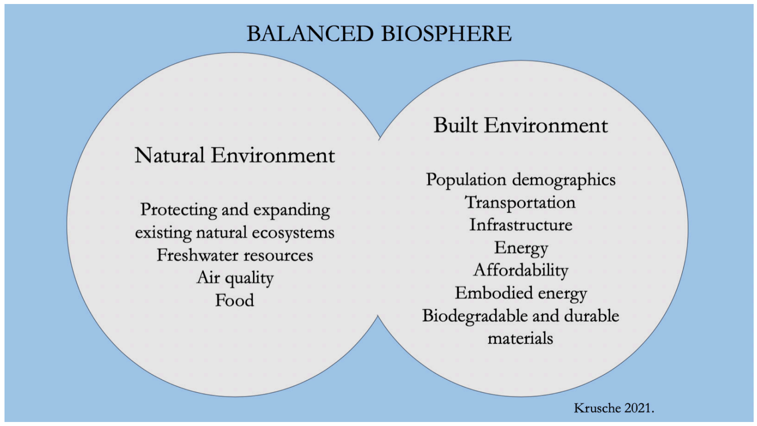


Figure 1. Balanced Biosphere between natural and built environments. Credit: Krusche

population of Mumbai was around 20 million and is projected to reach 25 million by 2025.[7] In 2016, an estimated 55 percent of Mumbai's population lived in slums. Furthermore, the city is facing, according to the latest IPCC AR6 Projections, massive loss of land due to sea level rise by 2050. Some reports even predict that Mumbai will sink by 2100 as the combined effect of sea level rise and excess rainfall creates extreme storm surge events as carbon emissions go unchecked.[8] The urgency of this issue is not only a concern in Mumbai but in many coastal cities around the globe. In Mumbai, where the land is surrounded by sea on three sides, the situation can get pretty dire, as evident when the rising level is compounded by significant levels of poverty and people living on encroached land on the edges of the city.

1.1 DENSITY VERSUS THE SIZE OF A CITY

A Metropolis is a city with a few million people mostly commuting with more extensive infrastructures in cities and regions. In this century, we achieved a new level of a city called the Megalopolis, where a conglomeration of several smaller city areas, townships, and suburbs come together to create an urban settlement. There are only a few megalopolises in the world, but they exist nationally in many countries. And these places generally have a population of more than 5 million people. So, the scale of these cities is much larger than typical cities, with average populations of around 300,000 to 3 million. In the past 100 years, the global population has incrementally increased. Thus before the 1900s, we had a population of approximately a billion people, which today has reached six times that number.[9] As we continue from 2000 to 2050, we will have another 2 billion people in the next 30 years that get added to present population, which is a very alarming rate at which we are growing.[10] Therefore, population growth and decline is an essential factor that impacts the need to create more places for people to live and occupy.

Two continents will experience the most considerable impact of this growth change. One is in Africa, where the population growth is high and will transform from one billion to two. But in the case of Africa, though the increase will be significant in a short period of 30 years, the amount of land and natural resources available on land are high too. Therefore, the existing infrastructure will have to be expanded exponentially to accommodate the community's needs. Lessons learned from lost natural resources, especially large forest ecosystems, during urban expansions must improve the decision-making process in the future planning of the cities on this continent. The second and more affected continent will be Asia, where one sees a compounded effect in an already dense environment as the population grows from 4.6 to 5.3 billion people by 2050.[11] On both these continents, there are finite resources, one more limited than another, and the increased population growth will create added pressures on existing cities, towns, and rural areas. Planners will have to design solutions to resolve these issues in creative ways.

In the case of the population of North America, the numbers are stable, and it doesn't have enormous projected growth in the next 20 to 30 years. But it is interesting to note that while the cities in India and China are expanding because of the population needs, the United States has had the most enlarging footprint of cities in the world in recent years. If you compare that to the increase in population, you will see that there is not a significant change in the rise of the population. However, we are still observing the most expansive cities simultaneously. This is caused due to migration of the population from the center to the suburbs. Since 1930s till today people moved from rural towns to urban areas due to extensive expansion in the infrastructure of cities and very little support for rural communities. When we start examining and estimating how this population is moving or changing its location from rural to urban to suburban locations, large cities in the United States indicate a troubling story. For example, the Metropolitan area covered by the city of Chicago in 1936 had a total density of population of 10,000 people per square mile with a total developed land area of 458 sq. miles and a regional population of 4.5 million people. If you looked at 2009, when a study was

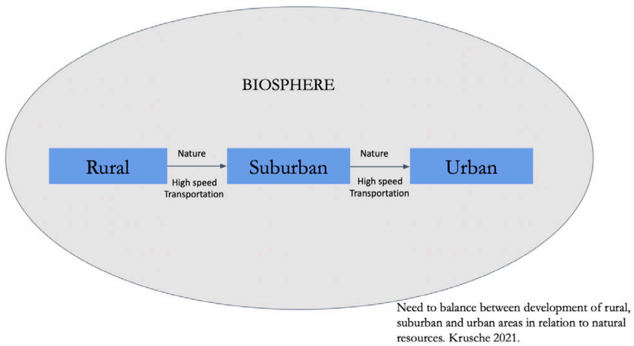


Figure 2.Relationship between, Urban, Suburban and Rural areas. Credit: Krusche.

done to measure density in various neighborhoods, the population density had reduced to 3900 people per square mile in places where the city expanded over the last century with total developed land of 2,165 sq. miles and population of 8.4 million people.[12] While the population doubled in the Chicago region in less than a century, the land use of urban activities went up a whopping four times its size in 1936. The impact on the land is that we have deforested our city to be able to occupy the urban spread we presently have created. Chicago region was 11% built and 89% green (agriculture and forest land) in 1936, reversed to 54% built and 46% green (23% in natural open spaces).[13] The balance between nature and built world has been lost because of the extensive need to move further away from the center and into suburbia.

Depending on the urban plan and layout, a neighborhood street with a single-family home can range anywhere from 2800 to 7000 people per square mile. The higher the density in such areas, the more pedestrian-friendly pathways and trees are on the street front. The density can be comfortably increased to 28,000 people per square mile, with housing that is just two to three-storey buildings. A good example is the famous Oak Park neighborhood of Chicago, with a much denser neighborhood featuring safety and walkability for people living in that area. Parts of the loop have a population density of 48,000 to 88,000 people per square mile.

The dimensions and sizes of cities reflect the extent of expansion and the number of people living in that density. This study helps in calculating the density needs of large metropolitan cities. Upper Manhattan has a population of around 70,000 people per square mile. Mumbai has a population density of 73,000 people per square mile and seems to have comparable densities. Another factor that influences climate change and dense urban living are the divisions of uses in urban areas. Manhattan utilizes daytime and nighttime population. Downtown Manhattan is largely composed of offices and commercial buildings with high use of annual energy to maintain these complexes. This is in stark contrast to the city's suburban neighborhoods where people live and commute to Manhattan every day. Energy consumption is mainly in the maintenance of these large buildings that are empty for 50% of their lifecycle and also for the commute from various locations in the region to the downtown core. The average estimated time for such commutes is assessed to be around 1 hour each way. This means that during the day, in peak hours, people can spend anywhere from 40 to 240 hours per year commuting to get to the city of Manhattan and at night, it is pretty much deserted, and there is not much of a large-scale population living within the Manhattan area. Anecdotally, Mumbai and Manhattan are both extremely dense, but Mumbai uses only three million cars in comparison to the 23 million cars used in New York, impacted by the number of people moving back and forth on a daily work basis. In Covid especially, we have seen the situation that people have started working from home, and the amount of travel and energy consumption that would be related to such places is drastically reduced.

1.2 URBAN SOLUTIONS THAT CAN IMPACT THE CONCERNS RELATED TO CLIMATE CHANGE

Improvements in Urban Code: Urban design in the cities need to become more compact and denser in areas with low or medium population density. Urban planning codes should reduce isolated zones that serve only one primary function and integrate multi-functional buildings where we do not just have offices in one location and residential on the other side, but moreover, it's a mixed-use development that is walkable and compact enough to include enough amenities such that the use of a personal car is limited. Impacting three factors — land use ratio (built versus natural resources), daily commute and transportation, and carbon emission through energy consumption that influences climate change. Added benefits are walkability and health improvement through easy access to multiple amenities for a population in all income brackets.

Suburbs become new towns: Instead of spreading further out in the suburbs, these suburbs can stay as suburbs, but they need to act like new towns developing independently. They need to have their own town center providing the basic amenities needed in the area and helping the suburb at some point become an independent town by itself. It needs to have all amenities and possibilities of mixed-use, just like the urban areas do. These areas are generally not on city water and septic systems and create huge amounts of contamination that can be reduced with proper town infrastructure.

New codes for Rural planning: Rural areas have long been treated as poorly developed zones with little need for good infrastructure and amenity support. For example, in rural areas, typically, agriculture is a major need with a smaller population and large-scale cultivated land. Rural design should include rural areas with the infrastructure and planning needs based on these rural places that are different from the suburban and urban locations. These need green infrastructure solutions

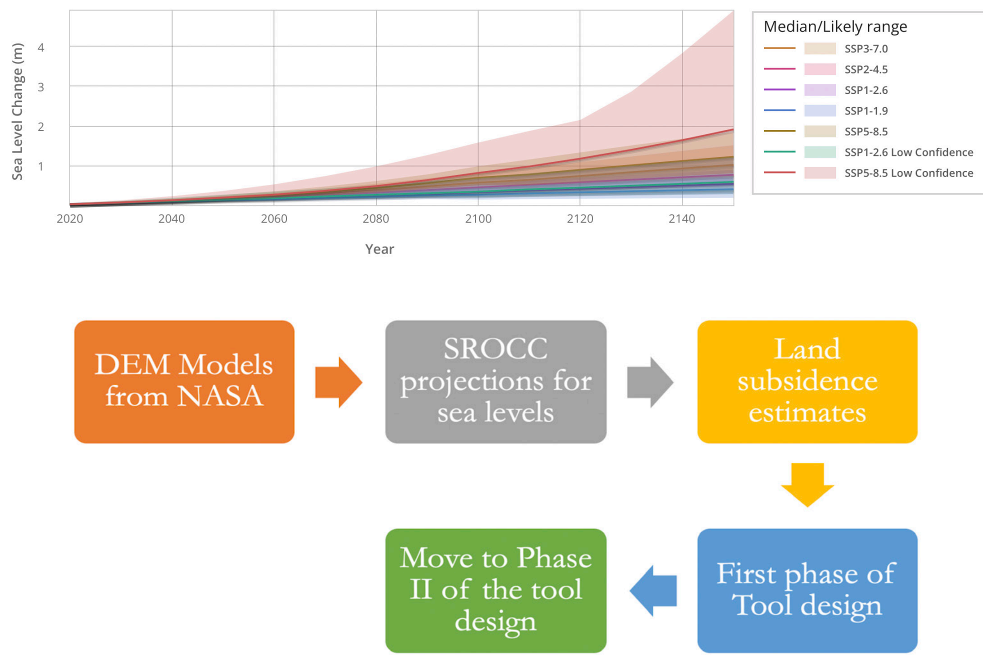


Figure 3. NASA Projections for Sea Level Rise in Mumbai and flow chart of datasets. Credit: NASA (N-SLCT) tool.

that reduce agricultural runoff concerns and contribute in a net climate-positive way.

The connectivity between these three needs, urban, suburban, and rural places, should be created based on individual aspects of development. Secondly, natural resources can act as a barrier within these built environments to create a natural form of containment so that the density can improve but not spread. And finally, each of these built environments needs to be connected by high speeds of public transportation. By doing so, people could move from these areas without causing a considerable burden on the environment. Finally, strategic infrastructure investments need to be made such that the infrastructure doesn't just expand everywhere but creates meaningful long-term value.

Water resource management planning: A balance between cultivated land and natural ecosystems should be created in the natural areas surrounding these human developments. Water quality, water harvesting, salt water, and drinking water ratios all relate to the balance within the area's natural ecosystem and help reduce the heat island effect on the site. We understand that sea levels are rising largely due to glacial ice melt.[14] Generally, sea level rise is seen as an issue associated with coastal cities, but one of the more significant problems we don't talk about is that this glacial water is drinking water mixed in salt water and can't be reversed into drinkable water so easily.[15] Along with the glacial melt, depletion of the freshwater resources in the form of natural auqifers and water table levels are depleting pretty fast due to the increased needs of the human population. Architecture and urban planning can play a critical role in inscribing building codes that involves water harvesting, and urban interventions that collect precipitated water from various sources before landing into stormwater drains that eventually finds their way into our rivers and the sea.

2. DESIGNING MUMBAI'S EASTERN WATERFRONT

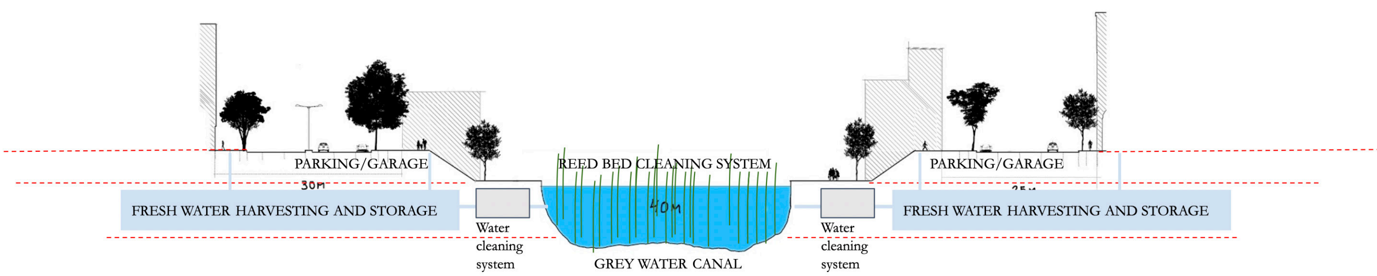
The Eastern Waterfront of Mumbai city is a property mainly under the Mumbai Port Authority (MPA), a large holding for the Indian Navy and other Government activities. This area is predominantly used as a port and has been opened for new development in recent months. As the city grows, this land will play a vital role in the future development of the city. It's a brownfield site and has issues related to contamination of the soil and contamination of water. The land has been slated for redevelopment, and some of the first urban solutions do not consider the climatic impact of sea level rise and the higher risk of flooding in this area. The solution presented below is now being developed with the Port authorities and attempts to mitigate what is proposed with climate concerns and ways to make the site climate positive for the future years.[16]

2.1 CLIMATE RELEVANT DATASETS

To design and plan for climate resilience – retreat, mitigation or adaptation strategies,[17] it is first important to get the right datasets that present the projections of natural hazards affecting the region. The research question posed was how to predict which datasets are correct and should be used to predict the impact on site. As in many cases, existing datasets for sea level rise for coastal cities may have limited information available. It was difficult to predict sea level and flooding impacts on the future development of the eastern waterfront of Mumbai due to dataset limitations. Mumbai's largest concern is monsoon

Early Areas of Focus

- Located above flood plains
- Divide green spaces amongst site
- Variety of sequential experiences
- Variety of unique urban and green open places
- Breaking monotony of high rise developments



Section across the canal and water storage and cleaning system

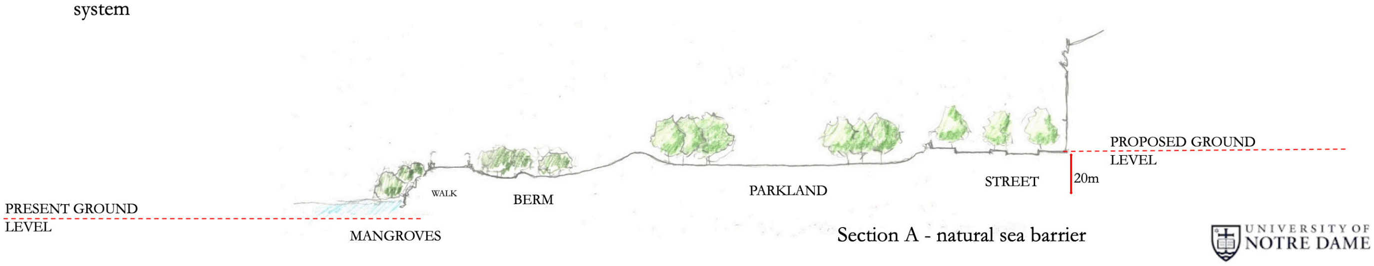


Figure 4. Masterplan and sections through the site with tidal lagoon, water storage and green infrastructure solutions. Credit: Mumbai Studio 2022@ND.

rains and the floods they cause. The compounded effect of sea level rise with backup in stormwater drains causing flooding is a major concern for the city. The goals of this project have been to 1) improve the understanding of the cumulative effect of sea level rise, vertical land motion, and land inundation on the site and 2) translate this knowledge to inform the planning solutions for the site.

Sea Level Rise data: To provide actionable science information for planning and adaptation activities related to rising seas in coastal cities, NASA has created an interdisciplinary science team called the NASA Sea Level Change Team (N-SLCT).[18] This is the most reliable data on sea level rise, as these projections are created from satellite imagery and tide gauge data collected as early as 1993. Agencies like NOAA and others use these same datasets to create tools on the internet with compounded studies of scenarios for specific regions. These datasets are much more precise in the context of the United States but also fairly strong in the case of Mumbai. These are being used to examine the sea level predictions for the site. While a predictable scenario includes many factors, including projections of SSP1-1.9 to SSP5-8.5, it is important to understand the most relevant projection to your planning scope.[19] This can be complicated, and while the low confidence values are generally not used for short-term and long-term planning purposes, a comprehensive study of how this impacts the flooding data on site is critical to understand.

Digital Elevation Model (DEM) and Vertical Land Motion (VLM) datasets: In order to see the impact of sea level rise of the sire, a detailed DEM of the site with contour information was important to relate to the behavior of the site during episodes of monsoon rains. The value of this information is also in examining Vertical Land Motion (VLM), which is important in coastal Asian cities due to rapid land subsidence, as observed in Jakarta due to groundwater exploitation.[20] This data is being collected by the University of Colorado CIRES group for various coastal cities in India.[21]

Water indentation datasets: Xylem Water Solutions is collecting inundation information for the site for this project.[22] The Government of India has measured tidal wave information and seen a dramatic increase in water levels in just a timespan of the last seven years. Each year the city faces a direct loss of approximately 100 million dollars due to severe flooding, affecting 10 million people living in the peninsular part of the city alone. So, the project includes a water budgeting study to examine the overall concerns associated with flood water management on site.

The city also faces issues related to drinking water scarcity. It has an estimated 55% of people live under poverty conditions and have impoverished housing available. With depleting resources, including groundwater which is slowly drying up and is being utilized at a very high rate, the impact of sea level rise is not just from the fact that it is around and surrounding the land, but it is slowly entering into the groundwater tables of the city, creating issues of contamination of water.

2.2 COMPILING THE RIGHT DATASETS

ESRI, the developer of the ArcGIS platform, is collaborating on this project to bring the datasets, as mentioned earlier, together on one platform. We are cross-referencing NASA and CIRES datasets with the tidal data for the Government of India and land data we are collecting with Xylem water solutions. All this information allows for a collective examination of the impact of sea level and heavy rainfall on the city of Mumbai. These datasets allow the various teams that we have at Notre Dame, including computer science, engineering, hydrology, and the Lucy Family Institute for Data, have created a consortium to tackle the problem of understanding the cumulative impact on site. This ongoing study will be available visually for various researchers to use for future study on a Python platform that we hope to integrate on the NASA website and give to the Indian government authorities for proper predictability and resourceful use of the data for planning.

The city of Mumbai is made up of many islands before the British era. It was filled in with soil, and by 1812 it was already one single island used as an area to develop the city.[23] Earlier research by CIRES shows a strong correlation between where the infill of land was in the 1800s and where there is an issue of water increase or vulnerability because of water flooding. This was compared with NASA's studies on sea level rise. On the NASA Sea Level Change portal, the study on Mumbai shows a reasonable SSP2-4.5 scenario projecting the city to have a 0.21m change by 2060 and a 0.46m change by 2100. These are half the value compared to the SSP5-8.5 low confidence value indicated at 0.82m by 2100. These numbers are much more modest than the indicated numbers in various news media. But with the compound impact of flooding, vertical land motion, and sea level rise, we found out that by 2060 already crucial parts of the site will start having problems with flooding.

They also lost the green foliage that existed around the city. There were lots of mangroves and an intact ecosystem that existed in the city mostly lost in the last 100 years of the city. Another problem that the local community is starting to face is fast depletion in the water table and seepage of saltwater from the sea being pulled into the city's local water wells creating problems with good drinking water facilities being available to people living in this area. It has created problems in the monsoon that you have lots of flooding and overflow of fresh water and in other months, fast depletion of order drinking water conditions within the city.

2.3 CLIMATE POSITIVE SOLUTIONS

The right solution for the Eastern Waterfront of Mumbai would be to create a balanced biosphere around the site, allowing the natural environment and built environment to coexist positively. A good urban plan would normally be able to balance both in a manner that allows the coexistence of natural ecosystems and building ecosystems in which we survive today.

The proposal shown here is an ongoing study where the University of Notre Dame, Mumbai Studio of classes 2020, 2021, and 2022 participated in collaboration with the Mumbai Port Authorities.[24] It is the first conceptual thought process around planning this balanced on-site intervention. The proposal examines solutions to re-integrate the knowledge of green ecosystems back within the framework of the city while mitigating water concerns and generating creative forms of water harvesting.

Regeneration of Green ecosystems: Our research showed that the site is highly suspectable as it sits in a low-lying area on floodplains in certain parts of the site. The solution for the design was to take the low-lying areas of the site and create green natural parkland and wetlands to act as water basins and collect the rainwater during the monsoon period. Suppose the right conditions for combining fresh water with salt water can be created with the help of mangrove nurseries. In that case, the outer edge of the site facing the sea can be repopulated with mangrove varieties available in the area, helping mitigate the large waves crashing around on the sides. This will at the same time also bring back the interconnectivity of the local ecosystem to support the natural flora and fauna of the area. The whole area would have a lagoon that would protect the site from large tidal impacts and also act as a natural barrier between sweet water and saltwater zones. The tidal lagoon would protect the city's outer edge, similar to the current lagoon concept proposed in Wales.[25] These waves can be harvested for natural forms of energy while securing those large tidal impacts to be reduced on the site. A new green ecosystem full of natural lowland greens common to this area is proposed, allowing various natural species to coexist mutually. The biggest impact we have is the proposal brings from 0% of present green to 52% of the development being green, allowing both the natural and built world to coexist.

The Built Design Solution: The remaining land could be the built part of the development by raising its level on top with green infrastructure solutions that allow water storage and cleaning systems, natural reed bed water purification plants for clean water provisions, parking, and other facilities. Also, we want to bring in ways in which the monsoon water can be mitigated within the city to contain water areas and resources that allow for a better supply of fresh water throughout the year. Beyond the storage space, there is also grey water in the canal that would be cleaned with reed bed cleaning systems.

The urban design solution supports working and living in the same location. This area is where most of the low-cost housing exists. Interestingly, the people living here presently don't have good infrastructure but are self-sufficient as they work in small-scale industries with housing above.

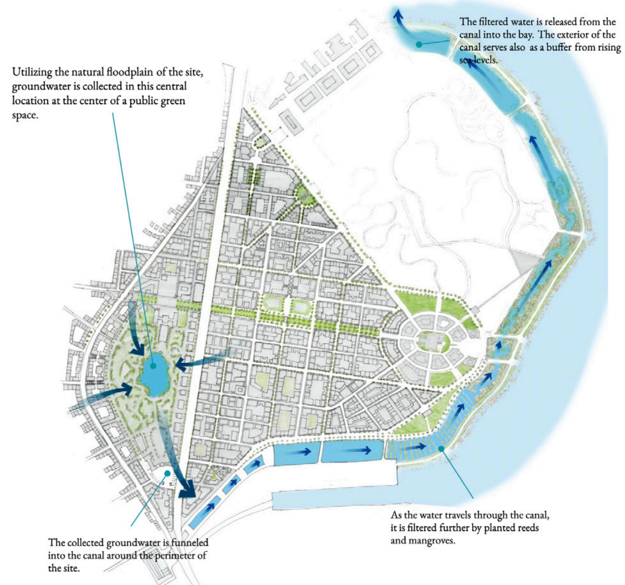


Figure 5. Waterflow plan for the cachment areas created on site. Credit: Mumbai Studio 2022@ND.

The development gives new infrastructure and strengthens the beautiful small-scale industrial and housing stock to promote these work opportunities while also creating residential neighborhoods. We have one such area where we're trying to mitigate housing with units underneath for small-scale industries and residential to create beautiful, walkable streets and neighborhoods. Such developments allow people to work and live in the same area without gentrification concerns. And when compared with new development proposals that consist of towers, it gives you the same amount of density but a much better quality of living for the community. The proposal recommends a three- to four-story variety of neighborhood types where people move through designed places with a cultural identity uniquely related to the city of Mumbai. Thus allowing people to feel at home and not be abandoned or removed from their present location while also creating economic value through new development in the area. These housing types would include a terrace food culture where all the houses can produce food on small scales for individual families or in society that can be utilized for various needs throughout the year. The climatic conditions in Mumbai are very warm and allow for full-year food production.

The development allows the built-up area to be located such that people have easy access to water and green locations simultaneously, allowing people to have ways in which they're integrating their experience with the natural resources without feeling disconnected from the ground. And the environmental impact also is very positive because we are finding ways in which the monsoon waters raining at very high speeds in the city of Mumbai are completely stored and utilized while recharging the water tables and the natural water resources in the area.

The development code of these buildings would include long-term durable materials and zero energy designs as a critical aspects that can allow us to impact climate change positively.

3. CONCLUSIONS

The alarming rate at which climate change affects the planet is of greater concern today than ever. Thus, making it a global priority and a critical subject of deliberation within the architectural profession. In recent years, people have been sporadically trying to bring attention to this important topic, and now there is an international movement towards recognizing and working on a national level to improve the conditions impacting climate change.

For architects and planners to be part of the larger frame of conversation on climate change, we need to collaborate with scientific teams to tap into the latest research in the field and apply research with local and national agencies. Successful, collaboratively employed methods will be used to create a model that can be implementable in other cities around the planet that are facing similar peril.

While we can't completely change the impact of sea level rise, the way cities in the future would be planned will allow us to be a climate-positive place while creating better movement, higher circulation, great connectivity, and a sense of place creating an environmentally conscious site.

ACKNOWLEDGMENTS

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ENDNOTES

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