Climate Risk and Vulnerability Assessment Report

(For PCMC – Nigdi and Swargate- Katraj corridor of Pune Metro, Phase 1 Extensions)

महा मेट्रो

PUNE METRO

IND: Pune Metro Rail Project

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The purpose of a Climate Risk and Vulnerability Assessment (CRVA) is to inform all relevant stakeholders, including project developers and financiers, about the potential impacts of climate change on the Project, and to identify measures to enhance resilience. The CRVA outlines key climate risks, exposure levels, and adaptive capacity relevant to the Project area, and presents recommended adaptation measures to address them during design, construction, and operation phases. The purpose of this template is to provide an overview of the most common contents of a CRVA, with examples to support understanding. This template is to be used only as a guide and should be adapted to the specificities of the project at hand.

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1. Overview

Railway infrastructure is the pillar for the growth and development of nation, economy and society. Due to an exponential increase in population and demand for transport network infrastructure, the current infrastructure is experiencing loads higher than that of the designed capacity limits. Transport infrastructure is always exposed to extreme weather events and climate change evolution, creating more excessive deterioration. Considering practical constraints related to capital investment, government policies, and sustainability issues of building new railway infrastructure, utilizing climate adaptation options on the operation and maintenance of existing railway infrastructure is inevitable. Adaptation options are measures and actions that can be implemented to improve adaptation to climate change. Climate adaptation for Pune Metro Rail Project (PMRP) Phase 1 extensions, refers to the process by which traffic administration, including infrastructure and rolling stock, should mitigate and control risks due to extreme weather events and gradual degradation of infrastructure. The overall objective of the PMRP Phase 1 extensions is to achieve long-term serviceability and economic benefits.

An overview of the project and its objectives, as well as the climate change plan and policy of Government of Maharashtra (GoM) for Pune Metro Rail Project (PMRP) Phase 1 extensions (North and South) are provided in this report. It describes the project background, including the need for the extension of metro rail project in Pune and Pimpri-Chinchwad cities, and provides details about the project area, such as its geographic, edaphic, and seismic status, topography, and climate, etc. Overall, the report provides a comprehensive overview of the PMRP Phase 1 extensions project. It addresses the importance of climate change adaptation measures in railway infrastructure and emphasizes the need to mitigate risks due to extreme weather events and infrastructure degradation. The report also highlights the government's climate change plan and policy, showcasing the efforts to incorporate climate change considerations into development planning.

2. Climate Change Plan and Policy of Government of Maharashtra (GoM)

The Maharashtra State Action Plan on Climate Change (MSAPCC), first released in 2010 and subsequently updated, serves as the key policy framework addressing climate change at the state level in Maharashtra. The plan was prepared under the guidance of the Maharashtra State Government's Environment Department, with technical inputs from various research organizations and academic institutions. It outlines the state's strategies for climate change mitigation and adaptation across critical sectors such as agriculture, water resources, forestry, and urban infrastructure.

The MSAPCC process followed the 2008 directive from the Government of India, which mandated all states to develop State Action Plans on Climate Change (SAPCC) aligned with the National Action Plan on Climate Change (NAPCC). Maharashtra's SAPCC emphasizes integrating climate resilience into state development planning, with a particular focus on sectoral vulnerabilities and long-term sustainable growth.

In Maharashtra, the preparation of the SAPCC involved collaboration between the State Environment Department, the Maharashtra Pollution Control Board (MPCB), and research institutions such as the Indian Institute of Tropical Meteorology (IITM), Pune, which provided climate modelling and impact assessment expertise. Additionally, non-governmental organizations and academic bodies contributed to stakeholder consultations and technical studies.

For the Pune Metro Rail Project Phase 1 extension, climate projections and vulnerability assessments from the MSAPCC were adopted to evaluate potential climate risks and inform mitigation measures. The MSAPCC utilized regional climate projections developed by IITM using downscaled simulations from global climate models such as the Hadley Centre's HadGEM2 model. These projections cover temperature and precipitation trends under various greenhouse gas emission scenarios for the mid-century period (2041–2070), compared to the historical baseline (1971–2000).

The climate scenarios indicate rising average temperatures and variable monsoon rainfall patterns in the Pune region, which have direct implications for infrastructure resilience, water availability, and urban heat management. Accordingly, the MSAPCC includes adaptive strategies to enhance water resource management, improve urban green cover, and reduce carbon emissions through promotion of sustainable transportation, including metro rail systems.

3. Project Background in Brief

The Pune Metro Rail Project (PMRP) Phase 1 extension corridors — PCMC to Nigdi and Swargate to Katraj — have been proposed by the Government of Maharashtra (GoM) in collaboration with the Pune Metropolitan Region Development Authority (PMRDA), Pune Municipal Corporation (PMC), and Pimpri-Chinchwad Municipal Corporation (PCMC) to address Pune's growing urban mobility challenges. These extensions aim to ease road congestion, improve public transport connectivity, and enhance access to key suburban and peripheral areas.

To increase public transit usage and provide an efficient, reliable, and sustainable system, detailed feasibility studies and alignment assessments were conducted by agencies including Maharashtra Metro Rail Corporation Limited (Maha-Metro). These studies analysed travel demand, congestion hotspots, and urban growth to optimize routes with minimal land acquisition and environmental impact.

The PCMC to Nigdi corridor is primarily planned as an elevated alignment, improving connectivity between industrial, residential, and commercial zones in Pimpri-Chinchwad and Nigdi, while reducing travel times and surface traffic. The Swargate to Katraj corridor is mainly proposed as an underground alignment, serving Pune's southern suburbs with minimal disruption to the dense urban environment.

These corridors will complement Pune's existing transit network by offering high-capacity, rapid transport options that encourage a shift from private vehicles. The project employs advanced technologies and sustainable design to enhance energy efficiency, safety, and passenger comfort.

Aligned with Maharashtra's urban mobility and climate resilience goals, the PMRP Phase 1 extensions are expected to reduce vehicular emissions and promote sustainable growth. Environmental and social impact assessments have guided the planning to ensure minimal adverse effects and maximize benefits.

4. Project Area Description

4.1. General Features of the Project Area

4.1.1. Geographic, Edaphic and Seismic status

The Pune Metro Rail Project (PMRP) Phase 1 extension corridors cover areas within the Pune Municipal Corporation (PMC) and Pimpri-Chinchwad Municipal Corporation (PCMC), spanning an approximate aerial coverage of 600 km². Geographically, the project area lies between north latitudes of approximately 18º24' and 18º38' and east longitudes of 73º45' and 73º58'. The region is situated on the western edge of the Deccan Plateau with an average elevation ranging between 550 m to 700 m above mean sea level (amsl).

The terrain predominantly comprises basaltic rock formations, characteristic of the Deccan Traps, with lateritic and black cotton soils prevalent in various parts of the project area. The soil profile mainly consists of clayey to loamy textures with moderate to high fertility suitable for urban landscaping and vegetation.

In terms of seismicity, the Pune region falls within Seismic Zone III of the Indian seismic zoning map, indicating a moderate risk of earthquakes. Historical records and geological studies suggest that the area may experience earthquakes of moderate intensity, typically up to magnitude 6.0 on the Richter scale.

4.1.2. Topography

The project area features varied topography typical of the western Deccan Plateau region. The terrain is generally undulating with gentle slopes, interspersed with small hills and valleys. Elevation in the project area ranges from approximately 550 meters above mean sea level (amsl) in the low-lying plains to around 700 meters amsl in some of the elevated parts, particularly towards the northern and north western outskirts. The region is drained by several seasonal and perennial streams, contributing to the local drainage system that ultimately connects to the Mula-Mutha river basin.

Urban development has significantly altered the natural topography in many parts of the corridor, with extensive levelling and reclamation for residential, commercial, and industrial purposes. However, pockets of natural terrain and vegetation remain, especially near hillocks and water bodies.

The topographical features influence the alignment and design of the metro corridors, with elevated structures used to traverse flatter, open areas and underground tunnels planned in denser, built-up zones or regions with significant elevation changes.

4.1.3. Climate

Pune has a tropical wet and dry climate (Köppen climate classification Aw) with distinct wet and dry seasons. Situated on the leeward side of the Western Ghats at an average altitude of about 560 m amsl, Pune generally enjoys a moderate climate throughout the year with seasonal variations.

April and May are the hottest months, with temperatures rising up to 38°C during the day and around 22°C at night. December to February is the winter season, with maximum average temperatures around 28°C and minimum temperatures rarely dropping below 10°C. January is usually the coldest month.

In recent years, Pune's climate has been affected by rapid urbanization, increased pollution, and loss of vegetation and water bodies, contributing to a heat island effect. Maximum temperatures during April–May have occasionally risen to 40°C.

The summer season extends from March to May, followed by the monsoon season from June to September. The mean annual rainfall ranges between 700 and 900 mm, mostly received over 40–50 days during the southwest monsoon. Occasional post-monsoon rains occur in October and November, while December to February are mostly dry.

Pune receives most of its rainfall from the southwest monsoon, with some influence from retreating monsoon systems.

4.2. Project Design Methodology

The Pune Metro Rail Project (PMRP) Phase 1 Extensions aim to enhance urban mobility by expanding the existing metro network through two key corridors: the elevated PCMC to Nigdi segment and the underground Swargate to Katraj segment. The overall design methodology emphasizes sustainable, efficient, and context-sensitive engineering solutions that integrate advanced construction technologies while minimizing environmental and social impacts. A comprehensive approach combining detailed site investigations, environmental and social assessments, and stakeholder consultations guides the design process to ensure safety, reliability, and operational efficiency in line with national and international standards.

The PCMC to Nigdi extension is a fully elevated corridor spanning around 4.413 km, featuring four elevated stations at Chinchwad, Akurdi, Nigdi, and Bhakti Shakti. The design uses precast segmental construction for the viaducts, which helps reduce on-site construction time and disturbances to existing urban infrastructure. Stations are planned to handle six-car train sets and include provisions for passenger safety, fire protection, and accessibility for differently-abled users. The alignment has been optimized to minimize land acquisition and environmental footprint while ensuring smooth integration with the existing metro network.

The Swargate to Katraj extension is an entirely underground corridor of roughly 5.9 km, constructed using twin-tube tunnel boring machines (TBMs). This method allows efficient tunnelling through variable geological strata while minimizing surface disruption in densely populated urban areas. Underground stations at Market Yard, Bibwewadi, and Katraj are designed with modern ventilation, fire safety, and emergency evacuation systems, and are integrated with surface transport nodes to facilitate seamless connectivity. The design carefully considers geotechnical and hydrogeological conditions to ensure long-term structural stability and operational safety.

Both extensions (North and South) incorporate mitigation measures identified through comprehensive Environmental and Social Impact Assessments (ESIA), including noise and vibration control, dust suppression during construction, and stakeholder engagement to address community concerns. These measures have been integrated into the project design to minimize environmental and social impacts and ensure compliance with applicable national and international standards. The project will fully comply with all Environmental, Social, and Governance (ESG) requirements and standards set forth by the European Investment Bank (EIB).

4.3. Salient Features of Project in Brief

The Pune Metro Rail Project (PMRP) Phase 1 Extensions are designed to augment the existing metro network, providing enhanced connectivity and sustainable urban transport solutions in Pune Metropolitan Region. The project consists of two major corridors: the elevated PCMC to Nigdi segment and the underground Swargate to Katraj segment. Both corridors aim to improve commuter convenience, reduce traffic congestion, and promote environmental sustainability while adhering to stringent design and safety norms.

Table 1 provides a consolidated overview of the key project parameters for the Pune Metro Rail Project Phase 1 Extensions.

Table 1: Salient Features of the Project and Design Norms

Feature	Details
Project Name	Pune Metro Rail Project (PMRP) Phase 1 Extensions (North and South)
Project Length	PCMC-Nigdi (4.413 km Elevated) + Swargate-Katraj (5.9 km Underground)
Corridor Type	Elevated (PCMC-Nigdi), Underground (Swargate-Katraj)
Number of Stations	9 (4 Elevated + 5 Underground)
Train Configuration	Three-car trains
Operating Speed	Up to 80 km/h
Track Gauge	Standard Gauge (1,435 mm)
Construction Method	Precast segmental viaduct (elevated), Tunnel Boring Machine (TBM) for tunnels
Power Supply	25 kV AC Overhead Catenary (OHE)
Signalling System	Communication Based Train Control (CBTC)
Passenger Capacity	Approx. 30,000 passengers per hour per direction
Project Cost	Approx. ₹5560 crores (estimate for Phase 1 extensions)
Project Implementation Agency	Maharashtra Metro Rail Corporation Limited (Maha-Metro)

Table 2 summarizes the design and operational standards governing the project, while **Table 3** compares the key features of the two extension corridors—PCMC to Nigdi (elevated) and Swargate to Katraj (underground)

Table 2: Design Norms and Salient Features of the PMRP Phase 1 Extension Alignments

Parameter	Details
Design Standards	Indian Railway Standards, Metro Rail Design Guidelines, EIB Standards
Structural Design	Seismic zone III compliant structures
Station Design	Universal accessibility, fire safety norms, passenger amenities
Tunnel Design	TBM tunnels with reinforced concrete lining
Ventilation	Mechanical and natural ventilation for underground stations and tunnels
Environmental Compliance	Mitigation for noise, vibration, dust, waste management per ESIA guidelines
Safety Measures	Fire detection & suppression, emergency evacuation plans
Energy Efficiency	Use of energy-efficient lighting, regenerative braking in trains
Drainage & Flood Management	Dedicated drainage systems, flood resilience incorporated

Table 3: Salient Features of the PMRP Phase 1 Extension Alignments (North & South)

Feature	PCMC to Nigdi (Elevated)	Swargate to Katraj (Underground)
Alignment Length	4.413 km	5.9 km
Stations	4 Elevated Stations (Chinchwad, Akurdi, Nigdi and Bhakti Shakti)	5 Underground Stations (Market Yard / Gultekdi, Bibwewadi, Padmavati, Balaji Nagar and Katraj)

Construction Technique	Precast segmental viaduct	Twin-tube TBM tunnelling
Structural Material	Precast concrete segments with steel reinforcement	Reinforced concrete tunnel lining
Land Acquisition	Minimal, primarily along existing road corridors	Minimal surface land use; mainly underground
Impact on Urban Traffic	Temporary but managed via traffic diversion plans	Minimal surface disruption
Geotechnical Conditions	Typical urban soil with shallow foundations	Variable strata including basalt and weathered rock
Safety Features	Fire safety systems, platform screen doors, CCTV	Advanced tunnel ventilation, fire detection & suppression
Accessibility	Elevators, escalators, ramps for differently-abled	Full accessibility provisions at underground stations
Integration	Connects with existing Purple Line, park-and-ride facilities	Integration with bus terminals and major transit points
Estimated Construction Time	36 months	36 months

Alignment Map showing location of the stations of Pune Metro Phase-I Extension project (North & South extensions) is presented as **Figure 1**.

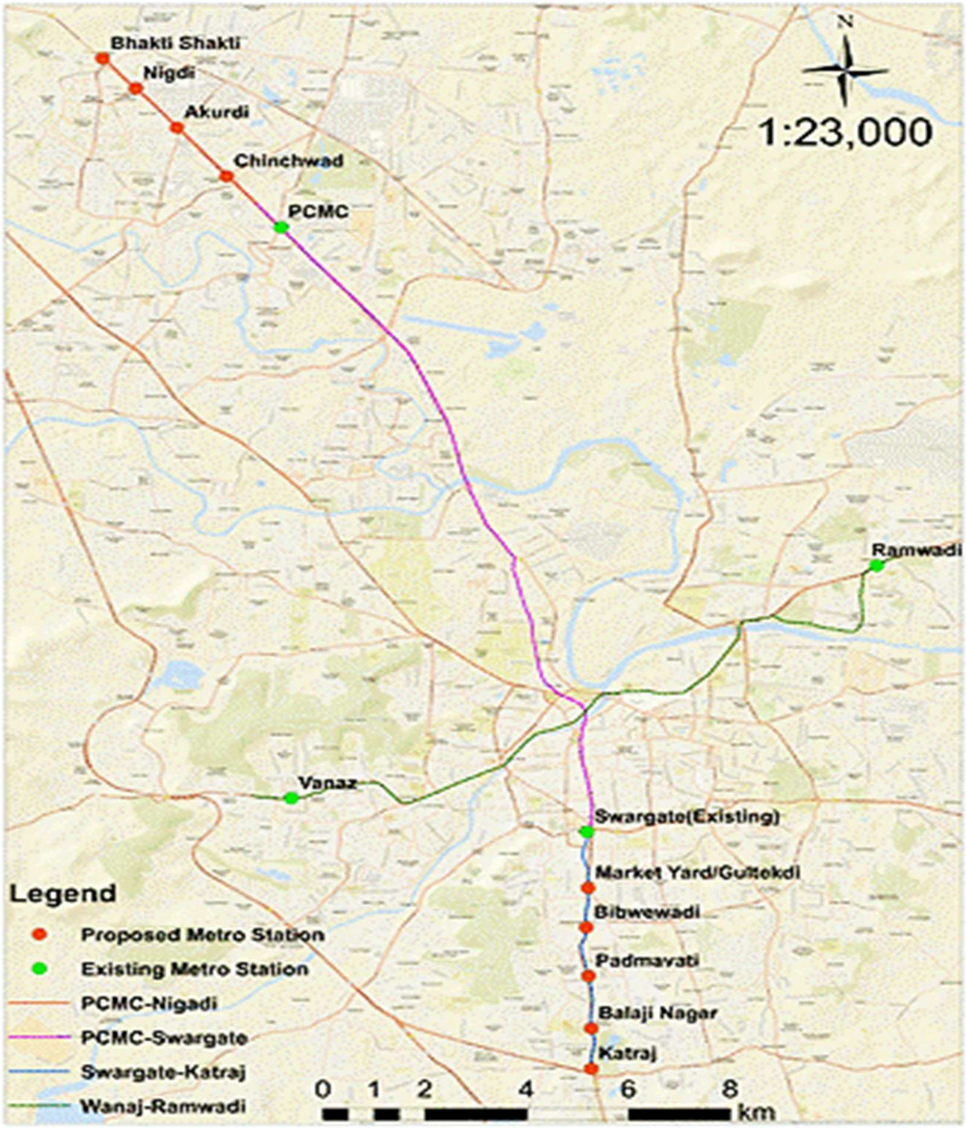

Figure 1: Alignment Map of Pune Metro Phase 1 Extensions Project

5. Scope and Objectives of Climate Change Risk Assessment Study

The Climate Change Study is a critical component for the proposed Metro Rail extension projects in Pune. Given the increasing intensity and frequency of climate-related hazards—such as extreme rainfall, urban flooding, and heatwaves—there is a pressing need to assess and address the potential risks associated with a changing climate. Implementing the project without incorporating climate resilience considerations may lead to increased vulnerabilities, operational disruptions, and long-term service inefficiencies. The objective of this study is to understand the multifaceted impacts of climate change on urban rail infrastructure and to ensure that appropriate adaptation measures are embedded in the planning, design, and implementation stages. Additionally, the study aims to equip project stakeholders with the knowledge, tools, and capacity required to foster climate-resilient development and act as proactive agents of change within the broader urban sustainability agenda.

The broad objectives of this CRVA are as follows:

- To assess the exposure, sensitivity, and adaptive capacity of the Pune Metro Rail Project Phase 1 Extension to climate-related risks.

- To qualitatively identify and evaluate the impacts of climate change on metro infrastructure, operations, and associated systems.

- To examine climate-risk adaptive interventions that enhance the resilience of project components to current and future climate hazards.
- To recommend appropriate adaptation measures for identified risks, including infrastructure-specific responses and associated incremental costs.
- To support integration of climate resilience into project planning, design, and operations for long-term serviceability and sustainability.
- To empower project stakeholders with the knowledge, tools, and capacity needed to proactively address climate change challenges within the urban transport sector.

6. Methodology

The Climate Risk and Vulnerability Assessment (CRVA) for the Pune Metro Rail Project (PMRP) Phase 1 Extension was conducted using the following approach:

- A comprehensive review of relevant regulatory frameworks, climate resilience guidelines, and applicable national and international standards.
- An assessment of emissions from surrounding sources such as transport, industrial activity, and urban development to understand the baseline environmental context.
- Collection and analysis of data related to potential greenhouse gas (GHG) emissions from key project activities during both construction and operational phases.
- Identification, evaluation, and documentation of climate-related risks, along with the development of feasible adaptation and mitigation measures aimed at enhancing resilience and reducing CO_2 emissions throughout the project lifecycle.

Desk Study & Reviews: As part of the Climate Change study for the Pune Metro Rail Project (PMRP) Phase 1 Extension, a comprehensive desk-based review was conducted using a variety of sources, including academic research papers, technical reports, government publications, policy documents, scientific articles, and relevant news materials, both online and offline. The review drew on findings from previous climate risk assessments and resilience studies related to metro and rail infrastructure, particularly in urban and transport sectors across India and globally. By analysing lessons learned and best practices from similar projects, the study identified key issues and adaptation measures relevant to Pune's context. This desk review provided critical insights into potential climate vulnerabilities and informed the development of targeted strategies to enhance the resilience of the PMRP Phase 1 Extension.

Consultations with stakeholders, Engineers and Experts: Representative consultations were conducted across a broad spectrum of stakeholders for the PMRP Phase 1 Extension project, with key inputs from the primary project authority, Maha-Metro, as well as experienced experts and engineers. These consultations helped capture diverse perspectives on climate change impacts and the necessary adaptation measures. Maha-Metro provided valuable first-hand information on the extent to which climate stressors currently affect, or may potentially affect, the project infrastructure and operations. Subject matter experts contributed to the identification and analysis of climate risks, while engineering professionals offered insights into design sensitivities, construction standards, and the adaptive capacity of project components in response to evolving climate conditions.

7. Limitations

Climate change adaptation must go hand-in-hand with mitigation efforts, as mitigation alone is insufficient to prevent the adverse impacts of a changing climate. However, several limitations exist in the context of assessing and addressing climate risks for infrastructure projects such as the PMRP Phase 1 Extension project.

- Climate variables interact in complex and often unpredictable ways, making the process of climate-proofing infrastructure inherently challenging—particularly at the project-specific level where localized impacts may differ significantly.

- Despite growing recognition of climate change risks, there remain significant gaps in the availability of standardized guidance materials, modelling tools, and region-specific data necessary to fully integrate climate resilience into infrastructure planning and design.
- Currently, there is no universally accepted methodology for assessing the adverse effects of climate change and incorporating them systematically into engineering practices. This creates variability in the quality and depth of vulnerability assessments across projects.
- As a result, certain assumptions and uncertainties persist in this assessment, and the application of adaptation strategies may be subject to revisions as better data and tools become available.

Nonetheless, Maha-Metro has demonstrated a proactive understanding of climate change risks and is committed to incorporating mitigation and adaptation measures throughout the project lifecycle to enhance the long-term resilience of the PMRP Phase 1 Extension project.

8. Baseline Natural Hazards and Risks in Pune

8.1. Likelihood of Natural Hazards

ThinkHazard, a web-based analytical tool developed by the Global Facility for Disaster Reduction and Recovery (GFDRR), was accessed to gain an overview of natural hazards relevant to Pune and to support climate-resilient planning for the Pune Metro Rail Project (PMRP) Phase 1 Extension. The tool provides a rapid yet robust assessment of hazard likelihoods for a given location, helping infrastructure projects integrate disaster and climate risk considerations during design and implementation.

ThinkHazard evaluates current climate risks and provides future projections based on IPCC guidance, classifying hazard levels—very low, low, medium, and high—across 11 categories. It also offers actionable recommendations for each hazard type and links to further resources.

When applied to the Pune Metropolitan Region, the tool indicates varying risk levels for hazards such as extreme rainfall, urban flooding, water scarcity, extreme heat, earthquakes, and riverine floods. These assessments are based on hazard data compiled from authoritative public, academic, and private sources.

A snapshot of hazard likelihoods for Pune, generated using ThinkHazard, is presented in **Figure 2**, highlighting the importance of accounting for these risks in the design and operation of climate-resilient metro infrastructure.

ThinkHazard provides a general overview of hazards; however, detailed site-specific studies are recommended to fully assess risks for Pune and Pimpri-Chinchwad. Based on currently available information, the following hazard accounts and recommendations should be considered during all phases of the project to reduce risks effectively:

1) **Cyclone:** Cyclone hazard is classified ***high***, which means there is more than a 20% chance of potentially damaging wind speeds in the project area in the next 10 years. Although Pune and Pimpri-Chinchwad are inland, associated heavy rainfall and wind impacts during cyclonic activity should be considered. The impact of cyclones must be considered in all phases of the project, particularly during design and construction.
2) **Water Scarcity:** Water scarcity hazard is classified ***medium***, indicating that droughts are expected to occur on average every 5 years. The effects of drought on personnel, stakeholders, and infrastructure must be considered in all phases of the project, especially during the design of buildings and infrastructure. Further detailed information should be obtained to adequately account for the hazard level.
3) **Earthquake:** Earthquake hazard is classified ***medium***, meaning there is a 10% chance of potentially damaging earthquake shaking the project area in the next 50 years. The impact of earthquakes should be considered in all project phases, with particular emphasis on design and construction methods aligned with seismic risk.
4) **Extreme heat:** Extreme heat hazard is classified ***high***, indicating there is more than a 25% chance that at least one period of prolonged exposure to extreme heat, resulting in heat stress, will occur in the next 5 years. Project planning, design, and construction methods should factor in the risk of extreme heat to protect personnel and infrastructure.
5) **River flood:** River flood hazard is classified ***low***, which means there is more than a 10% chance that potentially damaging and life-threatening river floods could occur in the next 10 years. Project

planning, design, and construction should consider river flood risks where applicable, especially near local water bodies.

6) **Urban flood:** Urban flood hazard is classified ***low***, with more than a 10% chance of potentially damaging and life-threatening urban floods occurring in the coming 10 years. Given the urban drainage challenges in Pune and Pimpri-Chinchwad, project decisions and designs should take urban flood risks into account.

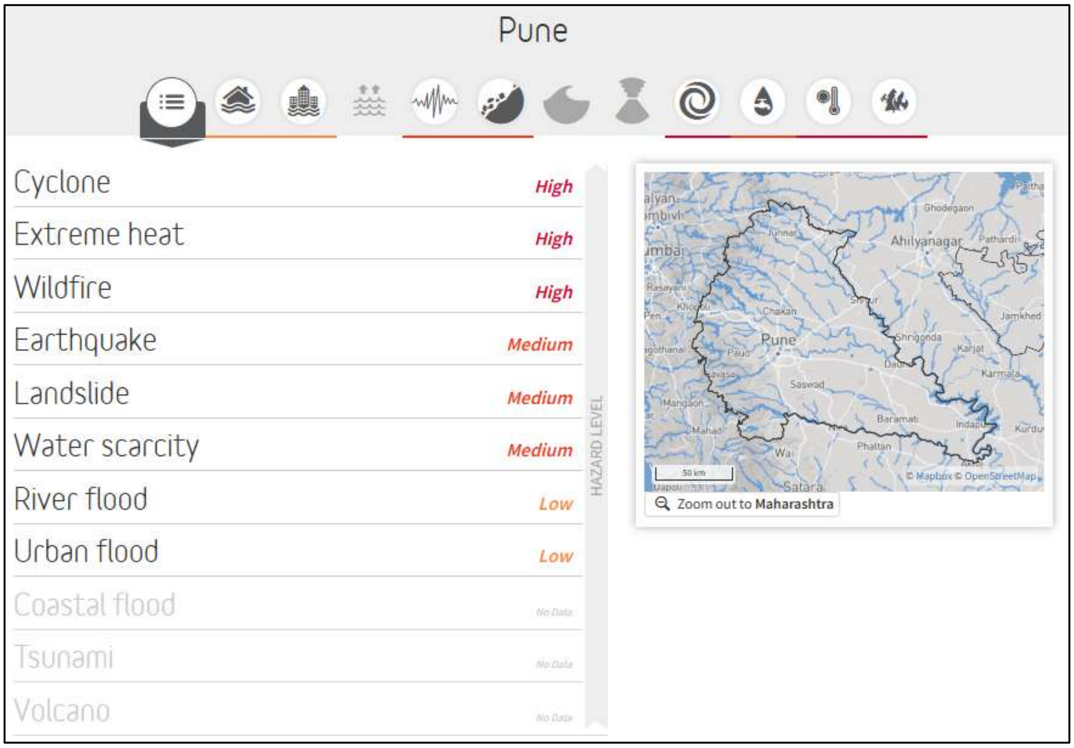

Figure 2: Likelihood of Natural Hazards in Pune District[1]

Inference:

Global average tropical cyclone wind speeds and associated rainfall are projected to increase in the future, while the overall frequency of tropical cyclones may decrease or remain unchanged. However, the frequency of the most intense tropical cyclones is likely to rise substantially in some ocean regions (IGPC, 2010). Consequently, the current cyclone hazard levels in affected areas, including regions influenced by cyclonic weather patterns, may increase over the long term. Projects in such areas, including Pune and Pimpri-Chinchwad, should be designed to withstand potential future increases in cyclone-related risks.

It is important to note that cyclone-related risks cannot be completely eliminated, as damages arise not only from high winds but also from heavy rainfall and consequent flooding triggered by cyclones. Therefore, comprehensive risk management must account for all cyclone-induced hazards.

Regarding river and urban floods, model projections show inconsistencies in rainfall change estimates. Despite this, the present hazard levels for river and urban flooding in Pune and Pimpri-Chinchwad could increase due to climate change impacts. It is therefore prudent to ensure that projects in these areas incorporate designs that are resilient to potential increases in river and urban flood hazards over the long term.

[1] *Source: ThinkHazard webtool (https://thinkhazard.org/en/report/17776-india-maharashtra-pune)*

8.2. Urban Flooding in Pune

Urban flooding in Pune and Pimpri-Chinchwad has been a recurring issue, exacerbated by rapid urbanization and inadequate infrastructure planning. The first recorded instance of urban flooding in Pune occurred on 28th September 1912, when intense rainfall inundated the central business district around Fort Area, submerging roads and buildings in knee-deep water. Overflowing drains led to widespread flooding that persisted for six days, prompting the municipality to acknowledge the inadequacy of the existing stormwater infrastructure.

Over a century later, these cities continue to grapple with urban flooding, primarily due to the encroachment upon low-lying floodplains and the transformation of numerous lakes into urban infrastructure, compromising the natural drainage systems. The replacement of permeable surfaces with impervious ones has intensified surface runoff and diminished groundwater recharge. Concurrently, issues such as improper waste disposal, obstruction of stormwater drains, and the construction of buildings over natural watercourses have further aggravated the situation.

According to the National Disaster Management Authority’s Guidelines on Management of Urban Flooding (GoI, DMA, 2010), urban flooding in cities like Pune and Pimpri-Chinchwad can range from localized incidents to major events, with inundation lasting from a few hours to several days. The cities' vulnerability is heightened by factors such as rapid urban expansion, inadequate drainage systems, and the loss of natural water bodies. Recent heavy rainfall events have underscored the urgency of addressing these challenges to mitigate the impacts of urban flooding.

9. Climate Change Trends in Pune

9.1. Baseline Climate of Pune

Pune experiences a tropical wet and dry climate (Köppen Aw), influenced by its elevation (~560 m above sea level) and proximity to the Western Ghats. The climate data presented below is based on over 30 years of observations (from 1985 onwards), combined with climate model simulations aligned with projections from the Intergovernmental Panel on Climate Change (IPCC). The data reflects average monthly variations in temperature and precipitation and offers insights into expected seasonal patterns, including temperature extremes and rainfall distribution. However, due to the spatial resolution (~30 km), localized weather phenomena such as thunderstorms or microclimatic variations may not be fully captured.

Pune’s average monthly temperatures range from mean daily minimums of around 12°C in January to mean daily maximums approaching 35°C in May. The hottest months are typically April and May, preceding the monsoon season, while December and January are the coolest. Extreme temperature days can occasionally exceed 40°C in summer and drop close to 8°C during winter nights.

Rainfall in Pune is strongly seasonal, dominated by the southwest monsoon from June to September. Average monthly precipitation peaks in July and August, with typical monthly totals exceeding 500 mm during these months. The pre-monsoon months (March–May) and post-monsoon months (October–November) experience moderate to low rainfall, while the winter months (December–February) are generally dry. Annual rainfall averages approximately 700 to 900 mm.

Average monthly baseline information in terms of these two important climatic variables, temperature and precipitation, for Pune (18.52°N 73.85°E, 554 amsl) is presented in **Figure 3**. These climatic characteristics influence urban planning, water resource management, and infrastructure design in Pune, making it critical to consider both typical and extreme weather conditions for project development and risk mitigation.

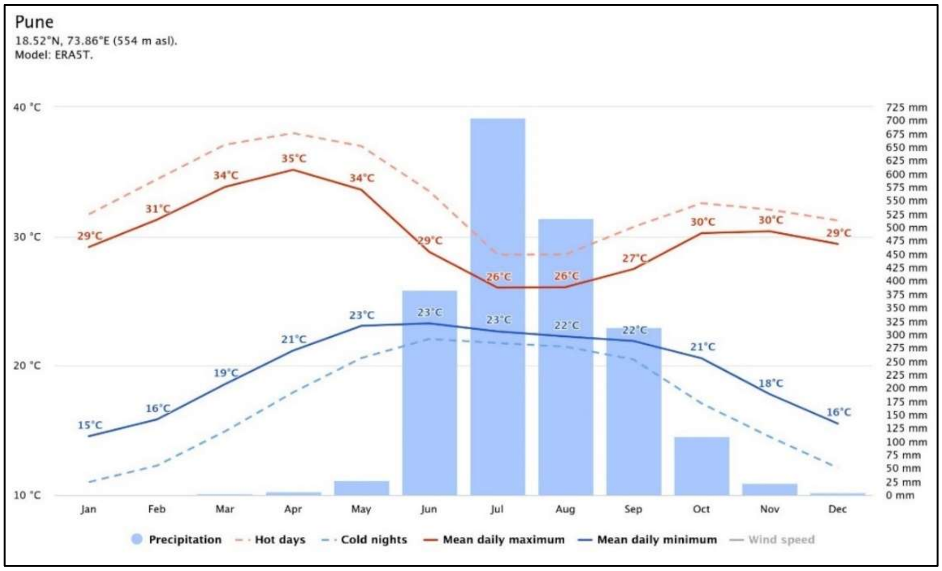

Figure 3: Modelled Average Monthly Temperature and Precipitation for Pune[2]

9.2. Climate Trends in Pune

Recent climate data indicates that Pune is experiencing notable shifts in temperature and precipitation patterns. Over the past few decades, average temperatures have shown a gradual increase, particularly during the summer months. For instance, the mean maximum temperature in April has risen from approximately 37°C in the early 1990s to around 38°C in recent years. This warming trend is consistent with broader regional patterns observed across India.

In terms of precipitation, Pune has witnessed increasing variability in monsoon rainfall. While the overall annual rainfall has not shown a consistent increasing or decreasing pattern, the intensity and frequency of extreme rainfall events have increased. For example, in May 2025, Pune recorded its highest rainfall in 64 years, with Shivajinagar observatory noting 135.2mm, a significant surplus over the monthly norm. These changes are attributed to shifts in monsoon dynamics and urbanization effects, which exacerbate runoff and drainage challenges. Future climate projections suggest that these trends are likely to continue, emphasizing the need for adaptive urban planning and resilient infrastructure to manage heat risks and flood hazards effectively.

9.2.1. Temperature Trends

Long-term temperature observations in Pune indicate a gradual warming trend over the decades. Analysis of meteorological data from 1951 to 2010 shows a steady rise in both mean maximum and mean minimum temperatures across annual and seasonal timescales. The increase in minimum temperatures is more pronounced, especially during the monsoon and post-monsoon seasons. These trends suggest a shift toward warmer nights and an overall increase in thermal stress. Such temperature changes have implications for urban infrastructure, water demand, and public health. Details of annual and seasonal temperature trends for Pune are presented in **Table 4**.

Table 4: Observed Temperature Trends in Maharashtra State, 1981–2010[3]

Seasons -→	Annual	Winter Season	Summer Season	Monsoon Season	Post-Monsoon Season
Mean maximum temperature trend in °C per year	+0.005	+0.002	+0.004	+0.003	+0.006
Mean minimum temperature trend in °C per year	+0.014	+0.007	+0.012	+0.015	+0.018

[2] *Source: Meteoblue.Data.org [https://www.meteoblue.com/en/weather/historyclimate/climatemodelled/pune_india_1259229]*

[3] *Source: Indian Meteorological Department (IMD), Climatological Normal data (1981 to 2010)*

Mean temperature trend in °C per year	+0.010	+0.005	+0.008	+0.009	+0.012
Mean diurnal temperature range trend in °C per year	-0.009	-0.005	-0.008	-0.012	-0.012

Note: Increasing trend is indicated by a (+) and decreasing trend by a (-) sign.

9.2.2. Rainfall Trends

Pune experiences a tropical wet and dry climate, with significant seasonal variations in rainfall. The average annual rainfall in Pune is approximately 722 mm, with the majority occurring during the southwest monsoon season from June to September. July typically receives the highest monthly rainfall. Long-term analysis indicates that while the total monsoon rainfall has remained relatively stable, there has been a noticeable increase in the frequency of extreme rainfall events. Between 2000 and 2020, nine years recorded days exceeding the 95th percentile of daily rainfall (over 40 mm), compared to only four such years from 1978 to 2000. This trend suggests a rise in short-duration, high-intensity rainfall events, contributing to the city's growing vulnerability to urban flooding. Seasonal and annual rainfall trends for Pune over the observed period are presented in **Table 5**.

Table 5: Rainfall Trends in Maharashtra State, 1981–2010 (mm/year)

Seasons -→	Annual	Winter Season	Summer Season	Monsoon Season	Post-Monsoon Season
Annual and Seasonal Rainfall Trends (mm/year)	+0.20	-0.10	+0.30	-0.50	+0.10

Note: 1. Increasing trend is indicated by a (+) and decreasing trend by a (-) sign.
2. mm = millimetres

9.2.3. Extremes of Temperature and Precipitation

From a historical perspective, the recorded extremes of temperature and precipitation up to the year 2010 for two key meteorological stations in Pune are summarized in **Table 6** below (IMD Pune, 2010). The table highlights the highest maximum temperature, lowest minimum temperature, and the heaviest rainfall recorded within a 24-hour period, along with their respective dates of occurrence. These records provide valuable insights into the climate variability and extreme weather events experienced in the Pune region.

Table 6: Ever-Recorded Maximum and Minimum Temperatures and 24-hour Heaviest Rainfall till 2010[4]

Station Name and Number	Highest Maximum Temperature in °C	Lowest Minimum Temperature in °C	24-hour Heaviest Rainfall in mm
Pune City (Station No. 430)	43.3	4.1	293.3
Lohegaon Airport (Station No. 43001)	42.5	5.0	212.0

Note: mm = millimetres

9.3. Future Climate Projections

9.3.1. Temperature[5]

A comprehensive set of global climate models is hosted on the World Bank's Climate Change Knowledge Portal (CCKP) to support decision-makers in understanding future climate change projections and associated impacts. This multi-model ensemble approach provides a robust range of plausible outcomes by incorporating 35 global circulation models (GCMs) used in the IPCC Fifth Assessment Report (AR5). The CCKP utilizes data from the Coupled Model Intercomparison Project Phase 5 (CMIP5), offering climate projections at a spatial resolution of 1° x 1° grid cells worldwide. It enables visualization of climate variables and indices across multiple timeframes, emission scenarios, and models.

[4] Source: Indian Meteorological Department (IMD), Climatological Normal data (1981 to 2010)
[5] Source: World Bank, Climate Change Knowledge Portal (2025) [https://climateknowledgeportal.worldbank.org/]

For infrastructure planning, particularly in land transport, temperature extremes and their diurnal ranges are critical variables influencing design criteria, often more so than average temperatures. The projected anomalies in daily maximum temperature (Tmax) and daily minimum temperature (Tmin) for Pune (approximately 73.85°E, 18.52°N) are shown relative to the baseline period of 1986–2005. These projections, derived from CMIP5 models, illustrate changes under two Representative Concentration Pathways (RCPs): the lower emissions scenario RCP2.6, representing aggressive mitigation, and the higher emissions scenario RCP8.5, representing a business-as-usual trajectory (IPCC, 2014).

The projections indicate a clear increase in both Tmax and Tmin over the 21st century, with greater warming expected under RCP8.5. This trend highlights the necessity for resilient infrastructure design that accounts for increased heat stress and temperature variability to safeguard the long-term functionality and safety of transport assets in Pune (see **Figure 4**).

Climate change projections for Pune district are derived from regional climate assessments including the Maharashtra State Climate Change Action Plan (MSCCAP) and research supported by the Indian Meteorological Department (IMD). These projections utilize downscaled outputs from global climate models such as HadCM3 and CMIP5, calibrated for local conditions, and focus on the midterm period 2021–2050 relative to the baseline period 1961–1990.

Under the IPCC's SRES A1B emissions scenario—which assumes balanced energy use and rapid economic growth—Pune is expected to experience a rise in mean, maximum, and minimum temperatures by approximately 1.0°C to 1.6°C during the mid-21st century. Seasonal warming is projected to be most prominent during the summer months, intensifying heat stress conditions. Precipitation projections for Pune indicate moderate variability, with some models forecasting slight increases in monsoon rainfall intensity, although overall annual precipitation may remain relatively stable or show minor fluctuations.

These midterm climate projections underscore the need for climate-adaptive planning and resilient infrastructure design in Pune, particularly to address heightened temperature extremes and potential changes in rainfall patterns (see **Table 7**).

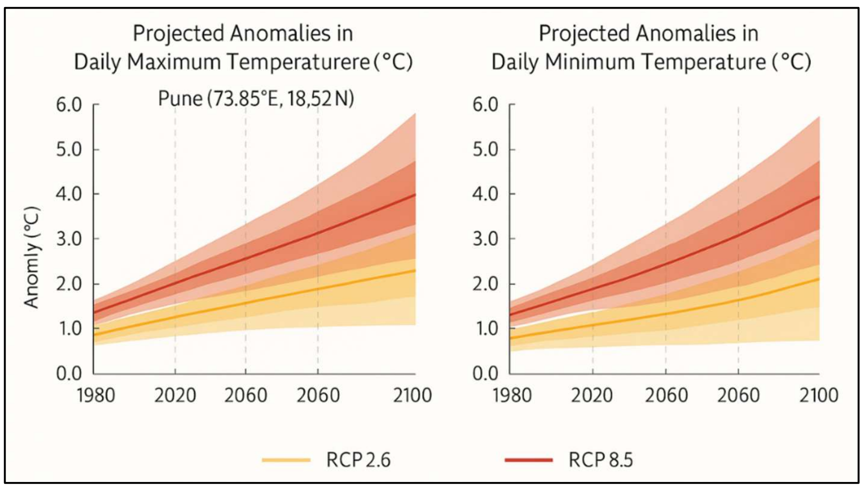

Figure 4: Projected Changes in Temperature for Various Timeframes (Location: 73.85°E, 18.52°N)

Table 7: Projected Increase in Mean, Maximum, and Minimum Temperatures, 2021– 2050

District	Projected Increase in Mean Temperature (Tav, °C)	Projected Increase in Mean Maximum Temperature (Tmax, °C)	Projected Increase in Mean Minimum Temperature (Tmin, °C)
Pune	1.1 – 1.4	1.2 – 1.6	1.0 – 1.3

9.3.2. Heat Waves

It is projected that extreme heat waves will become increasingly frequent across India due to rising average global temperatures. For Pune, climate models suggest a rise in mean maximum temperature by approximately 1.8°C to 2.2°C by the 2030s under moderate to high emissions scenarios (CMIP5, IPCC AR5). This increase is expected to elevate the frequency and intensity of extreme heat events. Pune has already experienced unseasonal heat spells in recent years, with maximum temperatures exceeding 40°C during April and May—significantly above the city's climatological average of around 36°C for the same period. According to the India Meteorological Department (IMD), the city recorded one of its highest ever maximum temperatures of 43.3°C on 26 April 1897, and more recently, temperatures have crossed 41°C in May 2020 and 2023. The increasing heat stress poses challenges for public health and urban infrastructure, especially during the pre-monsoon months of April to June.

9.3.3. Rainfall

Changes in extreme precipitation are critical for infrastructure planning, especially for designing drainage systems, culverts, and flood resilience measures. While percentile-based trends of daily precipitation are useful, engineering design demands understanding return levels—the maximum expected rainfall within defined intervals such as 10 or 25 years. According to climate projections from the World Bank's Climate Change Knowledge Portal (CCKP), daily maximum rainfall intensities are expected to rise with climate change. The 25-year return level refers to the highest daily precipitation likely to occur on average once every 25 years (with a 4% annual chance), although such events may occur more frequently due to variability.

For Pune (73.85°E, 18.52°N), under the CMIP5 model ensemble, projections indicate a significant increase in extreme rainfall by mid-century. Under the low emissions scenario (RCP2.6), the 25-year return level of maximum daily precipitation is projected to increase by approximately 6–8%, while under the high emissions scenario (RCP8.5), the increase may reach 12–15% compared to the 1986–2005 baseline. These shifts underscore the necessity of adapting urban drainage systems and transport assets to accommodate higher-intensity rain events.

Based on available regional climate projections and studies, the following **Table 8** summarizes the projected changes in seasonal and annual rainfall for Pune district for the period 2021–2050 under the SRES A1B emissions scenario.

Table 8: Projected Change in Annual and Seasonal Rainfall, 2021–2050 (SRES A1B Emissions Scenario)

District	Projected Change			
	for Pre-Monsoon Months (%) [Jan. – May]	for Monsoon Months (%) [Jun. – Sept.]	for Post-Monsoon Months (%) [Oct. – Dec.]	for Annual Mean (%)
Pune	–5% to +10%	+5% to +20%	–10% to +15%	+5% to +15%

10. Climate Change Risks and Vulnerability Assessment (CRVA)

10.1. General

Urban rail systems, such as metro networks, represent one of the most energy-efficient modes of transport, offering significant environmental benefits and supporting the transition to low-carbon urban mobility. The expansion of metro rail infrastructure, including the Phase 1 extensions of the Pune Metro Rail Project (PMRP), holds strong potential for contributing to climate change mitigation by reducing vehicular emissions and promoting modal shift from private to public transport.

However, the climate mitigation potential of metro systems can only be fully realized if they are designed and operated to withstand the growing risks associated with climate change. Infrastructure that is not climate-resilient may face performance disruptions, structural damage, and escalating maintenance costs over its lifecycle.

Climate risk and vulnerability are typically understood through the interrelationship between three key dimensions: exposure, sensitivity, and adaptive capacity. The degree of vulnerability is influenced by multiple factors, including:

- the geographical and topographical characteristics of the project area,
- the level of environmental degradation and urban development in surrounding areas, and
- the institutional capacity of local agencies to anticipate, respond to, and manage climate-related risks through planning and adaptation.

Rail-based transport infrastructure—particularly fixed civil assets such as viaducts, tunnels, and stations—is inherently exposed to natural forces and environmental hazards. Without timely and adequate adaptation interventions, such infrastructure is highly susceptible to climate-induced impacts, especially in dense urban settings like Pune where stormwater drainage limitations, urban heat island effects, and land use pressures amplify vulnerability.

A critical limitation of urban metro systems is their relatively low operational flexibility in the event of climate-induced disturbances. Disruptions to supporting infrastructure—such as electricity supply, drainage systems, or urban access roads—can directly compromise metro functionality. Moreover, given the long operational life of metro infrastructure, often exceeding 100 years, it is essential that climate resilience be systematically integrated into planning, design, and maintenance strategies from the outset.

This CRVA aims to qualitatively assess the potential climate change risks affecting the PMRP Phase 1 Extension corridors—PCMC to Nigdi and Swargate to Katraj—and to recommend appropriate adaptation measures to mitigate identified vulnerabilities. The assessment has been guided by relevant international standards, including the World Bank's Environmental and Social Standards (ESS 3 – Resource Efficiency and Pollution Prevention and Management) and the European Investment Bank's Environmental and Social Standards (EIB ESS 5 – Climate Change), ensuring alignment with global best practices for infrastructure resilience.

10.2. Climate Change Risk Screening

Sensitivity of metro rail infrastructure to climatic and geological conditions is a key consideration in the planning and design of the Pune Metro Rail Project (PMRP) Phase 1 Extension. The screening aims to identify vulnerabilities of key project components to climate-induced hazards such as extreme heat, heavy rainfall, and urban flooding.

a) ***PMRP Phase 1 Extension Project Components:*** The project involves the development of two metro corridor extensions—PCMC to Nigdi (4.413 km, elevated) and Swargate to Katraj (~5.9 km, underground)—adding critical links to the existing urban transit system. Key components include elevated viaducts, underground tunnels, stations (elevated and subsurface), ancillary utilities, and associated electrical and communication systems.
b) ***Sensitivity of Project Components:*** The infrastructure components of the PMRP Phase 1 Extension are inherently exposed to climate-related risks. Elevated sections are particularly vulnerable to high temperatures, which can result in thermal expansion and rail deformation, requiring track realignment, repairs, or operational restrictions. Prolonged and intense heatwaves may also affect electrical systems and passenger comfort, especially at elevated or non-air-conditioned stations. Heavy rainfall and increasingly erratic monsoon patterns pose significant risks to both elevated and underground segments. Flooding can damage substations, signalling equipment, and platform areas, especially in low-lying zones. For the underground Swargate–Katraj section, high-intensity rainfall events may lead to water ingress, ventilation stress, and service disruptions unless robust waterproofing and pumping systems are in place. Tropical weather events, though less frequent in Pune than coastal regions, can still bring high winds and debris, affecting power lines, access infrastructure, and system reliability. Passenger comfort and operational safety are additional areas of concern. Elevated temperatures within trains and stations can lead to heat stress, particularly in the absence of adequate HVAC systems.

Table 9 provides a preliminary risk screening matrix that categorizes the identified climate risks associated with the proposed project components. This classification serves as the basis for the subsequent detailed vulnerability assessment and the development of adaptation strategies.

Table 9: Initial Climate Risk Screening

Sl	Projected Climate Change Risks	Description	Risk Severity Level
1.	Increase in Temperature	Rising average and extreme temperatures, particularly from March to June, increasing heat stress.	Moderate
2.	Variation in Average Precipitation	Monthly precipitation is highly variable; Uneven monsoon distribution may impact construction timelines and water management strategies.	Moderate
3.	Extreme Events:		

	i. Heat Waves	Relatively increasing number of hot days (higher than 40ºC) is expected in March to June (summer) months; risk to track systems, HVAC loads, and workers.	Moderate
	ii. High or low Rainfall leading to floods or droughts	Increased intensity in Rainfall during the monsoon season. Water scarcity, which is an identified risk for the area, may also be exacerbated	Moderate
	iii. Heavy Rainfall and Urban Flooding	Short-duration, high-intensity rainfall events can cause flooding, especially in underground sections.	High
4.	High Winds / Remnant Cyclonic Weather	Though rare, residual systems from Arabian Sea cyclones can disrupt operations with wind/rain.	Low to Moderate
5.	Lightning and Electrical Storms	Frequency based on severity of rains; observed during transitional seasons; potential risk to signalling, OHE, and construction safety.	Low

Based on the provided table and aligning with the European Investment Bank (EIB) guidelines, the overall climate change risk level for the project can be classified as **Moderate Risks**.

10.3. Indicators of Risk Assessment

To assess the impact of climatic changes on the operation and maintenance of the metro rail network, an attempt has been made during the desk study to identify the potential effects of climate variability on key aspects relevant to the PMRP Phase 1 Extension corridors (PCMC to Nigdi and Swargate to Katraj). The identified indicators for assessing climate risks are as follows:

- Robustness of metro infrastructure
- Continuity and efficiency of operations
- Safety of passengers and metro systems
- Economic implications for stakeholders
- Associated vulnerabilities and exposure risks.

10.4. Climate Change Risk and Vulnerability Assessment (CRVA)

Climate change risk assessment is an essential step in planning metro corridor extensions, aimed at mitigating potential climatic impacts and identifying vulnerable infrastructure components and sensitive geographic areas along the route.

The Climate Risk and Vulnerability Assessment (CRVA) for the PMRP Phase 1 Extension project will:

i. evaluate how projected climate change may affect the proposed metro system and its broader physical and social environment, including potentially impacted communities; and
ii. recommend appropriate adaptation measures to minimize climate-related risks to the project and the interconnected systems within which it operates.

10.5. Project-specific CRVA

10.5.1. Casual Factors

Rapid urbanization and infrastructure development in Pune have significantly increased pressure on natural resources and public utilities. The Pune Metropolitan Region (PMR) has seen its population grow from approximately 1.5 million in 1981 to over 7 million in 2021, resulting in higher greenhouse gas emissions, traffic congestion, and inadequate access to electricity, water supply, drainage, and sanitation in several areas. These changes have also led to greater vulnerability to climate change impacts.

The city has experienced a rise in local temperatures due to the Urban Heat Island (UHI) effect, with an increase of around 1.5°C to 2°C over the past decade. Short-duration, high-intensity rainfall events have become more frequent, causing urban flooding, particularly in low-lying and densely built-up zones. Green cover and open spaces have declined, and natural drainage channels (nallahs) are increasingly encroached upon. These trends highlight the need for integrating climate-resilient measures into metro infrastructure planning, particularly for the PMRP Phase 1 Extension corridors.

10.5.2. Potential Risks of Climate Change on PMRP Assets

Increased frequency and intensity of extreme weather events driven by climate change can adversely affect metro rail service performance and increase overall lifecycle costs. Studies from global urban rail systems indicate that adverse weather accounts for a notable share of operational failures and delays, emphasizing the vulnerability of rail infrastructure to climatic hazards. The extent of climate change impacts depends on asset design, geographic location, operational patterns, and the maturity of adaptation measures implemented.

Extreme weather events such as heavy rainfall, flooding, heatwaves, and storms pose significant risks, including service disruptions, safety incidents, and elevated maintenance requirements during the operation and maintenance (O&M) phase. Therefore, a thorough assessment of climate change effects on O&M is essential, drawing on insights from international best practices and local conditions.

For the PMRP Phase 1 Extension corridors, climate change will likely amplify existing hazards rather than introduce entirely new threats. Flooding and heat-related stresses are among the most critical challenges identified. While factors like snow, permafrost, and sea-level rise are irrelevant due to Pune's inland location and climate, temperature extremes, erratic precipitation, and urban flooding remain key concerns.

The PMRP assets include elevated viaducts, stations, track systems, signalling, electrical and mechanical installations, and other interconnected infrastructure components. These are vulnerable to climate-induced stresses such as thermal expansion, water ingress, and electrical system overloads. Effective risk management and climate-adaptive technical measures will be essential to ensure the metro system remains safe, reliable, and efficient over its operational lifespan.

The detailed potential impacts of climate variations on the vulnerable assets of the PMRP Phase 1 Extension corridors are presented in the combined **Table 10**.

Table 10: Impact Matrix of Climate Change on Vulnerable Assets

Vulnerable Infrastructure / Assets	Temperature	Rainfall	Floods	Wind	Storm / Cyclone
Bridges	Yes – Thermal expansion causing stress and deformation	Yes – Increased wear due to moisture and corrosion	Yes – Structural weakening due to inundation and erosion	Yes – Possible damage from strong gusts	Yes – Low risk, but residual storm effects possible
Drainage Systems	No – Minimal direct impact	Yes – Blockage and overflow risks due to intense rainfall	Yes – Overloading causing urban flooding	Yes – Potential damage to exposed structures	Yes – Low to moderate risk due to heavy rains
Railway Tracks	Yes – Expansion/contraction causing track buckling	Yes – Waterlogging affecting track stability	Yes – Flood damage causing track washouts	No – Minimal direct impact	No – Low risk
Culverts	No – Thermal effects minimal	Yes – Blockage from sediment and debris during rains	Yes – Floodwater flow obstruction and structural damage	Yes – Potential damage from debris flow	Yes – Low to moderate risk
Slip Slopes	Yes – Increased drying causing soil cracking	Yes – Increased saturation leading to slope instability	Yes – Landslides and erosion risks	Yes – Wind erosion effects possible	Yes – Moderate risk due to heavy storms
Signalling and Telecommunication	Yes – Overheating causing equipment failure	Yes – Water damage due to heavy rains	Yes – Flooding impacting underground cables and stations	Yes – Electrical interference	Yes – Moderate risk from storm-induced outages
Solar Panels	Yes – Efficiency reduction at high temps	Yes – Damage from hail or heavy rain	Yes – Flooding risk in low-lying installations	Yes – Possible physical damage	Yes – Low to moderate risk

Significant risks to the project arise from both ambient and extreme variations in temperature, intense heat events (heat waves), heavy and variable precipitation, flooding, as well as medium-level and indirect impacts from lightning. These climate factors affect multiple critical assets including bridges, tracks, drainage, and signalling systems. The key risks and their implications are briefly outlined in the following sections.

A. Risks due to Extreme Temperature:

Temperature is a key climate parameter influencing climate change impacts. For the PMRP Phase 1 extension project, temperature changes have a moderate impact on railway infrastructure robustness and service life, and a medium impact on railway operations, safety, and economic outcomes for stakeholders. Global projections indicate a temperature rise of about 1.2°C, with current mitigation efforts unlikely to achieve net-zero emissions by 2050–2060, making climate adaptation strategies essential.

Data for Pune district (**Table 4**) show increasing trends in annual average, minimum, maximum, and monthly mean temperatures, contributing to more frequent extreme heat events.

The project comprises two corridor types with different exposure to temperature extremes:

- The **PCMC to Nigdi alignment** is fully elevated, with tracks and supporting structures approximately 5.5 meters above road level, directly exposed to solar radiation. This direct exposure makes rails and elevated structures vulnerable to thermal stress. Steel rails can heat up to 20°C or more above ambient temperature; with Pune’s pre-monsoon ambient temperatures exceeding 38°C, rail temperatures could reach or exceed 60°C. This causes metal expansion, increasing risks of track misalignment and deformation under train loads.
- The **Swargate to Katraj alignment** is entirely underground, where temperature fluctuations are less extreme due to natural insulation from soil. However, underground structures still face thermal stresses due to operational heat loads and ventilation system effectiveness, which must be carefully managed.

Increased frequency and intensity of extreme heat due to climate change will elevate risks of track failures from thermal expansion. Typical mitigation involves operational measures such as reducing train speeds or suspending traffic in severely affected sections during peak heat. Other assets like elevated viaducts (reinforced concrete bridges), signalling, telecommunication equipment, and solar panels on the elevated corridor are exposed to daily and seasonal thermal cycles. Concrete structures undergo expansion and contraction; expansion joints and bearings accommodate these movements under normal conditions, but persistent higher temperatures and extreme heat events can cause accelerated material fatigue, cracking, spalling, and aggregate distress. These effects require robust design and maintenance planning. In contrast, underground structures benefit from thermal buffering but require efficient ventilation and cooling systems to manage heat generated by trains and equipment.

B. Risks due to heavy precipitation / extreme Rainfall

Flooding in Pune is driven by factors such as (i) increased urbanization and loss of permeable surfaces, (ii) inadequate drainage infrastructure, (iii) blockage of drains due to solid waste and debris, (iv) encroachment on stormwater drains, and (v) loss of natural water bodies and floodplains.

Flooding poses a high impact risk to Metro Rail operations due to soil erosion beneath tracks and potential submergence of rail infrastructure, affecting signalling and overhead contact systems. Floodwaters rising above the track level may force speed reductions or service interruptions, causing delays. Moderate impacts are expected on infrastructure robustness and service life, safety, and socioeconomic impacts on stakeholders.

As shown in **Table 5**, rainfall variability in Pune has increased over recent decades. While projections in **Table 8** indicate minor changes in monsoon precipitation (June–September) for 2021–2050, climate change is expected to increase the frequency and intensity of extreme rainfall events, raising flood risks. The Mula and Mutha rivers, flowing through Pune, have experienced reduced natural floodplain functions due to urban encroachment and pollution, further exacerbating flood risks.

The PCMC to Nigdi corridor is predominantly elevated, reducing direct flood exposure but increasing stormwater runoff, which can overload local drainage systems. The Swargate to Katraj corridor is mainly underground, necessitating robust drainage and pumping systems to prevent water ingress during heavy rains or flash floods.

Given these challenges, integrated stormwater management, drainage maintenance, and resilient infrastructure design are essential to mitigate flood risks and ensure reliable metro operations under changing climate conditions.

C. Storms/Extreme Wind Impact

Storms and extreme winds with their impacts on rail infrastructure are not recorded in Pune. However, it is known that if there are events of storms or extreme winds, they tend to have medium or minor impacts on railway infrastructure robustness and service life. This impact is lower when compared to the rated impact of temperature and flooding. The significant impacts of storms and extreme winds on railway operation, railway safety, and economic impacts to various stakeholders are very minimal or negligible. Storms and extreme winds have a very minimal or negligible impact on railway operation and services in the Pune Metro Rail Project.

D. Lightning Impact

Signal systems, including onboard and trackside devices, are particularly vulnerable to lightning and electromagnetic interference due to their sensitivity to radiation, electric, and magnetic fields. The impact of lightning on railway operation is considered moderate. The effects of lightning on railway infrastructure robustness and service life, railway safety, and economic impacts to various stakeholders are minimal.

10.5.3. Climate Change Risks due to Carbon Footprint (GHG Emissions)

Currently, data and tools to support CO2 impact analysis in the transport sector are inadequate to address assessment. Only web-based tools are applied in this study along with required consultation with Stake holders, concerned personnel or directly or indirectly related organizations, and public. Climate change includes both the global warming driven by human emissions of greenhouse gases and the resulting large-scale shifts in weather patterns. The development and operation of the Project (Metro Rail) has the potential to contribute to the greenhouse effect through emissions produced by various activities throughout the construction and operation of the PMRP Phase 1 extension project. The 3 main GHGs include carbon dioxide (CO2), Hydrocarbons (HC) and nitrous oxide (N2O).

A. Carbon Footprint (GHG Emission) during Construction Phase

- The GHG emissions during construction of the Pune Metro Rail Project Extension will arise mainly from vegetation removal, wastewater treatment, transport, building material manufacturing, and energy use. These emissions occur over a limited timeframe and are relatively low compared to the metro's full operational lifecycle.
- Tree felling and vegetation clearance along the project alignments (PCMC to Nigdi and Swargate to Katraj) will affect 433 trees, resulting in a loss of carbon sequestration estimated at 9.53 tonnes of CO2e per year due to decreased absorption capacity. This corresponds to the loss of about 43.3 tonnes of oxygen production annually.
- Compensatory afforestation at a ratio of 1:10 (planting approximately 4,330 saplings) will help offset this loss over time. Once matured (in about 5 years), these trees are expected to sequester around 85.7 tonnes of CO_2e annually, effectively compensating for the tree removal and contributing to the restoration of the local carbon balance.
- The majority of GHG emissions during construction are attributable to machinery and vehicle operations, estimated at approximately 1,566.81 tonnes of CO_2e over the three-year construction period. This accounts for around 69% of total construction-phase emissions, primarily due to diesel consumption by heavy equipment and material transport vehicles.
- Mitigation measures including energy efficiency, use of cleaner fuels, and adopting sustainable construction practices are recommended to further reduce the project's carbon footprint during construction.

B. Factors affecting the construction equipment emissions

Several factors influence the exhaust emissions of construction equipment, many of which are challenging to measure or quantify precisely. These factors can be broadly categorized into four groups, as illustrated in **Figure 5**.

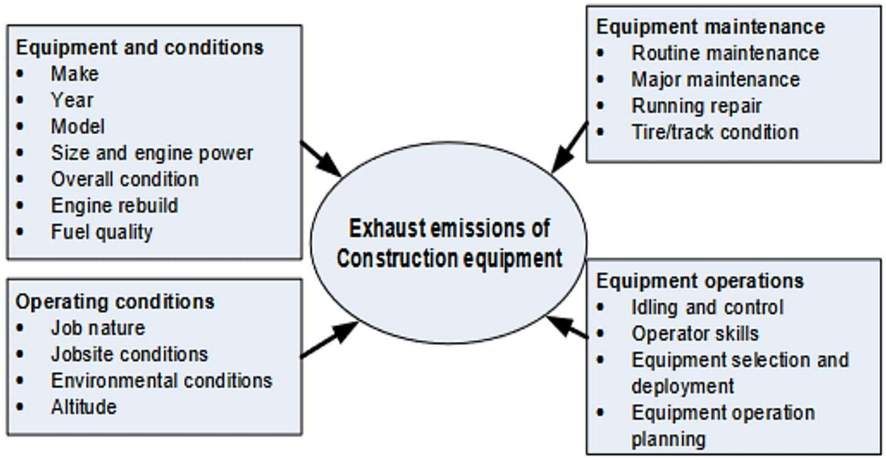

Figure 5: Factors influencing the Impact of Exhaust Emissions from Construction Equipment[6]

Table 11 presents the net GHG emissions from construction equipment, machinery, and vehicles during the construction phase of the Pune Metro Rail Project Phase 1 Extension. These emissions are generated from fuel combustion in construction equipment, transport vehicles, and auxiliary machinery during the entire construction period.

Table 11: Net GHG Emissions from Equipment, Machinery, and Vehicles during Construction Phase

Source	Fuel Consumption (litres)	Emission Factor (kg CO_2e/litre)	Estimated Emissions (tonnes CO_2e)
Diesel-powered Construction Equipment	160,000	2.68	429
Petrol-powered Vehicles	45,000	2.31	104
Generator Sets (Diesel)	35,000	2.68	94
Transportation Vehicles (Diesel)	190,000	2.68	509
Miscellaneous Machinery	28,000	2.68	75
		Total	**1,211**

C. Carbon Footprint (GHG Emissions) during Operation Phase:

Electricity generation in India accounts for approximately 37.8% of CO_2 equivalent emissions, primarily from coal-based thermal power plants with high fly ash content, contributing to particulate pollution (MOEF, 2010; Senapati, 2011). The PMRP Phase 1 Extension will have no direct operational emissions but will indirectly contribute to emissions from electricity consumption.

During the operation phase, the project will significantly reduce GHG emissions by shifting commuters from fossil-fuel-based transport modes such as diesel buses, cars, and motorbikes to electric metro services. These emission savings are projected to be approximately 35 tonnes CO_2e per day (~12,800 tonnes/year) in 2025, increasing to about 60 tonnes CO_2e per day (~21,900 tonnes/year) by 2041 due to this modal shift, as detailed in **Table 12**.

Table 12: Vehicular Emissions and Reduction in GHG Emissions due to the Project in Operation Phase

Year	Estimated Vehicular Emissions without Metro	Estimated GHG Emissions with Metro Operation	Net Reduction in GHG Emissions (t CO_2e/year)	Average Daily Reduction (t CO_2e/day)
2025	40,800	28,000	12,800	35.1
2030	44,000	29,500	14,500	39.7
2035	48,000	30,000	18,000	49.3
2041	49,900	28,000	21,900	60.0

Conversely, the project's electricity consumption contributes indirectly to GHG emissions at power plants. Annual emissions from electricity consumption are estimated at around 36,900 tonnes CO_2e

[6] Source: H. Fan, 2017 - A Critical Review and Analysis of Construction equipment emission factors

in 2025, rising to about 42,640 tonnes CO_2e by 2041, based on projected electricity usage and the Indian grid's emission factor. These figures are summarized in **Table 13**.

Table 13: Annual GHG Emission due to Power Consumption by the Project during Operation Phase

Year	Estimated Annual Electricity Consumption (MWh)	Emission Factor* (t CO_2e / MWh)	Annual GHG Emissions (t CO_2e)
2025	45,000	0.82	36,900
2030	47,500	0.82	38,950
2035	50,000	0.82	41,000
2041	52,000	0.82	42,640

** Note: Emission factor taken as 0.82 t CO_2e/MWh based on Indian coal-dominated grid average (latest MoEF&CC and CEA data)*

Thus, while the PMRP Phase 1 Extension incurs indirect emissions from power consumption, the overall operation results in net reductions in carbon emissions by substantially reducing road vehicular traffic.

10.5.4. Risks on Biodiversity

Human activities, especially urban expansion and infrastructure development, remain the dominant cause of biodiversity loss in Pune. Large areas of natural habitats have been converted for residential, commercial, and industrial use, leading to fragmentation and reduction of green spaces that support diverse plant and animal species.

Climate change is becoming an increasingly significant factor contributing to biodiversity decline. Altered temperature and precipitation patterns disrupt terrestrial and freshwater ecosystems, affecting species distribution, breeding cycles, and food availability. While Pune is an inland city with no nearby oceans, thus avoiding marine-related issues like ocean acidification, the terrestrial biodiversity here faces pressure from shifting climatic conditions.

Rising temperatures are driving species to seek cooler habitats, often moving to higher altitudes in the Western Ghats or shifting their ranges northward. These movements can upset ecological balances, leading to competition for resources, altered predator-prey dynamics, and the loss of species unable to adapt or migrate. The risk of local extinctions increases proportionally with the magnitude of warming, with projections indicating a possible rise in global temperatures by over 1.5°C by 2030 relative to pre-industrial times.

In Pune, specific climate-related risks such as forest fires, intense storms, and prolonged droughts are less frequent due to the city's climatic and geographical characteristics. The region does not possess extensive dense forests near the project area, reducing the likelihood of large-scale fires impacting biodiversity. Similarly, storms and extreme weather events are rare, and drought conditions have not shown prolonged severity to cause significant stress to local ecosystems.

Despite these relatively lower direct climate risks, the cumulative pressures from urbanization combined with climate variability underscore the importance of conserving remaining natural habitats and enhancing ecosystem resilience. Healthy ecosystems around Pune can provide critical services such as carbon sequestration, temperature regulation, and water filtration, all of which support climate adaptation and biodiversity conservation.

For the Pune Metro Rail Project Phase 1 extension, proactive measures to minimize habitat disruption during construction and operation, alongside integration of green infrastructure and urban biodiversity corridors, will be essential to mitigate biodiversity risks and promote sustainable urban development.

10.5.5. Health Risks due to Climate Change

Climate change and increasing climate variability are expected to further exacerbate health risks in Pune, particularly impacting vulnerable populations such as children, elderly, urban poor, and those with pre-existing health conditions. While India-wide data highlights various climate-sensitive health issues, specific focus on Pune reveals emerging concerns related to heat stress, vector-borne diseases, and waterborne illnesses that could be aggravated by ongoing climate shifts.

In Pune, changing temperatures and precipitation patterns linked to climate change are expected to affect health by influencing the ecology of vector-borne diseases such as dengue and chikungunya, which are common in urban areas during and after the monsoon season (Kumar et al., 2018; Singh et al., 2020). Vulnerable populations include the elderly, children, urban residents, and low-income communities living in areas with inadequate drainage and sanitation (Patil & Bhat, 2019). Diseases like malaria, encephalitis, kala-azar, and filariasis are not significant public health concerns in Pune due to effective control measures and urban conditions (Sharma et al., 2017).

Climate change affects people's health in two main ways:

- By increasing the severity or frequency of existing health problems; and
- By introducing new or unanticipated health risks in populations or areas previously unaffected.

A person's vulnerability to climate change impacts depends on three key factors 9as illustrated in **Figure 6**):

1) **Exposure** - People will encounter climate hazards differently. Exposure will depend on where and how long people spend time and what they do. For example, people who spend a lot of time outdoors may be more exposed to extreme heat.
2) **Sensitivity** - Some people are more sensitive than others to climate hazards due to factors like age and health condition. For example, children and adults with asthma are particularly sensitive to air pollutants and wildfire smoke.
3) **Adaptive capacity** - People can adjust to, take advantage of, or respond to climate change hazards. A person's ability to adapt may depend upon their income, age, living situation, access to health care, and many other factors.

Overall, climate change affects the health of ecosystems, influencing shifts in the distribution of plants, viruses, animals, and human settlements. This can increase opportunities for the spread of vector-borne diseases such as dengue and chikungunya, which are prevalent in Pune during and after the monsoon season. Human health is also impacted by reduced ecosystem services, including the availability of food, medicinal plants, and livelihoods dependent on natural resources. Climate variability and human health in Pune are interconnected with underlying vulnerabilities such as poverty, urban overcrowding, and inadequate sanitation. Greater understanding is needed on the relationship between climate variability and emerging infectious diseases like dengue and chikungunya, as well as chronic illnesses related to cardiovascular and respiratory conditions, asthma, and diabetes. Health effects related to climate change in the region include respiratory diseases aggravated by air pollution and heat stress, water- and foodborne illnesses, and increased risk of injuries during extreme weather events. Mental health impacts and social stress due to climate-related disruptions are also of concern.

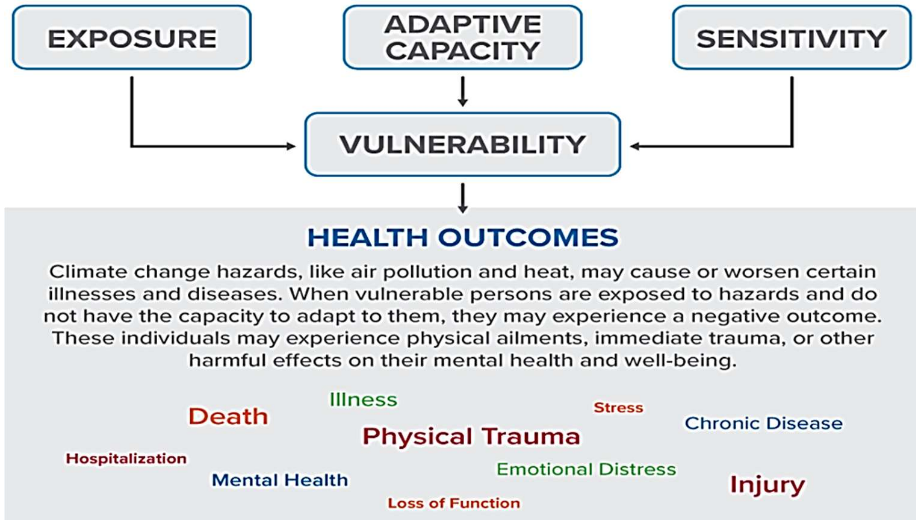

Figure 6: A person's vulnerability to climate change impacts[7]

Potential health impacts due to climate change fall into three categories:

1. **Heat stress and air pollution:** Pune experiences rising average temperatures and increasingly frequent heatwaves, particularly during the pre-monsoon months. High temperatures above 40°C have become more common, increasing the risk of heat-related illnesses such as heatstroke and dehydration, especially among outdoor workers and vulnerable groups. Air quality in Pune is affected by vehicular emissions and dust, with climate change potentially worsening pollution episodes through increased temperature and stagnant air conditions, exacerbating respiratory illnesses like asthma and chronic obstructive pulmonary disease (COPD).
2. **Waterborne infectious disease:** Changes in rainfall patterns and extreme precipitation events can affect water quality by increasing contamination risks in surface and groundwater sources. Incidences of waterborne diseases such as cholera, diarrhoea, and hepatitis may increase, particularly in informal settlements with inadequate sanitation. The risk of such diseases is higher among children under 14 and the elderly, who are more vulnerable to infections.
3. **Vector-borne disease:** Vector-borne diseases such as dengue, chikungunya, and malaria are influenced by climatic factors like temperature, humidity, and rainfall. Pune's urban environment, with pockets of stagnant water due to poor drainage or water storage practices, provides breeding grounds for mosquitoes. Increased temperatures and irregular rainfall patterns due to climate change may extend the transmission season and geographic range of these diseases, posing heightened risks to public health.

Additional Considerations:

- **Impact on Food Safety and Nutrition:** Climate change can disrupt food supply chains through extreme weather events, affecting availability and access to nutritious food. Elevated CO_2 levels and changing growing conditions may alter crop nutritional quality, potentially increasing malnutrition risks in vulnerable populations.
- **Mental Health and Social Well-being:** Extreme weather events, displacement, and economic stresses related to climate change can negatively impact mental health, increasing anxiety, depression, and social instability.

10.6. Consequences of Climate Change Risks

Assessing the consequences of climate change on metro rail infrastructure—particularly for an urban elevated and underground transit system like the PMRP Phase 1 Extension—is inherently complex.

[7] *Source: US EPA - How Climate Change Affects Human Health (https://www.epa.gov/climateimpacts/climate-change-and-human-health)*

The very nature of metro systems, which interact closely with both built and natural urban environments, makes them sensitive to climate variability, though impacts are often nonlinear and context-specific.

Meteorological parameters such as elevated temperatures and intense precipitation events, which are projected to increase under future climate scenarios, are not hazards by themselves. However, these become hazardous when they impact infrastructure in a way that affects its functionality, safety, or longevity. For example, high-intensity rainfall over short durations—expected to become more frequent in Pune—can overwhelm stormwater drainage systems, potentially flooding access points or approaches to elevated viaducts, even if the structures themselves are resilient.

As shown in **Figure 7**, climate-related weather hazards may have multiple cascading impacts not only on core metro infrastructure—such as tracks, stations, and viaducts—but also on auxiliary systems like signalling, communication, power supply, and commuter access. Though most metro systems are designed with redundancies, localized flooding, short circuits due to water ingress, or overheating of electrical equipment may cause delays, increase maintenance costs, and pose safety concerns. The long-term consequences of such events may be both direct—including deterioration of infrastructure assets, reduced service life, or even casualties in extreme cases—and indirect, such as financial losses due to service disruption, increased operating costs, and reputational impacts for the operating agency.

In the context of the PMRP Phase 1 Extension project, the elevated corridor from PCMC to Nigdi is more exposed to surface-level urban flooding impacts, while the underground Swargate to Katraj alignment may face localized risks from extreme rainfall, despite having flood protection and pumping systems in place. Additionally, the expansion corridors may increase impervious cover in the city, contributing to faster runoff, unless adequate compensatory drainage interventions are implemented.

Unforeseen events such as high-wind incidents or synoptic-scale storms, although rare in Pune, can lead to city-wide transportation disruptions. Such events could cause cascading infrastructure failures, especially if power supply, telecommunication lines, or emergency systems are affected. Therefore, climate risks must be integrated into asset management, routine maintenance, and long-term renewal strategies.

The impact of these climate change parameters on vulnerable railway assets leads to several consequences as listed below:

- track movement,
- track buckling,
- track washout,
- erosion of track bed,
- over-flooding,
- falling of trees,
- higher winds,
- visibility,
- drainage system clogging,
- landslips,
- disruption of bridge foundations,
- settlement of edifices,
- arcing of conductive components,
- wayside fires,
- vegetation, etc.

Severity of risks may lead to the following:

- Stoppage and / or cancellation of Rail services
- Inefficient acceleration and braking, slower speeds and delays
- Accidents
- Material damage to Rail fleet, equipment and infrastructures

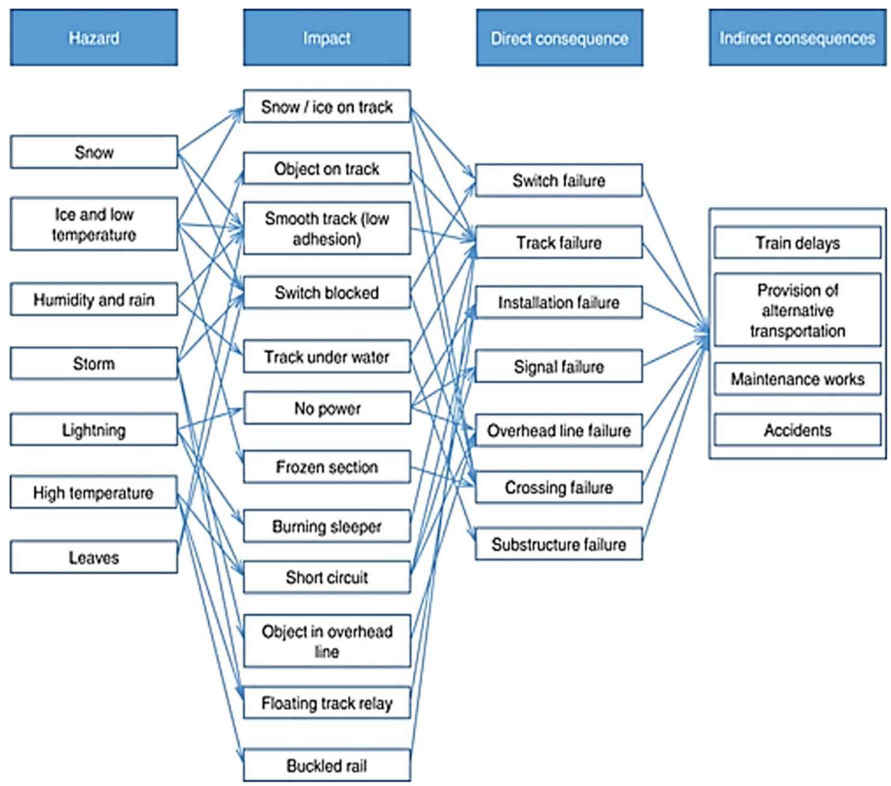

Figure 7: Direct or Indirect Consequences of weather hazards on Railway Elements

Metro Rail systems are highly sensitive to extreme weather, where a single asset failure can cause fatalities, costly repairs, service disruptions, and reputational damage. High replacement costs, especially for structures like bridges, may lead to prolonged closures. As climate change exacerbates these risks and public health challenges, proactive policies are essential to help stakeholders plan effective response strategies.

Risk Assessment Matrix:

Figure 8 illustrates the climate change risk management process flowchart, showing how risk assessment outcomes feed into decision-making. When the likelihood of a hazard occurring at a certain intensity can be quantified, it is referred to as the probability of occurrence (P). **Figure 9** presents the risk assessment matrix, which categorizes risk levels based on likelihood and severity. In cases where the extent of impacts, or consequences (C), are independent of the probability of occurrence—as is often true for natural hazards—risk can be expressed algebraically as the product of P and C.

i.e. **Risk = P × C**

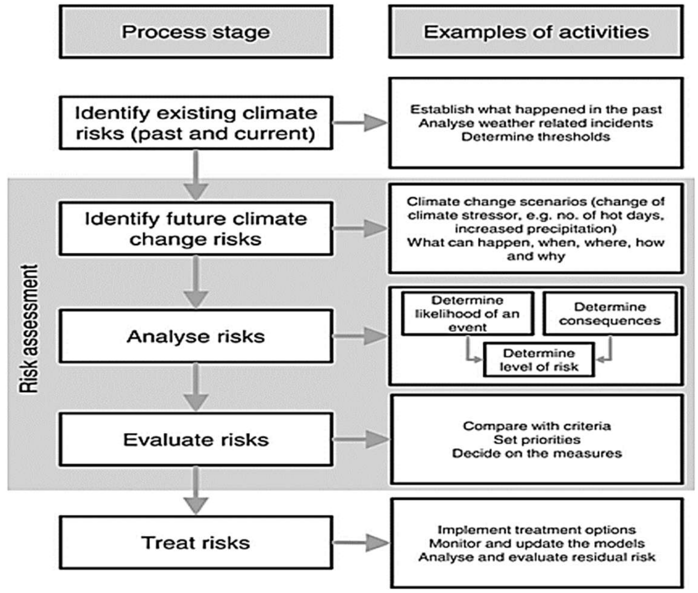

Figure 8: Risk Management Process

The color-coding in a 5×5 risk assessment matrix represents the combined levels of probability and impact for identified risks. **Figure 9** shows that high risks are marked in red, moderate risks in yellow (amber), and low risks in green.

	Negligible	Minor	Moderate	Major	Catastrophic
Almost Certain	5	10	15	20	25
Likely	4	8	12	16	20
Possible	3	6	9	12	15
Unlikely	2	4	6	8	10
Rare	1	2	3	4	5

Figure 9: Risk Assessment Matrix (5 × 5)

Adaptation measures aim to reduce high risks to moderate or low levels. The effectiveness of these measures depends on their robustness against a range of future climate scenarios involving variables such as heavy rains, temperature, and wind speed. **Figure 10** illustrates the Residual Risk Assessment Matrix, a 3×3 grid showing the likelihood and severity of risks remaining after adaptation measures are applied.

	Severity →			
Likelihood ↑	Residual Impacts	Minor	Moderate	Major
	Likely	3	6	9
	Possible	2	4	6
	Unlikely	1	2	3

Figure 10: Residual Risk Assessment Matrix (3 × 3)

11. Adaptation Measures to Climate Change and PMRP Asset Management

11.1. Introduction

Climate adaptation is a complex process that requires a thorough understanding of the interdependencies between climate variables and infrastructure assets, often supported by predictive models to assess asset health. Effective climate change management demands a holistic approach that considers local and regional climate conditions, anticipated climate impacts, active stakeholder participation, policy frameworks, and infrastructure performance throughout the operation and maintenance phases.

Adaptation strategies should be developed based on risk priorities to guide decision-making related to future maintenance, rehabilitation, and repair planning. Evaluating the economic viability of proposed adaptation measures is essential; however, this requires decision-makers to have access to data representing the net costs of climate change—information that is often difficult to isolate from other expenses and impacts.

Moreover, several challenges hinder effective adaptation, including:

- uncertainty in regional climate projections and the combined effects of multiple weather phenomena;
- lack of clear strategic guidance from legislation and policies to promote adaptation efforts; and
- insufficient sector-specific data and methodologies to evaluate the effectiveness of adaptation responses.

Addressing these gaps is critical to enable informed planning and implementation of climate-resilient infrastructure solutions. Adaptation measures to reduce the vulnerability of the proposed Railway infrastructure to climate change are evaluated based on the following factors:

- The magnitude and pace of climate change: adaptation is generally more achievable when changes are moderate and gradual rather than sudden or extreme.
- Clear identification of responsibilities for implementing adaptation options, including understanding who holds influence over these measures.
- The extent to which existing risk management strategies can integrate climate change considerations.
- The effectiveness of adaptation actions in meeting specific objectives, while recognizing that some responses may lead to unintended consequences.

The proposed project is categorized as a High-Risk project as per the European Investment Bank's Environmental and Social Standards (2021), specifically under Standard 1: Assessment and Management of Environmental and Social Impacts and Risks, which requires robust assessment and adaptation planning for projects exposed to climate-related hazards. Rolling stock procured under this project will operate on Metro Rail network areas that may be vulnerable to the impacts of climate change such as extreme heat, intense rainfall, or flooding. Effective adaptation to both climatic and non-climatic risks depends on ensuring that infrastructure components are soundly engineered from the outset. All structures must be built on resilient foundations to prevent premature deterioration due to poor construction practices, subpar material quality, or inadequate design standards. This approach, led by Maha-Metro, includes enforcing appropriate engineering and performance standards during the construction phase.

In the Metro Rail sector, adaptation options are generally grouped into engineering (structural) and non-engineering (institutional and planning) measures, as illustrated in **Figure 11**. Structural adaptation focuses on design elements that may be affected by climate change, including:

i. subsurface material stability and strength,
ii. physical and environmental performance of construction materials,
iii. dimensions and profiles of key structural components,
iv. drainage and erosion control tailored to future rainfall and runoff scenarios, and
v. protective works and barriers.

Non-engineering options relevant to the PMRP Phase 1 extension include:

i. proactive maintenance scheduling and climate-responsive early warning systems,
ii. integration of climate considerations into master planning and land use regulation, and
iii. local environmental management practices to enhance site resilience.

Environmental management is embedded within the project's planning and operational framework to minimize climate risks and ensure sustainable performance throughout the asset lifecycle. Risk mitigation and adaptation measures are integrated into design, construction, and operational protocols to enhance resilience against climate impacts.

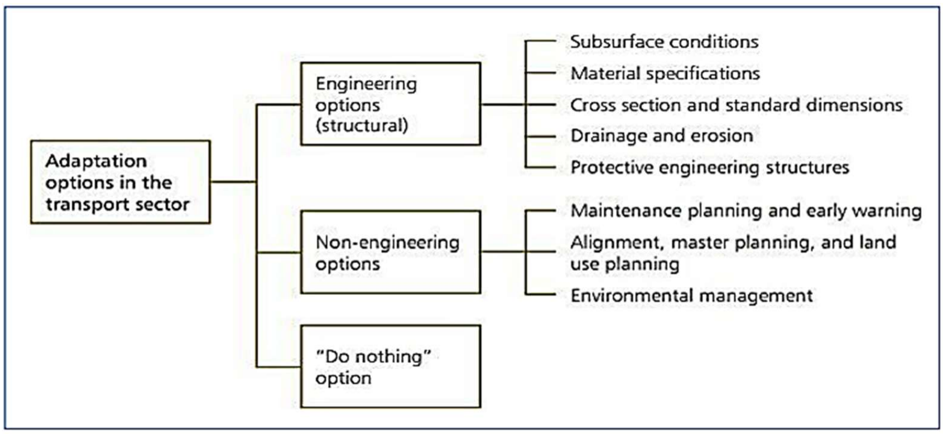

Figure 11: Nature of Adaptation Options in the Transport Sector[8]

Decision-making around climate change adaptation can be challenging due to the relative novelty of the subject, as well as existing gaps in data, limited information on long-term climate projections, and the uncertainties associated with assessing vulnerability, sensitivity, and potential impacts. In line with the adaptation options illustrated in **Figure 11**, the "do nothing" scenario is also considered, particularly in cases where adaptation may not be immediately justifiable.

For the PMRP Phase 1 extension, a practical approach involves incremental or adaptive maintenance strategies, implemented over short, successive timeframes. This allows for flexibility and course correction as more accurate climate projections and risk information become available. Such an iterative approach helps avoid premature or excessive investment while managing uncertainty effectively. However, it is important to note that not all climate-related impacts can be eliminated through adaptation measures alone, and residual risks may still persist despite best efforts.

11.2. Project specific Climate Change Adaptation Measures

A significant cost component in metro rail systems lies in the maintenance and renewal of track infrastructure, particularly due to temperature-induced defects such as rail buckling, kinks (caused by thermal expansion under extreme heat), and rolling contact fatigue (RCF) associated with high-frequency operations.

For the PMRP Phase 1 Extension, elevated viaduct sections will be directly exposed to climatic extremes, including intense solar radiation and considerable diurnal temperature variation. This

[8] *Source: Asian Development Bank, Guidelines for Climate Proofing Investment in the Transport Sector, 2014.*

constant exposure heightens the vulnerability of rail tracks to thermal stresses and potential structural fatigue.

To mitigate such risks, Maha-Metro has proposed the use of UIC60 head-hardened 1080 grade steel rails for the extension corridors. These rails, developed through advanced heat treatment techniques, offer approximately 50% higher surface hardness compared to conventional rail steel grades. This technological improvement enhances resistance to wear and deformation, improves safety under severe climatic conditions, reduces long-term maintenance demands, and extends the operational life of the track system—supporting efficient and resilient metro rail operations under future climate stressors.

11.2.1. Temperature

Temperature impacts on rails primarily include buckling or alignment deformation due to thermal stresses that accumulate in continuously welded rail (CWR) systems. For the PMRP Phase 1 Extension, new tracks are proposed to be continuous welded rails, which will be mechanically or thermally stressed to establish a predefined stress-free temperature before being securely fastened. This process ensures that, at a specific ambient temperature—defined based on the local climatic conditions in Pune—there are no residual compressive or tensile thermal forces acting on the rail. By establishing this stress-free condition, the rail system is better equipped to withstand thermal expansion and contraction across seasonal extremes, thereby significantly reducing the risk of rail buckling or fracture. For Pune, where temperatures typically range from approximately 5°C in winter to over 45°C in peak summer, the rail design temperature envelope is considered to accommodate a thermal variation from -5°C to 65°C, ensuring performance reliability under anticipated climate variability and heat stress.

11.2.2. Precipitation/Rainfall

Projected increases in intensity and variability of precipitation in Pune due to climate change present notable challenges to urban infrastructure, including the Pune Metro Rail Project (PMRP) Phase 1 Extensions. As seen in **Table 5**, monsoon precipitation trends across Maharashtra indicate an increase in extreme rainfall events, resulting in heightened risk of urban flooding, especially during the June–September season.

The PMRP Phase 1 Extensions comprise both elevated (PCMC to Nigdi) and underground (Swargate to Katraj) corridors, each requiring tailored climate adaptation responses to precipitation-related hazards:

- The elevated viaduct structures, constructed from reinforced cement concrete, act as impermeable surfaces, rapidly converting rainfall to surface runoff. This runoff, if unmanaged, may contribute to waterlogging of roadways and surcharge of nearby drains. To mitigate these risks, the viaduct design incorporates camber/cross-slopes to guide runoff into a dedicated drainage network. The runoff is then directed to rainwater harvesting pits or soakaway structures positioned between piers. These features are intended to decentralize stormwater discharge, reduce pressure on urban drains, and promote groundwater recharge. This strategy aligns with adaptive stormwater management principles suited to increasing rainfall variability.
- For underground alignments, heavy rainfall and rising groundwater levels pose risks of water ingress into tunnels, stations, and ancillary structures. As an adaptation measure, the project includes comprehensive waterproofing systems, peripheral drainage arrangements, and automated sump pump mechanisms at critical tunnel points and stations. The design also factors in hydrogeological conditions, including rainfall-induced variations in groundwater, ensuring that tunnel linings, retaining walls, and station boxes can withstand both hydraulic pressure and prolonged saturation conditions.

These climate-resilient design features are supported by site-specific rainfall data, runoff modelling, and lessons learned from earlier phases of the project. As shown in **Table 8**, the return period of high-intensity rainfall events is shortening, suggesting that low-frequency, high-impact flood events may become more common. By integrating precipitation-specific adaptation measures into the engineering design and maintenance plans, the PMRP Phase 1 Extensions are better positioned to cope with future climate scenarios, reduce operational disruptions, and maintain safety standards throughout their lifecycle.

11.2.3. Ground water systems

Groundwater systems are critical to climate change adaptation and require appropriate structural and non-structural management to sustain the growing population. Adaptation options, as illustrated in **Figure 12**, should include both demand- and supply-side management to ensure groundwater withdrawals are adjusted based on realistic assessments, minimizing over-reliance on groundwater. Supply-side measures involve enhancing recharge potential while considering climate-change-induced variations in precipitation and ensuring water quality for aquifer recharge.

Along the proposed PMRP Phase 1 Extensions corridor, hard rock strata are encountered at depths of approximately 4.5 m to 5 m below the existing ground level, allowing foundations to be positioned on stable strata and eliminating risks from hydrostatic uplift forces. Where hard rock is deeper, elevated rail tracks and station foundations are supported on pile foundations socketed into weathered or hard rock based on geotechnical investigations.

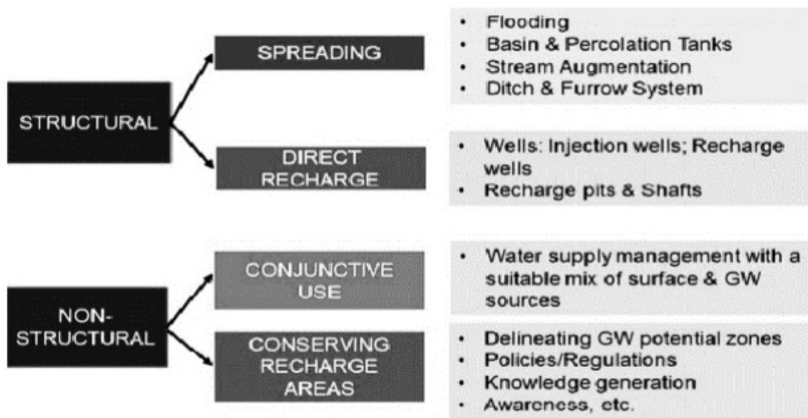

Figure 12: Potential adaptation options for groundwater management[9]

In addition to the adaptation measures outlined earlier, the following Climate Change Adaptation Measures are recommended for the PMRP Phase 1 Extension corridors:

1. Integrate climate change projections into the design and capacity of drainage systems to manage anticipated increases in flooding frequency and intensity. Drainage infrastructure should be designed with allowances for future climate impacts to ensure the resilience of metro assets.
2. Enhance wind resilience of catenary masts and maintain clear zones along tracks and catenaries by managing vegetation. While vegetation serves as a buffer for noise and pollution and provides track insulation, preference should be given to ecosystem-based measures that promote wind-resistant tree species to reduce wind-related disruptions.
3. Provide spare and emergency capacity for critical safety and operational systems, such as backup pass-by trucks, track switches, and the capability to operate on alternate tracks, to maintain service continuity during extreme weather events.
4. Develop operational strategies to minimize disruptions from extreme weather, including special timetables, alternative routing plans, and provision of replacement transport services (e.g., buses). Ensure real-time communication systems are in place to keep passengers informed and maintain coordination with emergency and relevant institutions.

Essential measures considered to protect metro rail infrastructure against specific weather events include the following:

- Switchgear protection and pile foundations for buildings with sensitive equipment.
- Cooling systems (e.g., fans) for signals and electronic devices to counter extreme heat.
- Enhanced preventive maintenance of infrastructure and protective systems.
- Vegetation and land use control along rail tracks to reduce climate-related hazards.
- Automated monitoring systems including anemometers, rain/water gauges, rail temperature sensors, and landslide detectors.

[9] *Source: Shrestha et al., 2018*

- Energy-efficiency measures: maximize natural lighting, install solar lighting for at least one-third of requirements, and adopt LED lighting across stations and facilities.

11.3. Plan for Climate Change Risk Assessment and Measures

The project-specific potential climate change risks and their associated mitigation measures for the PMRP Phase 1 extension are summarized in **Table 14**.

Table 14: Climate Change Risk Assessment and Measures provided for Construction and Operation Phase

SI	Climate Change Phenomenon	Scale	Predicted hazards	Predicted Risks/Impacts on Vulnerable Asset or Activity	Likelihood	Severity	Risk Level	Potential Adaptation Measures/ Activities	Residual Risk Level	Budget Considered in INR	Implementation Stage / Implementing agency / Monitoring Agency
1	**Precipitation / Rain fall**										
A	Low / Medium Rainfall	Medium to Moderate	-	Increased risk of earthworks failures due to desiccation	4	3	12	Re-vegetation programme, Re-ballasting and tamping interventions	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost.	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
B	High Rainfall	Major	Flooding (surface water, fluvial, groundwater); infiltration and Landslides	• Increased risk of earthwork failure and groundwater content in low-lying areas; landslides in wet weather landslide • Infrastructure slope failure; bridge scour; flooding of track, depots, buildings; water damage to electronic equipment; • Track buckling / washout, line closure • Reduced operating speeds	4	4	16	**Construction Phase:** • Usage of Protection boxes to shield equipment that can't be moved or require protection and ventilation. • Adopting Equipment protection systems safeguard essential equipment and items that cannot be relocated from flood-prone areas. • Flood panels serve as door barriers during hurricanes, offering excellent defence against flooding and water damage and for protection of construction materials. • Usage of Compression panels for glass during emergency, to create a sealed flood protection barrier around openings, preventing water entry. • Flood barriers offer a strong, long-term solution to protect buildings.	3 to 4	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC/ Operation / Maha-Metro/ PCMC/PMC / District Disaster Authority

								• Conducting Awareness programs for working staff and local Community. • Flood Preventive and Control Measures shall be in compliance with IRBM: 1998 and Handbook on Railway Construction, Second Edition, June 2020. **Operation Phase:** • Planting of 'protection Trees' Slope stabilisation programmes including installation of retaining walls, soil nails and sheet piles Counterfort retaining drains in slopes and crest drain refurbishment. • Regular monitoring during rainy season. • Review and update • Asset Risk Assessment and Action Plan in line with implementation timetable with identification of standards to be updated to take account of climate change. • Conducting Awareness programs for working staff and local Community. • Flood Preventive and Control Measures shall follow IRBM: 1998 and Handbook on Railway Construction, Second Edition, June 2020.			
		Moderate	Inland Erosion	• Overflow from Culverts and Cross Drainages • Disruptions from blockages affecting track stability	3	4	12	• Applicable Measures for High Flood Control as provided above shall be followed during construction and operation phases. • Periodic cleaning of drainages with the cooperation of PMC,	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective	Construction- EPC Contractor / Maha-Metro and GC/ Operation / Maha-Metro/ PCMC/PMC / District Disaster Authority

								PCMC and Local Authorities (SBM, etc.)		components has been included in Project cost	
		Moderate		Increased risk of bridge scour arising from flood events	4	3	12	Bridge scour protection programmes	3 to 4		
		Minor	Flooding	• Infrastructure slope failure; track mis-alignment; mis-alignment of poles supporting overhead lines; • Reduced operating speeds	2	5	10	• Increase capacity of spillways and culverts. Embankment protection through tree plantings, Vegetation. Improvement of longitudinal ditches and drains • Green planning; • Increasing height of Station Entrances. • Increase road embankment level to at least 0.5 m over the maximum flood level	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost.	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
		Minor		• Voluminous Mud flow causing structural damage to infrastructure. • Reduced operating speeds	2	5	10	• Installation of containment channels and dikes, Revetments using riprap, gabion mattresses and concrete facings; • Anchors, geo -grids and micro -piles	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
		Moderate		• Failure of other structure supports due to increased risk of scour Standing water fouling track ballast; • Reduced operating speeds	3	4	12	• Expanding drainage capacity, Discharge Capacity for infrastructure including culvert size, design for new flood event thresholds, • Increasing maintenance including clearing debris from culverts to reduce flooding Installation of emergency culvert etc., Installation of pumped drainage solutions. • Double twisted hexagonal woven steel wire mesh	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
2	**Temperature**										

A	High Temperature	Medium	Heat waves; wildfire (very rare)	• Track buckling line closure; thermal expansion in structures and / or associated misalignment problems. • Track stability may be affected. • Disposition of high-risk track segments may lead to incidences of high temperatures • Reduced operating Speeds.	3	4	12	**Construction Measures:** • Change Rail installation procedure to increase temperature threshold for thermal expansion. • During extreme winter and summer, ambient temperature should be monitored and necessary steps shall be taken to cold/hot weather concreting as applicable. • Using measures such as preventive grinding and milling to minimize the effects of temperature variation. • Measures during Concreting in Hot Weather: **DOs:** • Depute competent inspection personnel at site to anticipate the need for requirements during hot weather concreting and ensure them. • When temperature conditions are critical, carry out concreting during evening or night. • If ambient temperature is likely to exceed 40oC during period of concreting, start concreting only if arrangements for hot weather concreting are in place. • Plan the locations of construction joints ahead of time with hot weather contingencies in mind. • Do not add water to pre-mixed concrete at the job site unless it is part of the amount required initially for the specified maximum water-cement ratio and the specified slump.	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro

								• Use all available means to maintain the materials at as low temperatures as practicable. • Provide shades on stockpiles to protect them from direct rays of the sun. • Sprinkle water on the coarse aggregate piles & apply moisture correction accordingly. • Use cold water in concrete and keep it cold by protecting pipes, water storage tanks, etc. • Mix ice directly into the concrete as part of the mixing water. • Design the mix with minimum cement content consistent with other functional requirements • Use lower heat of hydration cements instead of that with greater fineness and high heat of hydration. • Check concrete temperature frequently using a metal clad thermometer by embedding it in concrete. • Keep the mixing time to the minimum as required to ensure adequate quality and uniformity. • Paint the exposed mixer surface yellow or white, cover it with hessian cloth and spray cool water. • Keep the period between mixing and delivery to an absolute minimum. • Coordinate the delivery of concrete with the rate of placement to avoid delays in delivery.			

								• Sprinkle forms, reinforcement, and subgrade with cool water just prior to placement of concrete. • Wet the area around the work to cool the surrounding air and increase its humidity. • Deploy ample personnel to place concrete immediately on delivery to minimise the delay losses. • Place concrete in thin layers and small areas to reduce time interval between consecutive placements. • Moist fresh the concrete by means of fog sprays, wet hessian cloth, cotton mats, or other means if cold joints or cracks tend to form, especially shortly after placement and before finishing. • Protect the concrete from evaporation of moisture, preventing ingress of external water, by means of wet (not dripping) gunny bags, hessian cloth, etc., immediately after consolidation and surface finish. • Commence the moist curing once the concrete has attained some degree of hardening sufficient to withstand surface damage (approximately 12 hours after mixing). • Sprinkle water on formed surface while forms are still in place. Keep the vertical and steeply sloping formed surfaces moist by applying water to the			

								top surfaces prior to and during form removal. • • Keep the exposed surfaces moist by wet curing & Provide wind breaker wherever possible. • Spray the covering material with water to keep them soaked. • Heavily reinforced area should be given special attention. **DON'Ts:** • Use such large chunks of ice that do not melt down completely before mixing is completed. • Use concrete if its temperature is above 40ºC. • Rely on the protection afforded by forms for curing in hot weather. • In initial stages of hardening, temp of curing water should be approximately equal to that of concrete. • Remove wet covers until they are completely dry. • Delay in finishing air entrained concrete in hot weather. • Let the concrete surface dry during curing causing alternate drying and wetting conditions. • Prolong mixing. • Finish slabs prematurely, e.g. while bleed water is still on the surface. **Operation Phase Measures:** • Change Rail installation procedure to increase temperature threshold for thermal expansion.				

								Replacement of jointed track with continuously welded Rail. • Painting Rails white in areas of known high risk to thermal expansion by direct sunlight. • Regular monitoring during summer season at extreme temperatures. • Review and update Asset Risk Assessment and Action Plan in line with implementation timetable with identification of standards to be updated to take account of climate change • To overcome the same, provision of thermal joint/ expansion joint is required to be provided. • Eventually, sensors may be installed directly on the tracks to monitor rail stresses in real time and implement an early warning system.			
		Minor		• Expansion of moveable assets such as swing bridges hindering operation. • Reduced operating speeds	2	4	8	• Sprinkler systems • Replacement of bridges with heat resistant materials with lower thermal expansion coefficients	1 to 2	Adaptation measures are embedded in Project design/Construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
		Low		• General increase in failure rate of assets in high temperatures. • Reduced operating speeds	3	2	6	• Use of coolers, fans and air conditioning to improve tolerance of signalling equipment. • Double-skinned equipment casings to assist cooling	1 to 2	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro

										been included in Project cost	
		Low		• Sagging of the overhead line equipment • Reduced operating speeds	2	3	6	• Removal of fixed termination overhead line equipment • Improved balance weight and head span technologies • Provision of Counter weights	1 to 2	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
		Low		• Increased fire risk. • Reduced operating speeds	2	4	8	Vegetation management along tracks	1 to 2	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
B	Low Temperatures	Low	-	• Rail-fracture, weld-failure, cracks and / or associated misalignment problems. • Reduced operating speeds	1	2	2	• Proper Supervisions and Inspections • Only ornamental trees will be planted at embankments, slope (if any), etc.	1	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro GC
3	**High Wind Speeds**										
	Wind Storms	Moderate	Tree fall; wind-blown objects; Severity of gusts at higher wind location	• Increased risk of leaf fall leading to low track adhesion • Rolling stock instability	3	4	12	• Leaf Removal and partly de - vegetation programmes. • During Operation & Maintenance Stage, periodic cleaning will be carried out.	3 to 4	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro

										been included in Project cost.	
		Moderate	Tree fall; wind-blown objects	• Damaged trees and debris falling onto track • Downed power lines; structural damage and / or track mis-alignment by fallen trees / wind-blown objects. • Reduced operating speeds	3	4	12	De-vegetation programmes; Establishment of tree-free zones in the metro rail corridor and control measures to avoid debris falling.	3 to 4	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
		Moderate		• Increased risk of damage to bridges in high winds. • Equipment destruction • Reduced operating speeds	2	5	10	• Install damping devices	1 to 2	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
		Major		• Excessive wind loading on structures such as masts and towers. • Reduced operating speeds	3	5	15	• Strengthening of existing equipment, build in resilience to design of new equipment. • Improved overhead wire tensioning systems.	3 to 4	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro
4	**Lightning and electrical storms**										
	Lightning and electrical storms	Minor	• Risk to line workers • Outages of power	Damage to buildings and structures from lightning strikes	2	4	8	• Install lightning conductors / arresters. • Fitment of surge protection.	1 to 2	Adaptation measures are embedded in Project design/construction Practices and cost of the respective components has been included in Project cost	Construction- EPC Contractor / Maha-Metro and GC Operation / Maha-Metro

Adaptation of Early Warning System in Climate Change Risk Management

An Early Warning System (EWS) is a comprehensive, adaptive framework for monitoring, forecasting, and predicting climate-related hazards, combined with disaster risk assessment, communication, and preparedness activities. It enables timely actions by individuals, communities, authorities, and businesses to reduce disaster risks before hazardous events occur. The effectiveness of EWS depends on its inclusivity and sensitivity to the socio-economic vulnerabilities of the populations exposed to these hazards.

Key components of an EWS include detection, analysis, prediction, warning dissemination, and coordinated response decision-making and implementation. These operate within phases of risk assessment, continuous monitoring, communication of warnings, and emergency response.

For the PMRP Phase 1 extension, the Early Warning Centre (EWC) will utilize real-time climate and seismic data from sources such as the Indian Meteorological Department (IMD) and national seismic networks. By identifying early warning signals indicating spatial or temporal changes approaching critical thresholds, the system helps trigger corrective actions to maintain system stability and safety.

The EWS integrates advanced communication technologies to ensure rapid dissemination of alerts through Emergency Broadcast/Alert Systems (EBS/EAS), supporting community preparedness and enabling swift response to extreme climate events. Effective implementation of EWS will help safeguard passengers, staff, infrastructure, and operations, contributing to the overall climate resilience of the metro system.

A robust Early Warning System not only saves lives and protects infrastructure but also supports sustainable urban mobility by minimizing service disruptions and economic losses. It empowers public officials and operators with actionable intelligence for proactive planning and emergency management, aligning with best practices for climate-resilient urban transport infrastructure.

The four key Multi-Hazard Early Warning Systems (MHEWS) required to be managed in PMRP Phase 1 extension project corridors by GC / Maha-Metro, during Disaster Management are as follows:

- *Disaster risk knowledge and management:* aims to collect data and undertake risk assessments to increase knowledge on hazards and vulnerabilities and trends.
- *Detection, observations, monitoring, analysis and forecasting of hazards:* Develop hazard monitoring and early warning services.
- *Dissemination and communication:* Communicate risk information so it reaches all those who need it, and is understandable and usable.
- *Preparedness and response:* Building regional and community response capabilities. It helps reducing harm to people and damage to assets ahead of impending hazards, including storms, floods, tsunamis, droughts and heat waves, etc. Multi-hazard early warning systems address several hazards that may occur alone or simultaneously.

It helps reduce harm to people and damage to assets by providing advance warnings of impending hazards such as storms, floods, droughts, heat waves, and other extreme weather events. Multi-hazard early warning systems are designed to address multiple hazards that may occur individually or simultaneously. For the PMRP Phase 1 extension, the Environmental and Social Management Unit of Maha-Metro will be responsible for implementing and managing the Early Warning System to effectively mitigate climate-related risks.

11.4. Mitigation Measures to Reduce GHG Emissions

11.4.1. Construction Phase Mitigation Measures

Construction phase mitigation measures are essential to reduce CO_2 emissions. The adverse impacts of greenhouse gas (GHG) emissions from the construction of the PMRP Phase 1 extension alignments are addressed through a hierarchy of avoidance, mitigation, and offsetting. These measures are integrated wherever possible during planning, design, and through the implementation of standard construction practices.

A. Reduction and Avoidance

Implementation of vehicle operating guidelines to encourage correct and efficient operation of vehicles includes as follows:

- The implementation of a traffic management plan, that:

  - Reduces the number of vehicles and/or trips required for transport;
  - Uses buses for transportation of large numbers of personnel to minimise number of vehicles operating
- Implementation of a wider fuel management strategy which encourages use of more efficient plants and vehicles, planning, logistics, driver education and maintenance;
- Efficient management of procurement and product supply
- Reduction on the amount of waste disposed to landfill and reuse of waste on site as much as possible, which will subsequently reduce the amount of vehicle movements and therefore fuel usage
- Use of teleconferencing and video conferencing to reduce travel to and from offices and associated gaseous emissions from fuel combustion
- GHG emissions and energy consumption will be measured in accordance with current legislative requirements
- Fuel consumption, energy use and GHG emissions will form part of reporting requirements to GC / Maha-Metro
- GHG emissions and energy consumption will be reported to relevant authorities in accordance with current legislative requirements
- A more comprehensive GHG emissions inventory will be addressed by the Contractor with approval by Environmental Specialist of General Consultant (GC) prior to construction that provides greater detail on construction emissions.

The next step will be to set achievable and realistic reduction targets and identify and investigate potential reduction opportunities to realise these targets. Activities such as vegetation clearing will be restricted to the required footprint only through the implementation of the EMP which will identify clearing limits. While fuel usage is a necessary requirement for construction of the project, so far as to reduce GHG emissions the following measures will be implemented as far as practicable:

- Adopting vehicle pooling for transport of construction personnel to minimise the number of vehicles operating
- Procurement of generators which use biodiesel or natural gas, where possible

B. Mitigation

On 10.08.2015, Government allowed direct sale of Biodiesel (B100) for blending with diesel to Bulk Consumers such as Railways, State Road Transport Corporations. On 29.06.2017 Government allowed sale of biodiesel to all consumers for blending with diesel. India's Ministry of Petroleum and Natural Gas (MoPNG) published its “National Policy on Biofuels" in 2018, and further amended it in June 2022. The policy's objective is to reduce the import of petroleum products by fostering domestic biofuel production as per (MoPNG, GoI Guidelines, 2018).

Biodiesel blends (diesel that has a percentage of the fuel replaced with biodiesel) may reduce greenhouse gas emissions due to fuel consumption. However, this is dependent on a number of factors including the origin of the biodiesel feedstock. When sourced from appropriate feed-stocks, the reduction in emissions is approximately equivalent to the percentage of biodiesel in the blend (for example diesel with 20 per cent biodiesel will reduce greenhouse gas emissions by approximately 20 per cent). Opportunities for the use of biodiesel will be further examined and used where possible on the PMRP Phase 1 extensions project.

The application of technical efficiencies in construction plant and equipment will also provide more efficiency. These options will be further investigated, including any new technologies available, expected benefits, potential risks and costs. Through the EMAP, appropriate management will be integrated into all construction activities and processes and GHG emissions will be monitored. Through assessment and review, the PMRP Phase 1 extensions project will seek continuous improvement in compliance and emissions reduction.

C. Energy Efficiency and Management

Given that energy is the largest source of GHG emissions, appropriate mitigation measures will be implemented to reduce energy use as far as practicable through the following:

- Identification of the significant energy consuming equipment and recognising opportunities where technical efficiencies in plant and equipment can be applied. To improve fuel efficiency, an understanding of energy uses and corresponding fuel consumption would help Maha-Metro to identify further opportunities where reduction in sources is most feasible and effective

- Site offices and accommodation buildings will be designed and constructed so as to include energy and water efficient equipment
- Implementation of a Construction EMP which establishes the baseline water, materials and energy use objectives and targets with the aim of introducing resources and emissions reductions targets through the construction phase
- The EMP will set out appropriate management and encourage integration of key activities and processes so as to effectively monitor GHG emissions

Implementation of mitigation measures such as resource efficiency, adoption of less carbon-intensive or renewable energy sources to reduce fugitive emissions will be followed as per the EMP to save CO_2 emissions.

D. Offset Measures

The feasibility of generating carbon offsets for the construction of the PMRP Phase 1 extensions project in accordance with the Carbon Farming Initiative is recommended to be investigated by GC / Maha-Metro. The feasibility study would need to consider legislative and development approval requirements in assessing whether the potential carbon offset projects comply with the additional requirements of the Carbon Farming Initiative. There is need to consider Offsetting additional GHG emissions through the purchase of carbon offsets generated in India or overseas, while assessing the PMRP Phase 1 extensions project liability under the carbon pricing mechanism.

11.4.2. Operation Phase Mitigation Measures

The PMRP Phase 1 extension project involves the operation of electrically powered metro trains, resulting in zero direct CO_2 emissions during train operations. As with similar electric transit systems, any indirect emissions primarily originate from electricity generation at the source. The anticipated CO_2 emission savings due to project implementation are summarized in **Table 12**.

Operational greenhouse gas (GHG) emissions are expected to be negligible. Energy-efficient systems, along with solid waste and wastewater recycling measures, will be implemented at stations and depots. Energy-efficient lighting and ventilation systems will also be installed at stations, depots, and in metro cars. Looking ahead, the project may transition to fully harness renewable energy sources such as solar power for lighting, ventilation, and other station and depot operations, further reducing CO_2 emissions during the maintenance phase.

Additionally, the use of energy-efficient construction equipment and practices during the construction phase will contribute to improved operational efficiency, reducing potential risks, costs, and environmental impacts.

11.4.3. Mitigation Measures to overcome Risks on Biodiversity

Climate change, driven by both natural factors and human activities, significantly impacts biodiversity, agricultural productivity, and food security. Species with narrow ecological ranges and endemic populations are particularly vulnerable to extinction. This is a major concern since biodiversity underpins ecosystem services essential for food production, health care, and overall ecological balance. The interconnection between climate change, biodiversity, and food security is well established. Studies show that many species are shifting their geographic ranges to higher elevations and latitudes at median rates of approximately 11 m vertically and 16.9 km horizontally per decade in response to changing climatic conditions. Species' ability to survive depends on their capacity for migration, adaptation, or phenotypic plasticity—temporary biological adjustments that may buffer short-term climatic stresses but may not prevent long-term decline.

Climate change also threatens food security, especially in regions reliant on rain-fed agriculture, where crops face physiological limits to withstand heat, drought, and other stresses. While expanding agricultural land or exploiting new fish stocks might appear as solutions, these approaches often come at the expense of biodiversity conservation and carry high social and environmental costs.

Mitigating biodiversity loss and supporting food security under climate change requires integrated approaches, including:

- Reducing food waste and enhancing food distribution to vulnerable populations,
- Conserving biodiversity through protection of natural habitats and genetic resources,

- Incorporating traditional ecological knowledge in management practices,
- Promoting restoration of degraded lands and sustainable land use planning,
- Supporting community-based biodiversity conservation initiatives,
- Implementing sustainable forest management and bioenergy use.

For the PMRP Phase 1 extension project, it is recommended that biodiversity considerations be integrated into environmental management plans, including habitat preservation measures during construction and operation, monitoring of local flora and fauna, and minimizing disturbance to sensitive areas to mitigate climate-related risks to biodiversity.

11.4.4. Awareness on Climate Change Adaptation and Mitigation Measures

Awareness of climate change and related adaptation measures is a critical factor in effectively managing climate risks. A lack of awareness among personnel involved in the operation and maintenance of the PMRP Phase 1 extension, as well as the general public, can hinder the successful implementation of adaptation strategies. Therefore, dedicated training programs and workshops focused on climate change awareness, adaptation best practices, and mitigation measures for the PMRP staff are essential. These programs will equip operational teams with the knowledge needed to recognize climate-related risks and integrate adaptive responses into daily activities.

Public awareness initiatives are equally important to foster community understanding of climate impacts, promote support for adaptation policies, and encourage proactive behaviour in mitigating climate risks. Target groups for these awareness efforts include government officials, local authorities, project staff, and the public living along the metro corridors. Such awareness-building measures will support the broader objective of enhancing climate resilience throughout the project lifecycle.

11.4.5. Assessment of CO2 Increase and O2 Deficit with Carbon Credits and Mitigation

Trees play a significant role in reducing atmospheric CO_2 by sequestering it during photosynthesis, converting it into carbohydrates essential for plant growth, and releasing oxygen (O_2) as a by-product. Since roughly half of the greenhouse effect is attributed to CO_2, trees serve as important carbon sinks that help mitigate climate change. For the PMRP Phase 1 extension project, the removal of trees along the alignments will impact this natural CO_2 absorption process. The estimated loss in CO_2 sequestration and oxygen production due to tree cutting is summarized in **Table 15**. Although most of the affected trees will be tried to be transplanted wherever possible, some loss remains inevitable.

Table 15: Assessment of CO2 increase and Oxygen Deficit due to Tree Loss

Sl	Description	Quantities
1	Total no. of Trees to be cut along both the alignments (PCMC to Nigdi and Swargate to Katraj)	258 + 175 = **433 trees**
2	Increase in CO2 in the atmosphere (or decrease in CO2 absorption by tree) @ ~22 Kg/year/tree	9526kg or **9.53 tons/year**
3	Decrease in Oxygen production @ ~100 Kg/year/ tree	43300 kg or **43.3 ton/year**

Mitigation Measures:

The removal of 433 trees along the PMRP Phase 1 extension corridors (PCMC to Nigdi and Swargate to Katraj) will result in a measurable loss in the ecosystem's ability to sequester carbon dioxide and produce oxygen. Based on estimates, the annual increase in atmospheric CO_2 due to this tree removal is approximately 9.53 tons, which corresponds to a loss of 9.53 Carbon Credits per year. As of 2025, the Clean Development Mechanism (CDM) price for one Carbon Credit is about €76.88, and with the current exchange rate of ₹93.23 per Euro, this equates to a financial loss of roughly €732.94 or ₹68,339.84 annually. In addition to this, the removal of these trees will lead to a decrease in oxygen production by approximately 43.3 tons per year. Valuing oxygen at ₹60,000 per ton, this loss translates to about ₹25,98,000 annually. This reduction not only affects the project's carbon balance but also has implications for local air quality and overall environmental health, emphasizing the importance of addressing these impacts as part of the project's environmental management.

To offset these impacts, the project proposes compensatory afforestation with a target planting ratio of 1:10, aiming to plant approximately 4,330 trees in consultation with relevant forest authorities and in alignment with CAMPA guidelines. Assuming a 90% survival rate, it is expected that around 3,897 trees will reach maturity within five years. These mature trees have the potential to sequester approximately 85.7 tons of CO_2 annually, which would generate about 85.7 Carbon Credits per year. At current rates, this equates to a financial value of approximately €6,593.62 or ₹6,14,976 (₹0.62 million) annually, thereby substantially mitigating the carbon loss caused by tree cutting. Furthermore, the oxygen production from these trees is estimated to increase by around 389.7 tons per year, valued at approximately ₹2,33,82,000 or ₹23.38 million annually. Through such afforestation efforts, the project will not only compensate for the biological and ecological impacts of tree loss but will also contribute positively to climate change mitigation and support local biodiversity conservation. These financial values are based on current 2025 market conditions and exchange rates, and they serve as an important benchmark for planning and monitoring the effectiveness of mitigation measures.

Residual Impacts & Measures

The project will result in the loss of 433 trees, reducing CO_2 absorption by about 9.53 tons and oxygen production by 43.3 tons annually during operation. Although electric trains minimize direct emissions, this tree loss impacts local carbon and oxygen cycles. To compensate, afforestation of 4330 trees will be carried out (at a 1:10 ratio) in consultation with the Forest Department. Over five years, the planted trees are expected to offset the initial loss by significantly increasing CO_2 sequestration and oxygen production, gradually mitigating the residual environmental impacts. Regular monitoring will ensure successful growth and ecological recovery.

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11.5. Adaptation measures to mitigate the health impact on Vulnerable Community

While climate change adaptation has gained attention, the effectiveness of targeted strategies to strengthen public health resilience remains underexplored, particularly for vulnerable urban populations near infrastructure projects like the Pune Metro Rail Project (PMRP) Phase 1 extensions. Adaptation to climate impacts occurs across physiological, behavioural, social, institutional, and organizational levels. For effective public health responses—especially for marginalized communities with limited healthcare access in urban and peri-urban areas—it is essential to develop a baseline understanding of local demographic, social, and environmental health determinants. Key considerations include the population's age distribution, socioeconomic status, baseline incidence of climate-sensitive diseases, public risk awareness, urban built environment, existing health infrastructure, and community-level autonomous responses to health impacts.

Adaptation measures addressing climate change health impacts on vulnerable groups within the project influence zone can be implemented at three levels:

- ***Primary level:*** Prevention strategies such as reducing mosquito breeding sites, promoting hygiene, and preventing disease spread.
- ***Secondary level:*** Surveillance and early detection through monitoring health indicators and environmental risk factors.
- ***Tertiary level:*** Ensuring access to effective medical treatment and healthcare services to mitigate disease severity.

In the context of PMRP, adaptation strategies should focus on controlling vector-borne diseases like dengue and chikungunya by eliminating stagnant water bodies at construction sites and nearby settlements. Enhancing sanitation and ensuring safe drinking water supply through improved water treatment, rainwater harvesting, and wastewater reuse will be crucial to prevent waterborne diseases. Given Pune's vulnerability to flooding and heat waves, emergency preparedness plans including early warning systems, heat action plans, and community awareness campaigns are essential to safeguard displaced and vulnerable populations.

Developing integrated health surveillance and early warning systems linked with meteorological and environmental data will support timely public health interventions. Understanding the relationship between climate variability and infectious diseases, as well as chronic illnesses aggravated by air pollution and heat stress, will guide proactive health measures. Climate modelling tailored for the Pune region, combined with spatial risk assessments, will help local authorities and health services anticipate emerging threats and prioritize resource allocation.

Furthermore, adaptation measures must be context-specific, addressing the spatial and temporal scales relevant to Pune's urban environment and the project corridors (PCMC to Nigdi and Swargate to Katraj). Strengthening community engagement, especially with vulnerable groups, and integrating government and non-governmental efforts will enhance resilience. Initiatives promoting equitable education, empowerment of women, improved sanitation, and healthcare access will support broader climate adaptation goals. Failure to invest in such adaptation now risks amplifying health impacts and economic costs in the future.

11.5.1. Environmental monitoring and surveillance

There is a critical need to enhance environmental monitoring and surveillance systems in Pune to effectively control and adapt to climate change impacts related to the Pune Metro Rail Project. New initiatives should focus on gathering high-quality, long-term data on climate-sensitive health outcomes, aiming both to understand existing climate-health relationships and to predict future scenarios. This includes comprehensive public health monitoring of total morbidity and mortality, non-communicable diseases like cardiovascular, respiratory, and asthma-related illnesses, as well as communicable diseases such as dengue, malaria, chikungunya, tuberculosis, typhoid, hepatitis, and other vector-borne and waterborne diseases. Alongside health data, relevant climatic variables like temperature, precipitation, and air pollution indicators must be recorded. Surveillance of extreme weather events and risk indicators such as mosquito population dynamics or pathogen prevalence is also essential. To enable effective analysis and response, creating integrated and accessible databases linking meteorological, environmental, and health data is necessary. Such systems will facilitate timely preventive and corrective actions to mitigate climate-related health burdens on local public health infrastructure and communities.

11.5.2. Geospatial technology

Geographic Information Systems (GIS) and spatial analysis are critical tools that must be further developed and utilized in Pune for conducting vulnerability assessments, mapping environmental exposures, prioritizing research, and communicating findings to policymakers and the public. Remote sensing and environmental monitoring technologies are particularly useful in cataloguing variables such as air pollution levels, urban heat islands, and vegetation cover changes resulting from metro construction activities. Integrating social data from census and surveys with environmental exposure layers provides insights into community-level sensitivity and adaptive capacity. Furthermore, land use and land cover data contribute additional context on environmental factors influencing risks and vulnerabilities. These geospatial tools support targeted interventions, enabling more precise identification of high-risk areas and vulnerable populations affected by climate variability and urban development.

11.5.3. Human and technical capacity

To implement effective surveillance and analytical methods addressing climate-related health risks in Pune, building human and technical capacity across public health and municipal sectors is essential. This includes educating the public about climate change impacts on health, promoting behavioural changes, and enhancing awareness through a mix of low-tech (flyers, community meetings) and high-tech (mobile alerts, web platforms) communication tools. Capacity building also involves developing localized climate action plans and early warning systems tailored to heatwaves, vector-borne disease outbreaks, droughts, and floods relevant to the metro area. Multidisciplinary research using environmental epidemiology will help elucidate health risks from climate variability, requiring partnerships among researchers, government agencies, and communities. Such collaborations will enable the design and implementation of co-benefit strategies addressing public health challenges linked to climate change, thereby improving preparedness, resilience, and adaptive capacity in vulnerable urban populations.

11.6. Barriers and Gaps in Implementation of Adaptation Actions

The Government of Maharashtra has formulated and implemented various policies and programs to support sustainable development and infrastructure projects in the state, including the Metro Rail projects. However, despite these efforts, there are certain gaps in information and barriers that hinder the achievement of the full potential of these policies and programs in the transport sector. A few such barriers are outlined below:

- Increased frequency and intensity of extreme weather events, such as floods, affecting project implementation and infrastructure resilience.
- Delays due to litigations, land acquisition issues, compensation disputes with landowners and farmers, and administrative lapses.
- Delays resulting from inadequate funding, infrastructure constraints, knowledge gaps, and lack of awareness among stakeholders, including government agencies, local communities, and NGOs.
- Implementation challenges due to unfamiliarity with existing laws, rules, and regulations, institutional capacity constraints, and coordination issues among various stakeholders.
- Technical issues, such as inaccurate geological surveys or faulty design, leading to project delays or infrastructure failures, like issues with tunnel boring or construction.

12. Transition Climate Risks and Adaptation

Maha-Metro faces transition climate risks associated with the pace and extent of adapting to a low-carbon economy, driven by policy, technology, and market changes aimed at reducing greenhouse gas emissions and transitioning to renewable energy. These risks can have varying levels of financial and reputational impacts on the organization. However, as a low-carbon emitting entity, Maha-Metro can also capitalize on market, technological, and reputational opportunities in the renewable energy and climate transition market.

The transition to a low-carbon economy requires significant changes, and the associated risks can be substantial. Climate change poses one of the most significant risks to organizations today, with potential damaging economic and social consequences. By understanding and managing these risks, Maha-Metro can ensure long-term sustainability and resilience. Key considerations for managing transition climate risks include improving data collection on failures, integrating climate change into asset management plans, and developing adaptation strategies that involve users. Given its low-carbon profile, Maha-Metro is poised to leverage opportunities rather than face significant risks from the transition to a lower-carbon economy, supporting its focus on climate change mitigation and adaptation solutions. Climate-related transition risks with opportunities and financial impacts are depicted in **Figure 13**, and a detailed breakdown of these risks and their financial implications can be found in **Table 16**.

Figure 13: Climate-Related Risks, Opportunities, and Financial Impact[10]

Table 16: Climate-Related Transition Risks and Financial Impacts[11]

Climate-related Transition Risks	Potential Financial Impacts	Applicability to PMRP Phase 1 Extension Project
	Policy and Legal	
• Increased pricing of GHG emissions • Enhanced emissions reporting obligations • Mandates on and regulation of existing services • Exposure to litigation	• Increased operating costs (e.g., higher compliance costs, increased insurance premiums) • Write-offs, asset impairment, and early retirement of existing assets due to policy changes • Increased costs and/or reduced demand for services resulting from fines or judgement	Significantly
	Technology	
• Substitution of existing services with lower emission options • Unsuccessful investment in new technologies • Costs to transition to lower emissions technology	• Write-offs and early retirement of existing assets • Reduced demand for services • Research and development expenditures in new and alternative technologies • Capital investments in technology development • Costs to adopt / deploy new practices and processes	Significantly
	Market	
• Changing commuter behaviour • Uncertainty in market signals • Increased cost of raw materials	• Reduced demand for goods and services due to shift in commuter preferences • Increased service costs due to changing input prices (e.g., energy, water) and output requirements (e.g., waste treatment) • Abrupt and unexpected shifts in energy costs • Change in revenue mix and sources, resulting in decreased revenues • Re-pricing of assets (e.g., energy reserves, land valuations, securities valuations)	Significantly
	Reputation	
• Shifts in commuter preferences • Stigmatization of sector	• Reduced revenue from decreased demand for services	Significantly

[10] *Source: Recommendations of the Task Force on Climate-related Financial Disclosures, 2017*
[11] *Source: Recommendations of the Task Force on Climate-related Financial Disclosures, 2017*

• Increased stakeholder concern or negative stakeholder feedback	• Reduced revenue from decreased production capacity (e.g., delayed planning approvals, supply chain interruptions) • Reduced revenue from negative impacts on workforce management and planning (e.g., employee attraction and retention) • Reduction in capital availability	

The following points related to transition climate risks are derived from research (Irina Stipanovic Oslakovic, et al., 2013):

- Improving data collection about failures is necessary, and the data should be structured to facilitate effective analysis.
- Considering broader effects beyond local impacts is crucial, as failures can have cascading effects on other components and long-term consequences.
- Consistent information about costs, delays, and safety is essential for informed decision-making.
- The database should be designed with a clear objective, such as developing maintenance and adaptation measures.
- Infrastructure managers require quick access to historical data to make informed decisions.
- Better integration of climate change considerations into current asset management plans is necessary.
- Adaptation strategies should involve changing users' mindsets to support successful implementation.

The primary objective is to support infrastructure development organizations in making informed decisions about intervention strategies and measures that ensure the development of climate-resilient infrastructure. Climate-related risks and the ongoing transition to a lower-carbon economy have far-reaching implications for various economic sectors and industries. For the PMRP Phase 1 Extension Project, Maha-Metro's existing low-carbon profile positions it well to capitalize on opportunities arising from this transition, rather than facing significant risks. By prioritizing climate change mitigation and adaptation solutions, Maha-Metro can leverage emerging opportunities, enhance its sustainability credentials, and contribute to a more environmentally conscious transportation system.

13. Economic Benefits of adopting Climate Change adaptation measures

he adoption of climate change adaptation measures for PMRP will yield significant economic benefits, primarily through the development of climate-resilient metro rail infrastructure and operations. This will ensure the continuity of transport network connectivity, with positive implications for economic prosperity and welfare. By investing in adaptation measures, PMRP can minimize the economic losses associated with climate-related disruptions, while also contributing to sustainable development and climate change mitigation.

The economic benefits of adaptation measures will be further enhanced by the potential co-benefits beyond the environmental field, such as structural protection measures that safeguard not only the railway track but also nearby settlements, roads, and energy supply infrastructure. This can lead to reduced damage and repair costs, as well as minimized disruptions to economic activity. The costs associated with adaptation measures will vary based on the type and design of measures, scale of implementation, local conditions, and climate challenges addressed. While Maha-Metro will primarily bear the costs, potential co-financing from public budgets, external funding sources, or other instruments can help to offset the financial burden. By adopting a proactive and adaptive approach to climate change, PMRP can ensure the long-term economic viability and sustainability of the metro rail system.

14. Summary and Conclusions

The Climate Risk and Vulnerability Assessment (CRVA) for the Pune Metro Rail Project – Phase 1 Extensions (PCMC to Nigdi and Swargate to Katraj corridors) was undertaken to evaluate the likely impacts of climate change on the metro infrastructure, operations, and surrounding urban environment. The study emphasizes the importance of integrating climate resilience into metro design, construction, and long-term operations, especially in light of Pune's changing climate patterns and rapid urban growth.

Pune is increasingly experiencing the effects of climate variability, with evidence of:

- Rising average and peak temperatures, leading to more frequent and intense heatwaves;
- Increased unpredictability and intensity of monsoon rainfall, often resulting in localized urban flooding;
- Reduced green cover and shrinking natural drainage systems due to urban development;
- Growing public health risks, including heat-related illnesses and vector-borne diseases.

14.1. Key Findings

Key findings of the CRVA report are summarized below:

- **Temperature Rise & Heat Stress:**
    - The region has seen a steady increase in both maximum and minimum temperatures. Heat stress impacts are particularly relevant for elevated tracks and structures, where thermal expansion can lead to deformation of rails and viaduct stress.
    - Passenger safety and comfort may also be affected, especially if adequate ventilation and cooling systems are not in place.
- **Rainfall Variability & Urban Flooding:**
    - Rainfall has become more erratic, with an increase in short-duration, high-intensity events that challenge drainage infrastructure.
    - The Swargate to Katraj underground section is especially vulnerable to flooding risks, requiring robust waterproofing and dewatering systems.
- **Sensitivity of Metro Assets:**
    - Elevated viaducts, tunnels, track systems, and power supply equipment are all sensitive to climate-related stress.
    - Underground stations may face water ingress, while elevated corridors could experience stormwater runoff issues that affect nearby urban roads and systems.
- **Greenhouse Gas (GHG) Emissions:**
    - Construction activities (e.g., fuel use, equipment emissions, and tree loss) will result in temporary GHG emissions, estimated at over 1,200 tonnes CO_2e.
    - However, the operational phase will lead to substantial **GHG reductions** due to modal shift—estimated to reach ~21,900 tonnes/year by 2041.
- **Biodiversity and Ecosystem Services:**
    - Tree felling and loss of green spaces will reduce carbon sequestration and oxygen generation. While compensatory afforestation is planned, long-term ecosystem recovery takes time.
    - Natural drainage paths and soil permeability are reduced due to infrastructure footprint, increasing runoff and erosion risks.
- **Public Health Impacts:**
    - Rising temperatures and water stagnation heighten the risks of heat-related illnesses and mosquito-borne diseases such as dengue and chikungunya.
    - Vulnerable populations such as children, the elderly, and low-income groups face higher exposure and limited adaptive capacity.

14.2. Recommended Adaptation Measures:

The CRVA recommends integrating the following measures to improve the project's resilience:

- Design infrastructure components (viaducts, bridges, tunnels) with climate tolerances for heat, rainfall, and flood exposure;
- Incorporate efficient drainage and pumping systems, especially in low-lying or underground segments;
- Use climate-resilient materials and allow for thermal expansion in track design;
- Establish a maintenance and monitoring framework for early warning and climate response;
- Include passive cooling and mechanical ventilation systems in stations to ensure commuter comfort;
- Implement urban greening and rainwater management to offset environmental footprint;
- Plan for resilient power backup and signalling systems to avoid service interruptions.

- Adaptation measures (refer table -14) have been embedded in the project's design, construction practices, and material specifications as per applicable codes and standards (e.g., IS 875, IRS, MoHUA norms) and cost of the respective components are included in the Project cost.

14.3. Conclusion:

The Pune Metro Rail Project – Phase 1 Extensions represent a major step toward building sustainable urban transport infrastructure. While the system offers long-term environmental benefits through reduced vehicular emissions and improved mobility, the infrastructure must also be prepared to withstand climate-related challenges. The CRVA confirms that the project faces moderate overall climate risk, particularly from extreme rainfall, urban flooding, and heatwaves which can be effectively mitigated through proactive adaptation measures already considered in the planning and design of the project.

By and large adaptation measures address the risks through project's design, standards, and construction methodologies—ensuring a baseline level of resilience without requiring additional costs.

By integrating climate resilience, the PMRP can serve as a model for future infrastructure development in Indian cities—balancing environmental sustainability with safe, efficient, and reliable public transport systems.