Role of treated wastewater in mitigating urbanization impacts and maintaining regulatory ecosystem services

都市化の影響を緩和し、規制生態系サービスを維持する上での処理済み廃水の役割

Ph D Thesis Submitted by
Manish Ramaiah
マニシュ ラマイア

Ph D Supervisor
Dr. Ram Avtar

Division of Environmental Science Development,
Graduate School of Environmental Science,
Hokkaido University, Sapporo, Japan

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By

Manish Ramaiah

M.Sc. (IPADS), University of Tokyo, JAPAN

Ph D COMMITTEE MEMBERS

Assistant Prof. Ram Avtar (Hokkaido University, Japan)

Prof. Teiji Watanabe (Hokkaido University, Japan)

Prof. Tatsufumi Okino (Hokkaido University, Japan)

Prof. Masaaki Kurasaki (Hokkaido University, Japan)

Prof. Masahiko Fujii (Hokkaido University, Japan)

Dr. Pankaj Kumar, Institute for Global Environmental Strategies, Japan

Dr. Sohail Ahmad, University of Glasgow, United Kingdom

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北海道大学
HOKKAIDO UNIVERSITY

Division of Environmental Science Development
Graduate School of Environmental Science
Hokkaido University
Sapporo, Japan

Abstract

Rapid urbanization -often unplanned- has been disrupting the environmental settings leading to degradation of resources and energy, environment pollution, elevated land surface temperature (LST) leading to urban heat island (UHI) effect and summer heat waves. In this regard creation, and sustenance urban green spaces (UGS) can effectively reduce these impacts. – In this regard, use of treated wastewater available year-round in the cities can be advantageous from climate change mitigation, urban sustainability, carbon storage, and sequestration perspectives as well as from improving the regulatory ecosystem services which harmonize microclimate features. Thus, the relationship between urban landscape patterns and microclimate needs to be sufficiently understood to make urban living ecologically, economically, and ergonomically acceptable.

With this background, the present study aimed (a) to address the adverse effects of UHI and elevated LST resulting from land use land cover (LULC) alterations along with the role of UGS in regulating microclimate; (b) to estimate water requirements of UGS during the non-rainy months, its carbon biomass and sequestration potential and (c) to evaluate whether treated wastewater is a dependable alternative for maintaining UGS as a measure to mitigate the adverse impacts of urbanization as well as to reduce groundwater extraction. Two traditional cities in India, experiencing different climatic features, were chosen for this study. Panaji city (Koppen classification: Am) situated on the west coast of India receives over 2,750 mm rainfall and Tumkur city (Koppen classification: BSh/Aw) located in interior region receives around 600 mm rainfall. Both cities are proposed to be developed as smart cities.

The methods followed included the analyses of satellite imageries for delineating land cover changes and characterization of the 2019 spectral indices of both cities for understanding the LST difference among other microclimate features. Primary (satellite imageries, field survey-based data, and inputs from key-informant survey questionnaires) and secondary (websites, reports in public domain) data were used to address the above stated objectives. By following the standard methods, the monthly evapotranspiration rates were also derived for both these cities for calculating the UGS water requirement. The calculation of water requirements and carbon stocks and sequestration rates of trees, hedge-plans as well as grass-cover was carried out by following standard methods.

While the LST varied within 38-42ºC range in Panaji with a substantial water spread area, it remained quite high in the 42-48 ºC range in Tumkur (a much larger but highly water scarce city). The average daily water requirements of 34 different tree species, hedge-plants m^{-2} and grass-cover m^{-2} were calculated following standard methods. The larger the canopy/crown area, higher the volume of water required. With the canopy area ranging from 4.491 m^2 to 593.66 m^2, the daily water requirement ranged respectively from 3.05 Ld^{-1} to 369.43 Ld^{-1} averaging 23.87 $Ld^{-1}tree^{-1}$. Similarly, for hedge plants the daily requirement was 6.77 Lm^{-2}, and for grass-cover(=lawns), 4.57 Lm^{-2}. Using this information, the water requirements for the entire UGS in Panaji and Tumkur were estimated. The UGS of 1.86 km^2 in Panaji city requires 6.24 million liters daily. This volume is under 50% of the of 14 MLD total treated wastewater (=recycled water which is environmentally safe) produced and available year-round in Panaji. Currently, over 99% of this treated wastewater is drained into a polluted creek. Notwithstanding the wide variance between 34 different tree species (covering 4012

individual trees), the weighted mean of CO_2 sequestered per tree averaged 55 kg y^{-1}. For 23 tree species the Carbon Sequestration Rates (CSR) estimated in this study are first reports. These rates are well within the ranges reported for many tropical species.

With a view of showcasing the possibility of improved regulatory ecosystem services, an option to use the treated wastewater for watering the entire UGS in Panaji was examined. From the UGS regulatory ecosystem services viewpoint, numerous ecological and economic advantages as well as some of the UN sustainable development goals met with the use of treated wastewater are highlighted. Ample reduction in groundwater extraction, compensation of evapotranspiration losses, enhanced thermal comforts, greater elimination of water-stress and additional employment opportunities are some of the ecosystem services that can be improved by using treated wastewater for sustainable UGS in Panaji or, many other cities.

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List of abbreviations

AGDB:	Above Ground Dry Biomass
BAEI:	Built-up Area Extraction Index
BGDB:	Below Ground Dry Biomass
CCP:	Corporation of the City of Panaji
CGWA:	Central Ground Water Authority
CSP:	Carbon Sequestration Potential
CSR:	Carbon Sequestration Rate
DBH:	Diameter at Breast Height
DWR:	Daily Water Requirements
EBBI:	Enhanced Built-up & Bareness Index
ET_0:	Evapotranspiration
FAO:	Food and Agriculture Organization
FLAASH:	Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubus
IPCC:	Intergovernmental Panel on Climate Change
LIMP:	Landscape Irrigation Management Program
LULC:	Land Use/Land Cover
LST:	Land Surface Temperature
MLD:	Million Liters Daily
MNDWI:	Modified Normalized Difference Water Index
NIR:	Near-Infrared
NDBI:	Normalized Difference Built-up Index
NDVI:	Normalized Difference Vegetation Index
PWD:	Public Works Department
RES:	Regulatory Ecosystem Services
SAVI:	Soil Adjusted Vegetation Index
SLIDE:	Simplified Landscape Irrigation Demand Estimation
STP:	Sewage Treatment Plant
SVM:	Support Vector Machine
SWIR:	Short-Wave Infrared
TIR:	Thermal Infrared
TM:	Thematic Mapper
TPH:	Tons per Hectare
UGS:	Urban Green Spaces
UHI:	Urban Heat Island
URDPFI:	Urban & Regional Development Plans Formulation & Implementation
UNSDG:	United Nations Sustainable Development Goals
USEPA:	United States Environmental Protection Agency
USGS:	United States Geological Survey
WUCOLS:	Water Use Classification of Landscape Species

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Chapter 1

Introduction

All of Nature's attributes stimulate curiosity. The countless valid causatives and the multiple roles various habitats play are captivating. Thus, understanding of environmental characteristics, ecological processes, and services ecosystems offer ought to be occupying mankind's interest and involvement. This must make the governments to act to tackle, researchers to probe to solve, policy makers to promulgate to ensure conservation/protection, and citizenry to diagnose to restore ecosystem to normalcy. Beginning this New Millennium there has been the dawning of an unprecedented global awareness to realize immense prospects of -and of created problems to- our ecosystems. Many minor to mega-scale new ways have unfolded, are being unfolded, and will continue to unfold to safeguard the stability of our biosphere, atmosphere, hydrosphere, and lithosphere.

The Earth's unique, inimitable, and unsurpassable roles demand inquisition. This is to both unravel its irreplaceable roles and to strive to restore the dynamic ecosystem stability lost to anthropogenic excesses. Thus, the enormous current global interest is mainly on the role the land-use systems play in stabilizing atmospheric carbon dioxide (CO_2) concentrations (Ravindranath & Ostwald, 2008). Globally, experts acknowledge that mitigation efforts for land-based developments are constrained by uncertainties and by limitations of both methodology and data. Essentially, the efforts for addressing climate change issues, all mitigation must consider regulating the mechanisms of land-water-energy management strategies.

The Intergovernmental Panel on Climate Change (IPCC) identified biodiversity loss, land degradation, deforestation, desertification, global warming, and climate change as the key environmental issues causally linked to terrestrial ecosystems, which are both natural and human-altered (IPCC, 2014). To mitigate global climate change, both conservation and sustainable development of land-use systems are critical (Ravindranath & Ostwald, 2008). Thus, efforts must be continuous for evolving methods to meet the growing demands of ever-increasing populations and to meet these demands sustainably.

Various abiotic and biotic components of an ecosystem are the primary resources requiring a variety of ways to distinguish -among other constraints- their large spatial and temporal variations, demand-linked pressures, and permanent losses (United Nations General Assembly, 1993). In addition to efforts to minimize emissions from land-use sectors, there is greater attention on the removal of CO_2 from the atmosphere to store it in vegetation and soil as well as using biofuels in place of fossil fuels. Indeed, forest and grassland conservation reclamation and development, roundwood production, and agroforestry development programmes are in place in many countries for stabilizing CO_2 concentration in the atmosphere.

Mitigation and adaptation are the two approaches adopted by global scientists and strategists to address climate change. Yet, the ever-growing demand for food, fodder, fuel, and wood exerting pressure on land-use systems (IPCC, 2007) needs to be addressed. So also, the water issues. Mitigation is the anthropogenic intervention to reduce the sources and/or enhance sinks of GHGs. Adaptation is a necessary strategy to complement mitigation. Also, adaptation is an adjustment in natural or human systems in response to actual or expected climatic stimuli and their impacts on natural and socio-economic systems.

1.1 Relevance of Urban Green Spaces (UGS)

Urban green spaces (UGS) are all green areas covered with natural vegetation (groves, unkept forests) or planned plantations (trees, grass cover/lawns, hedge rows, plant nurseries, flower gardens, recreation parks with manicured vegetation consisting of trees, lawns and hedge rows) in cities in any shape, form, function, and purpose. They can be consisted of open spaces, covered with either natural or planted vegetation (Rakhshandehroo Afshin, et al., 2017). They can be public and private open spaces available for all urban users (Baycan-Levent et al., 2009). In India, there are pockets of green cover in urban areas such as neighborhood parks, roadside plants, and trees (Chaudhary et al., 2011).

Rapidly accelerating urbanization globally provides several benefits such as employment and educational opportunities, better amenities for comfort-centric living, and improved living standards in the overall. The flip side, however, is dense crowding, which can cause enormous constraints in meeting the demands on power, intra-city transportation, water and can severely affect atmosphere, lithosphere, and hydrosphere. Disproportionate emissions of carbon from cities by automobiles and consequent air pollution in and around the urban settings is among the chief global environmental concerns (Uttara et al., 2012; Avtar et al., 2017). Besides rising pollution, congestion of spaces due to urban sprawl and depletion of groundwater due to its overexploitation and mismanagement are some of the other issues which need to be addressed (Hua et al., 2015; Arouri et al., 2014 ; Avtar et al., 2019). In view of these concerns, improvements in urban habitation are to be addressed on priority (Hunt & Watkiss, 2011).

From the sustainability perspective, rapid and unplanned urbanization are problematic. Therefore, the knowledge of the extent and shape of the urban settlement and altered ecological features, including removal or destruction of green spaces in these settlements is essential (Estoque et al., 2015). Alarmingly enough, by 2050, over 60% of the projected nine billion human population is expected to live in urban settings (United Nations Department of Economic and Social Affairs, 2018). In this regard, it is highly pertinent that urban planners consider green spaces in city development to realize sustainable urbanization.

1.2 Treated wastewater for synergizing ecosystem services of UGS

Sustainable urbanization must be a top priority program for planners and administrators. Among the many opportunities of pertinence in this direction, utilizing treated wastewater (=recycled water) for maintaining UGS is a reliable and pragmatic strategy. This can help mitigate the urban heat island (UHI) effect, a consequence of LST, and help address the larger issues of depleting groundwater resources and mitigation of climate change impacts. The direct benefit of reusing treated water is an adequate supply of water for innumerable non-potable uses. As such, it is technologically feasible to economically recycle wastewater (Ramaiah & Avtar, 2019), which is produced daily in enormous quantities in all the highly urbanized settlements worldwide.

From an apparent lack of previous information on the prospect of using treated wastewater for UGS in Panaji city, chosen for this study, it is hoped that the results of this study would be useful as baseline data for future studies, including those of experimental ones looking at the wide spectrum from the relief of water-stress to groundwater reserves. It was noted during this study that humungous volumes of treated wastewater are drained into quite unclean streams/creeks. This is a pointer to wastage of economic (from raw effluent collection-pooling-pumping-treating) resources and loss of ecological (groundwater, STP spaces and energy) capitals.

1.3 Appraisal of LULC changes for delineation of LST impacts

Urbanization brings about land use land cover (LULC) changes through the increased built-up area and human settlements (Patra et al., 2018). The US EPA (United States Environmental Protection Agency, 2020) reported some serious health hazards such as general discomfort, respiratory difficulties, heat cramps, non-fatal heat stroke, and heat-related mortality as rising with the increase of thermal surfaces and corresponding decrease in cooling surfaces. The Agency suggested that it is possible to reduce urban heat islands (UHI) by increasing trees and vegetative cover and by installing green roofs.

Changing land cover and land use patterns, including asphalting increase heating up land surfaces rather unduly. They can lead to depletion of groundwater and reduce recharge possibilities as well as deteriorate its quality (Komolafe et al., 2018). Increases in land surface temperature (LST) also alter groundwater vulnerability through reduced interaction with surface water and net recharge volumes (Sridhar, 2016). As urbanization transforms the LULC pattern by primarily increasing the built-up areas, the energy balance gets modified resulting in urban areas becoming warmer than the surrounding rural or lowly-urbanized areas (Avtar et al., 2019). Factors that contribute to the increased UHI phenomenon include high building density, reduction in UGS, and increases in built-up spaces (Lilly Rose & Devadas, 2009). Therefore, considerations on how haphazard/rapid urbanization and imminent climate change could affect groundwater resources are essential for sustainable land use management practices. While economic-and growth/progress-centric human development indices are welcome, the LULC changes are disturbing downsides.

One of the direct adverse impacts of LULC change (Hua & Ping, 2018) is the elevated LST leading to “urban heat island” (UHI) effect. This is a well-documented climatological effect of human activities on the urban environment (Hua & Ping, 2018; Rahman et al., 2020). The UHIs result from the formation of urban microclimates due to built-up areas, concrete zones, and high concentrations of various human activities (Hua & Ping, 2018). The LST and UHI increase with reduced vegetation, water spread and increased bare land creation and/or non-evaporative surfaces. Consequently, pollution of land, air, water as well as intense strain on resources (i.e., water, electricity, and land area) can be the outcome. Thus, unplanned spatial growth of cities brings numerous environmental problems. The increase of vegetation cover and water bodies or decrease in impervious surfaces can help to strengthen Green space Cool Island (GCI) effects (Yu et al., 2018).

Analysis of the spectral indices for Panaji and Tumkur was carried out by Ramaiah et al. (2020) to recognize the impact of LST on the existing green cover in these cities. Results from this study are presented in Chapter 3. In fact, they formed the basis for the estimation of daily water requirement (DWR) of trees, hedge-plants, and grass cover (=lawn) detailed in chapter 4 and the carbon stocks and sequestration potential (Chapter 5).

1.4 Prospects of Assessing Water Requirements in the UGS

Evapotranspiration efficiency is reduced in water-starved plants and trees. As a result, their carbon fixation, growth rate, inflorescence output, and fruiting physiology can be adversely affected (Qaderi et al., 2019). Consequently, it is quite likely that carbon sequestration potential during the warmer, non-rainy periods is lower. To examine this aspect, one of the primary objectives of this study was to infer whether or how the current practice of drawing borewell water for maintaining the parks could be avoided. The sewage treatment plant (STP) in Panaji produces nearly 14 MLD treated water meeting all the safe limits of water quality criteria. It was also the aim to check whether the same can be used in the entire UGS.

Currently, the treated water is discarded into an adjacent and already over-polluted creek. The warmer, humid, and non-rainy period of over 6 months from January might be slowing the photosynthesis, growth, and carbon sequestration potential in the parks and gardens of Panaji under water-stress. This reduced efficiency might add to the UHI effect because of LST staying higher. With this consideration, it was planned for this study to estimate the DWR of lawns (groundcover), hedge plants and trees in three parks. The evapotranspiration rates (ET_0 mm d^{-1}) for the study area were derived. Using these rates in the formula of Kjelgren et al. (2016), the estimates of DWR in these parks were made and adapted to estimate the water requirements in all 17 parks in Panaji city (Chapter 4).

1.5 Importance of UGS in carbon sequestration and storage

The quality of urban living is enhanced by the effectively managed urban green spaces (UGS). Through their basic, natural process of photosynthesis, the UGS offers many benefits (Hodel & Pittenger, 2015) and make many densely populated urban areas livable. In expanding cities where air pollution levels can be tremendous (Nouri et al. 2019), the UGS help in purifying air and serve as microclimate regulating, urban heat island controlling (Jennings et al 2016) units. They reduce noise pollution, soil erosion, energy consumption, and through evapotranspiration, regulate the surface temperature (Avtar et al., 2019). Bonan (2015) observed that researchers, planners, and the public are concerned about how rapid urbanization could affect sustainability and quality of life in the future.

Although many factors affect its reliable estimation, any reasonable derivation of CSP in urban settings would prove handy for urban planners and developers, among other needs. This will enable them to (a) make allowances for controlling pollution, (b) to reduce UHIs, (c) to look after and sustain existing UGS, and to (d) create new ones as can be expected in rapidly expanding urban developments, including to gear up to meet smart city guidelines. Lack of quantitative information from urban settings in different climatic regions seriously constrains the recognition of the important role UGS play in carbon storage and sequestration. While there is burgeoning literature from around the world portraying how agroforestry offers to increase carbon stocks/sequestration in the terrestrial biosphere, the role of UGS with analogous plant-growing practices is hardly recognized. These aspects comprise Chapter 5.

Large quantities of wastewater generated daily from households and workplaces are often disposed of without any consideration of the deleterious impacts the polluted waters cause when they get into the natural ecosystems (Nagappa, 2019). While the idea of the use of treated wastewater for irrigating crops and UGS is not unique or novel (Ávila et al., 2016 ; Nicolics et al., 2016), ecological and economic perspectives of its use for managing the UGS are yet to receive the due attention (Nagappa, 2019). As for the management of current and future UGS units, this study brings forth the importance of treated/recycled water and the details are included in Chapter 6.

The urban greenery fulfills many regulatory ecosystem services (RES) (Chichilnisky & Heal, 1998; Ramaiah & Avtar, 2019). The UGS help in reducing LST and regulating many parameters of microclimate via sequestering and storing substantial quantities of carbon. As for cultural services, the UGS are inspirational, therapeutic, recreational and tourism spots, biodiversity conservation motifs, as well as of interest for science and educational purposes. To maintain these vital ecological services, the UGS routinely need enough water. Treated wastewater is a regularly available resource. It will help prevent groundwater extraction and aid the UGS in their RES (Chapter 6). Use of treated wastewater in UGS also helps in recovering costs incurred to treat city's wastewater. Succinct details on these aspects as well as of meeting many Sustainable Development Goals (SDGs) of the United Nations are included in Chapter 6. A perspective on research outcome and relevant SDGs met up by this study are listed in Fig 1.1.

In addition to these SDGs, the research outcome of this study falls well within the ambit of the 2015 Paris Agreement (United Nations Framework Convention on Climate Change, 2021) covering the establishment of carbon neutrality targets, zero-carbon solutions by which context the UGS sector can be expected to contribute substantial carbon capture and storage.

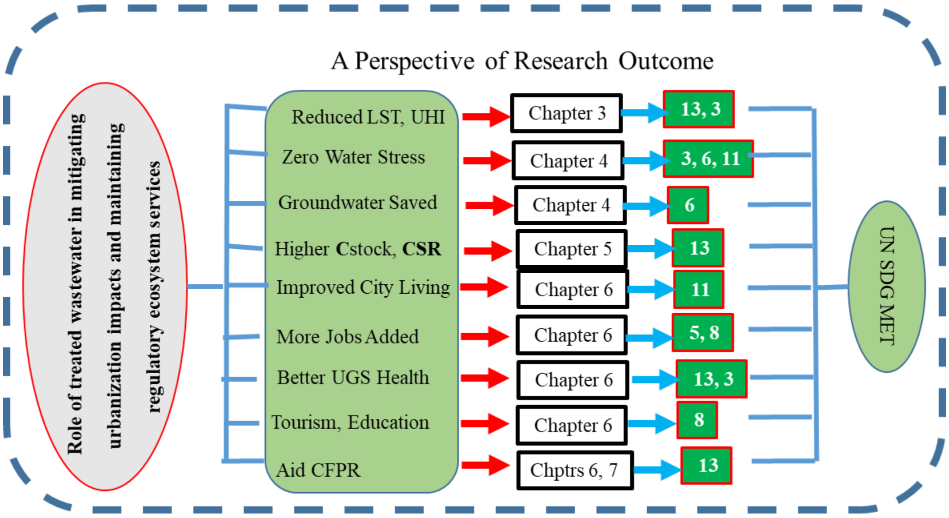


Figure 1.1: Flow chart depicting the outcome of this study and the UN Sustainable Development Goals (UN SDG) met. UN SDG 3 stands for good health and wellbeing, 5 for Gender equality, 6 for Clean water and Sanitation, 8 for Decent work and Economic Growth, 11 for Sustainable Cities and Communities, and 13 stands for Climate Action. LST-Land surface temperature, UHI- Urban heat islands, Cstock- Carbon stock/biomass, CSR-Carbon sequestration rate, UGS-Urban green space, and CFPR-carbon footprint reduction. Detailed discussions on SDGs 6, 11 and 13 are covered in Chapters 4 (SDG 6), 5 (SDG 13), and 6 (SDG11).

1.6 Study Area

Proposed to be developed as a smart city under the Government of India's National Smart City Mission (Corporation of the City of Panaji & CRISIL Risk and Infrastructure Solutions Limited, 2015), Panaji City (Lat 15°29'48.3972" N; Long 73°.49' 40'.1772"E) in the State of Goa on the west coast of India receives tourists from across the globe. It has been swiftly urbanizing in the recent two decades. However, any hasty and/or ill-planned developmental activities can be detrimental. As a result, rapid LULC changes leading to increases in LST can be expected (Ramaiah et al., 2020). Also, the possibility of decreased vegetation, including deforestation (particularly of mangroves), might render this coastal city vulnerable to undesirable climate change impacts.

So far, Panaji city on the west coast of India has been benefiting from the existing green cover. Based on realistic evaluations, reliable answers are needed for: (a) How would this fast-growing smart city cope-up when subjected to imminent -and often adverse-changes because of intense construction activities or other LULC alterations; (b) Whether there is a scope for increasing or efficient upkeeping of the existing UGS. This aspect seems to have not received the attention it deserved.; (c) Details of how to enhance UGS performance and upkeep for quenching the LST- during the eight non-rainy months (mid-October to mid-June) are required; (d) Pertinently crucial assessment needed is whether or, how the current practice of drawing borewell water for maintaining the parks could be avoided.; (e) Further, whether the diversion of significant part of the processed water meant for domestic use could be replaced with treated wastewater for maintaining the parks is not explored.

To provide an overarching compilation of information, this study was planned and carried out (a) to recognize the relationship between the landscape variables (enhanced built-up and bareness index [EBBI], soil-adjusted vegetation index [SAVI] and modified normalized difference water index [MNDWI]) and the LST in Panaji and Tumkur, (b) to obtain information on current practices of UGS maintenance, and (c) to propose whether a part of the current 14 MLD treated wastewater available from Panaji city's STP could be opted for maintaining the current UGS area which is only 9% of the city corporation area (Ministry of Urban Development, Government of India., 2015).

In addition to satellite image analyses to provide the variations in these parameters, visits were made to seven different parks and gardens and to a sewage treatment plant for the collection of relevant data. In this first-time endeavor, daily water requirements (DWR) as well as carbon sequestration potential (CSP) of tree species in three parks, hedge plants, and grass cover in the green spaces of seven different parks/gardens from where detailed data was collected was derived and compared to the literature reported CSP, to be contextual.

The hypothesis evaluated in this study can be stated as: Though Panaji city has more green cover, the applicable daily water requirement (DWR) is not met by the current quantities/supplies. By regularly watering the existing hedge-plants, grass cover, and trees, the UGS can be significant in not only reducing LST but also sequestering and sinking significant quantities of carbon. The use of treated wastewater can eliminate the need for groundwater extraction or freshwater diversion to parks.

1.7 Research Questions and Objectives

The overarching intent of the research questions addressed in this study is to highlight the co-benefits resulting from the use of treated wastewater for sustainable UGS.

1. Are the current UGS maintenance practices adequate in Panaji and Tumkur cities experiencing frequent LULC alterations?
2. What quantity of water is required daily for hedge-plants, grass-cover (lawns) and different species of trees in the city parks/gardens and, what are their present carbon biomasses and sequestration potential?
3. How can treated wastewater (=recycled water) be a dependable alternative to currently drawn groundwater for maintaining UGS as well as controlling LST in these cities?

Objectives

1. To evaluate the influence of UGS in combating LST/maintaining microclimate
2. To calculate/estimate water requirements of UGS in terms of regulatory ecosystem services
3. To monitor/assess the ecological and economic benefits of treated wastewater (recycled water)

1.8 Outline of the Thesis

Chapter 1 covers an overall introduction, background with an overall framework, research questions, hypothesis, and objectives. Chapter 2 covers literature review and related details, including some insights from earlier research. Chapter 3 addresses Objective 1 (Evaluating the influence of UGS in combating LST/maintaining microclimate). In Chapter 4, Objective 2 which deals with the estimation of daily requirement of water in UGS of Panaji city is covered. Chapter 5 covers the remaining part of Objective 2 i.e., estimation of CSP of UGS of Panaji city. Finally, in Chapter 6, Objective 3 (Ecological benefits of treated wastewater (recycled water) use for UGS) is addressed. Highlights of the results of this study are summarized in Chapter 7.

Chapter 2

Review of Literature

2.1 An overview of urbanization

In the past 3-4 decades, there has been an increasing global awareness and concern towards our environment. This global awareness about the severity of human-induced climate change was a defining moment in history when the Nobel Peace Prize was awarded in 2007 to Al Gore and the Intergovernmental Panel on Climate Change (IPCC) of the UN (United Nations). Current global-climate change (= global warming as it is also known) is the most serious environmental issue affecting human lives on a global scale. In simple terms, increase in temperature in recent decades of the Earth's near-surface air and oceans is global warming. It is understood to be brought about primarily by the increase in atmospheric concentrations of the so-called greenhouse gases (GHGs) (United Nations). In this review, the focus is on the relevance of urban green spaces (UGS), their sustainable management using treated wastewater (=recycled water) and their carbon sequestration potential (CSP). Also included are the aspects of land use land cover (LULC) changes and land surface temperature (LST). For this, various primary as well as secondary sources of information including books, databases, reports, and research papers published in scholarly and academic journals have been used. To contextualize the definitions, descriptions, and issues concerning urban green space management, several website articles and press articles were also referred to for this study.

As cities grow, changes in urban land cover and geometry/morphology/architecture coupled with intensifying human activities have led to a modified thermal climate, particularly at night, forming an urban heat island (UHI) effect (Ugle et al., 2010). This has significant implications for sustainability, with consequences for energy and water consumption, emissions of air pollutants and greenhouse gases, human health, and the emergence of regional heat islands (Zhang et al., 2017).

In these unbridled times of climate change, the prominent environmental concerns need workable solutions, small or large. Building up of acceptable resilience and adaptation to such adversities by creating green landscapes with suitable species of hedge-plants, trees, and lawn grasses as a solution-option needs to be recognized. In many rapidly expanding urban settings, reduction of adverse impacts can be effective and possible speedily by increasing green spaces such as parks, gardens, terrace agriculture, and vertical vegetation (Bonan, 2015). By creating UGS, carbon can be sequestered for decades or centuries in urban trees and durable social forestry and their products as proposed by natural forests, agronomic crops, salt-tolerant plants, and marine microalgae (IPCC, 2014).

2.2 Urbanization and consequences

Urbanization is ongoing worldwide, especially in developing countries (Cohen, 2006). About 60% of the world population will live in urban areas by 2030 (USAID, 2017). As Asia and Africa currently house 90% of the world's rural population, they are urbanizing faster than any other region and are predicted to achieve urbanization rates of 56% and 64%, respectively, by 2050 (USAID, 2017). The rise in urban population is expected to be high in India, China, and Nigeria, where 35% of the world urban population growth is predicted to occur during 2018-2050 (United Nations, 2018c). Urbanization brings a number of benefits to the Asian countries (Andrea, 2015; Sadashivam & Tabassu, 2016). By making better use of the opportunities provided by urbanization, India and other South

Asian countries have the potential to transform their economies (The World Bank, 2015; Sadashivam & Tabassu, 2016). It is predicted that India's current urbanization rate of 0.25% will double by 2050 (United Nations, 2018a) and this rate has kept pace with the annual average economic growth of approximately 8% during the last 15 years (Ahluwalia, 2014). The key reasons for increasing urbanization are ever-growing population and booming industrialization (Bhattacharya, 2002). As such, unplanned urbanization is environmentally unfriendly and unsustainable, leading to adverse effects on climate change.

Urbanization alters land use management, which leads to deterioration of groundwater quality and drops in groundwater level (Hua et al., 2015). Variations in temperature, precipitation, and evaporation also alter groundwater vulnerability through interacting with surface water, net recharge, and groundwater levels (Sridhar, 2016). Therefore, understanding how urbanization and climate change may affect groundwater resources could provide deep insights for framing sustainable land use management plans.

With global climate change intensifying, climatic conditions in urban areas need to be addressed immediately (Hunt & Watkiss, 2011). Furthermore, due to excessive carbon emissions from automobiles in cities, air pollution that affects a large number of urban inhabitants globally is a major concern (Grimm et al., 2008). Besides rising pollution, congestion of spaces due to urban sprawl and depletion of groundwater due to its overexploitation and mismanagement are some of the other issues which need to be addressed (Hua et al., 2015; Arouri et al., 2014). Tremendous burden on the management of energy, water, and transportation are due to overcrowding in the metropolitan cities of India viz. Mumbai, Kolkata, Delhi, and Chennai (Uttara et al., 2012). Also there have been serious adverse impacts on the atmosphere, climate, lithosphere, biosphere, hydrosphere, land, and water resources (Uttara et al., 2012).

Urban green spaces (UGS) are necessary, particularly in developing countries like India and China, where air pollution levels are extremely high. They play an important role in purifying air, thus improving the air quality and serve as a valuable source for enabling urban agriculture, regulating the microclimate, and controlling the urban heat island phenomenon (Jennings et al., 2016). Furthermore, the urban green spaces reduce soil erosion, noise pollution, and energy use by regulating the surface temperatures of urban canyons (Qian et al., 2015), (Wei, 2013). Further, the urban green spaces are greatly valuable for social interaction, urban festivals, public health (Uttara et al., 2012).

Urban green spaces, particularly trees, play a significant role in carbon sequestration (Ugle et al., 2010). One of the major impacts of urbanization on the climate is that the urban area becomes significantly warmer than its surrounding rural area, usually termed as *urban heat island* (Ugle et al., 2010). The government initiatives, strategies and policies on the urban green spaces are necessary for the success of sustainable management plans. It requires the implementation of master plans for increasing the density of urban green spaces (Xu et al., 2011). Also, methods to optimize existing urban green spaces need to be explored (Li et al., 2012). Other strategies include the promotion of urban green spaces as tourism spots involving local communities in ownership.

In recent decades, intensified emission of CO_2 from the urban areas into the atmosphere is among the serious environmental concerns. In this regard, the relationship between urban landscape patterns and microclimate needs to be sufficiently understood (Hua & Ping, 2018). Additionally, knowledge of diverse patterns of land-use intensity or spatial growth is essential to delineate both beneficial and adverse impacts on the urban environment (Amiri et al., 2009; Koomen et al., 2009). Thus, during these times of climate change and global warming-induced adversities, adequate resilience by the greening of urban landscapes with appropriate species of plants, trees, and lawn-grasses is essential.

The way in which water resources in urban settlements are utilized does play a significant role in the preservation, development, and maintenance of urban green spaces. While some studies have focused on how the water resource management practices in urban settlements affect the urban green space cover, due attention has not been paid to the treatment and reuse of wastewater for urban green space management. The collection of information, and insights thereof, on change in green spaces and wastewater treatment and reuse, can benefit policymakers and urban planners for environmentally friendly and long-term sustainable urban development. Therefore, the major objective of this research is to analyze the effect of management of water resources, particularly wastewater treatment and its non-potable reuse in urban green spaces. This review also explores the key challenges of wastewater treatment and its non-potable reuse for the maintenance of urban green spaces in major cities of India. It also aims to present ongoing efforts for treating and reusing wastewater in different parts of the world to find a set of potential solutions to mitigate climate change.

2.3 Identification of key problems

2.3.1 Adverse impacts of unplanned urbanization

Although urban areas offer better opportunities and improved standards of living, several problems arise from urbanization. Overcrowding and the strain on resources, particularly water and electricity, are the immediate ones. Environmental pollution due to large quantities of waste generation and excessive automobile use leading to increased carbon emissions exacerbates climate change impacts. Moreover, the unplanned urbanization problem is ecologically unsustainable because of the many pressing issues that are afflicting the waste management process. For instance, new immigrants to cities cannot afford municipal amenities like waste disposal and sanitary functions owing to their low incomes and to being either unemployed or underemployed. In developing countries, about 300 million urban residents are reported to have no sanitation access (Jhansi & Mishra, 2013). Over two-thirds of the population in these countries have no access to hygienic means of disposing of excreta and wastewater (Jhansi & Mishra, 2013). Thus, untreated sewage is often directly discharged into open, natural water bodies (Jhansi & Mishra, 2013). For instance, New Delhi, a megacity in a humid sub-tropical setting, has complex patterns of urbanization in terms of its commercial, residential, mixed-use areas, and traffic intersections. For this, the major contributing factors are high population density, high density of road network, and an extremely high amount of traffic flow. Unlike Delhi, the city of Pune is in a hot, semi-arid region with village nuclei and industrial sectors. Pune is affected by a sudden recent increase in population by 10 times compared to the last century. The city is being modified from a “bicycle city” to “motorbike city”. Also, the disproportionate increase in building heights as compared to street width affects the katabatic wind. The city of Chennai, with tropical wet and very dry seasons, is affected by large concrete surfaces, runways, and high traffic load. Post-1990s, there is an unprecedented increase in traffic, large areas of exposure to hard concrete surfaces, runways, and bus parking bays. In Visakhapatnam, another tropical wet and dry climate city with its population hotspots, the central and southern business district is affected by an increase in industrialization, large reclamations of the tidal swamp for port-based industries, haphazard urbanization, and the establishment of steel plants replacing agricultural and fishing villages. Except for New Delhi with a per capita green space of 21.52 m^2, other cities named above have only 1.4, 0.46, and 0.18 m^2 of green spaces, respectively, which are exceptionally low.

The other major impact of urbanization on landscape surfaces is the replacement of vegetated areas with artificial surfaces that are mostly impervious. These impacts modify the surface energy balance through a change in absorption and reflection of solar radiation (Bowler et al., 2010). Besides energy, the water cycle between land and atmosphere also gets altered. Impervious urban surfaces obstruct water from infiltrating the soil and vegetation cannot intercept water if it is absent. Since 1970, India has been undergoing rapid urbanization (Govindarajulu, 2014). The urban population rose from 109 million in 1971 to 377 million in 2011 by an 11.7% increase from 19.9% to 31.6% over four decades (Govindarajulu, 2014). The number of cities in the country with the population exceeding one million has steadily increased from 23 in 1991 and 35 in 2001 to 53 in 2011 (Govindarajulu, 2014).

Population growth forecasts indicate rapid global growth reaching 9 billion in 2030 and migration from rural to urban areas occurring on a large scale in developing countries (Jhansi & Mishra, 2013). Such growth and migration bring in untold number of problems in terms of urban planning and maintenance. In addition, the ordering of priorities for planned development including water and sanitation facilities, face multiple difficulties. Figure 1 shows India’s population growth. The urbanization rates since 1955 indicate a rise of about 35% (2019) from approximately 20% (1955) and are projected to reach 50% by 2050 (Worldometers).

Table 2.1: Major cities of India with per capita green space

City	**Geographical area (km^2)**	**Population in millions**	**Forest and tree cover (km^2)**	**Per capita green space (m^2)**
Delhi	435.00	16.31	90.74	5.50
Bangalore	226.00	8.43	150.00	17.79
Mumbai	735.00	18.48	122.00	2.01
Hyderabad	172.00	7.74	3.87	0.50
Ahmedabad	469.00	6.35	21.80	3.90
Chennai	174.00	8.69	9.00	1.03
Surat	395.00	4.58	11.84	2.70
Jaipur	484.64	3.07	61.40	20.00
Gandhinagar	75.00	0.20	30.75	147.60
Chandigarh	114.00	1.05	16.78	54.45
Panaji	21.60	0.26	1.86	9.45
Tumkur	48.60	0.36	0.93	4.60

Population data in the 10 most populous cities as of the 2011 Census (Govindarajulu, 2014). Table 2.1 also provides information about the geographical area, forest and tree cover, and per capita green space in the cities, including Panaji and Tumkur considered for this study.

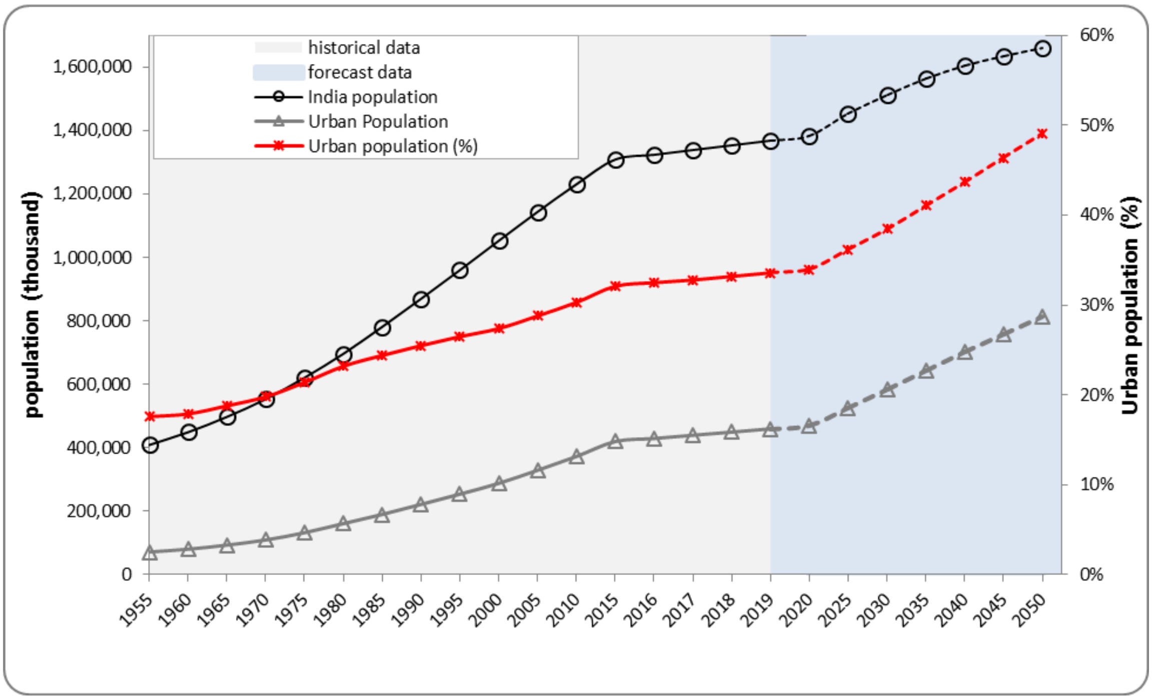


Figure 2.1: India's population growth and urbanization trend since 1955.

2.3.2 Challenges in creating green spaces in unplanned urbanization

Rapid urbanization and industrialization in developing countries are resulting in major problems such as air pollution and increased health risks (Wei, 2013). One of the prime factors for the reduced number of urban green spaces in cities is the overpopulation of cities, which results in increased scarcity of land and resources (Xu et al., 2011). The impact of urbanization on the climate is seen in the urban heat island (UHI) effect, wherein the air temperature in urban areas is considerably higher than in rural areas (Li et al., 2012; Wei, 2013). The urban heat island results in excessive use of air conditioners during summer, thus accelerating the formation of urban smog (Akbari et al., 2001). Availability and the ability to grant high-in-demand, expensive but limited land area within the precincts of the cities is a complex challenge. One of the challenges of unplanned urbanization is in the implementation of master plans with areas dedicated to green space (Xu et al., 2011).

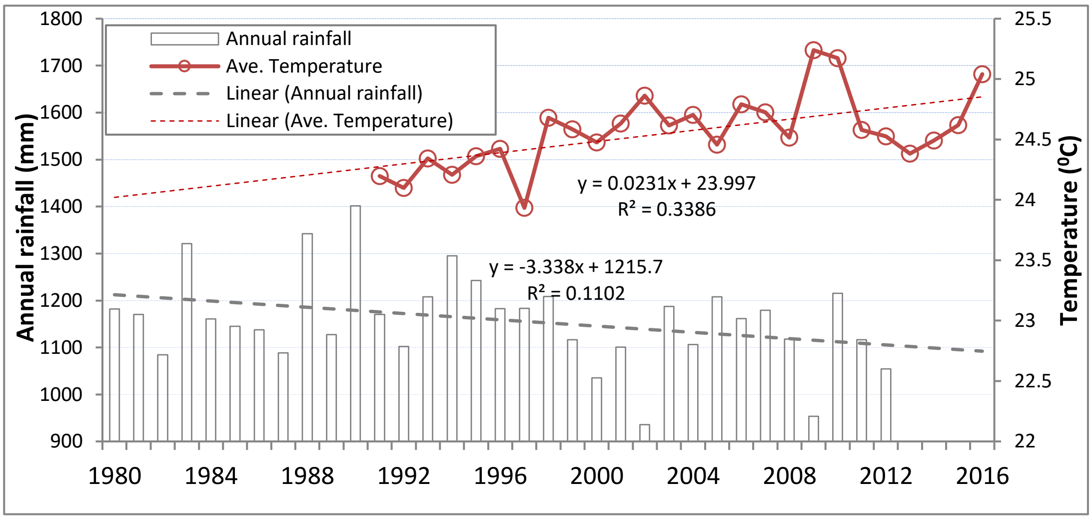


Figure 2.2: The pattern of annual rainfall and average temperature during the period 1980-2016. Data were collected from India Environment Portal.

Regarding the creation of urban green spaces, the two critical inputs are the availability of land areas and adequate water supply to maintain the existing green spaces or new ones planned. Firstly, cities face the challenge of the surge of rural migrants who tend to occupy any free space and not easily dislodge once anchored. Secondly, cities need to cater to the civic amenities of water, electricity, and road access for migrants. These factors might severely hinder the much-needed creation of parks, lawns, or avenue gardens for greening the city environs.

2.4 Challenges faced in the creation of green spaces

Urban green spaces are an important component that directly affects climate and water resources for sustainable development (Elgizawy, 2014). Designing interventions which support planning at the landscape level with a better understanding of the future spatial configurations of urban landscapes is a crucial step planning authorities need to take (Nor et al., 2017). In India, there are pockets of green cover in urban areas such as neighborhood parks, roadside plants, and trees (Chaudhary et al., 2011). However, the problem is that of maintenance (Singh et al., 2010). Impervious urban surfaces impact climate very differently from that of vegetated countryside areas (Gill et al., 2007). This is because of inefficient rainwater retention and storage, which lead to more run-off thereby reducing the availability of water plants. These autotrophs, in turn, would have helped ease the microclimate through evapotranspiration.

The main maintenance-related problem of urban green spaces is that of irregular watering. With the growing populations in the haphazardly urbanizing cities, the water scarcity can be alarming and can be a great detriment for maintaining the green spaces. In Figure 2.3, the months during which the shortages can be severe are depicted; and in Fig.2.4, the projected water demand in India in relation to the available resources. Without an overemphasis, the reuse of wastewater is central to the sustained availability of water.

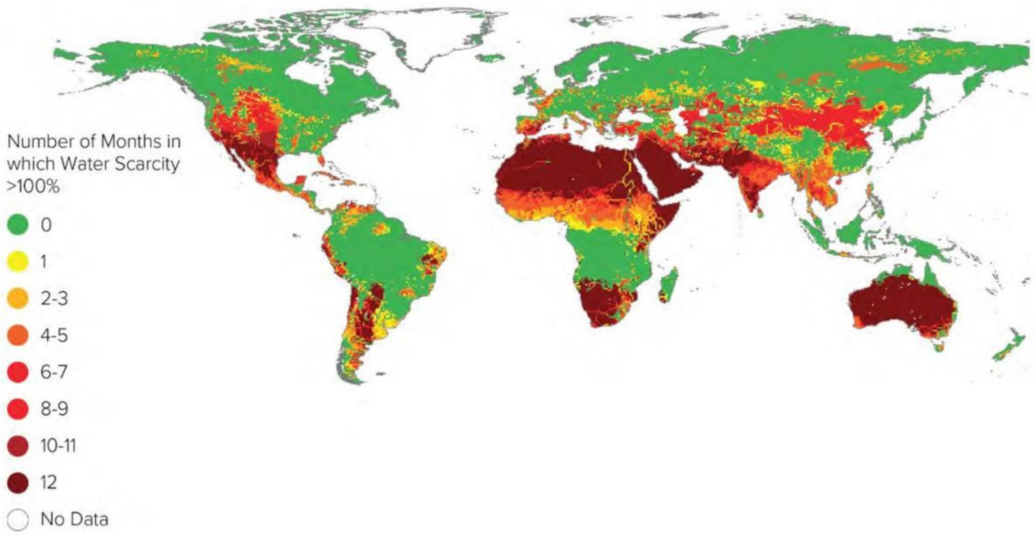


Figure 2.3: The number of months per year where water scarcity exceeds 100% during the period 1996-2005 (*Section 4: Water*, 2018).

Increasing immigration into cities creates severe pressure on the water. For example, Pune city is experiencing a surge of external population in search of economic opportunities (Padigala, 2012). Consequently, there is a rapidly increasing demand for land and water. This is also affecting other habitats of the city such as urban green spaces. The encroachment of hill slopes, riverbeds, barren and fallow land by slums have led to the degradation of both these habitats. For example, the artificial plantations of exotic species result in degradation of the local habitat and disturb the local biodiversity (Padigala, 2012).

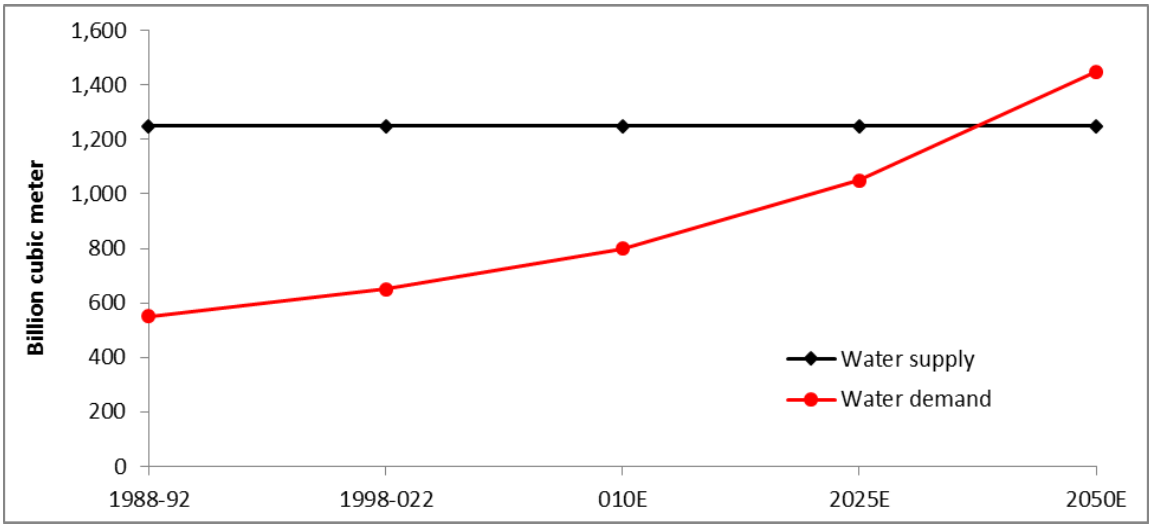


Figure 2.4: As the urban population in India is rapidly increasing, the demand for water is predicted to exceed the estimated (E) available supply by 2050 (Klynveld Peat Marwick Goerdeler (KPMG), 2010).

A 10-year data-based analyses of land cover changes of Pune City (Table 2. 2) suggests that the built-up area has grown substantially to 43.01 sq. km., an increase from 30.86% in 1999 to 48.50% in 2009. Correspondingly, there is a decrease from 36.20% in 1999 to 21.80% in 2009 in the barren and fallow land area due to encroachment. Both sparse and dense vegetation has decreased by 5.58 and 1.66 sq. km., respectively. From these reports, it can be clearly seen that rapid urbanization due to the exponential increase of population in urban centers such as Pune leads to various environmental issues both at regional and global levels.

Table 2.2: Land Use Land Cover changes in Pune city (Padigala, 2012)

Land use land cover	**Area (km^2)**		**Area (%)**		**Area Difference**	
Land use class	**1999**	**2009**	**1999**	**2009**	**(km^2)**	**(%)**
Water Bodies	3.58	2.93	1.47	1.20	-0.66	-0.27
Built Area	75.25	118.26	30.86	48.50	43.01	17.64
Barren & Fallow Land	88.27	53.16	36.20	21.80	-35.11	-14.4
Dense Vegetation	32.92	31.26	13.5	12.82	-1.66	-0.68
Sparse Vegetation	43.82	38.23	17.97	15.68	-5.58	-2.29
Total Vegetation	76.74	69.49	31.47	28.50	-7.24	-2.97

2.5 Problems of urban water supply and sanitation

One other major and complex challenge is water supply to all the sub-divisions in the urban setting. It is quite a day-to-day encounter in most cities in the underdeveloped or developing countries to reach treated, potable water to the last house in the block. Low water levels of many sources during the summer season also hamper the water supply leading to inadequate volumes in many cities. The migrants usurping water by competing with the regular and accounted households creates a lot of pressure on civic authorities. According to Gill et al. (2007), one of the distinctive biophysical features of urban areas compared to surrounding rural areas includes the urban heat island resulting from altered energy exchange. Another feature is the modified hydrology, such as increased surface runoff of rainwater. These changes partly result from the altered surface cover of urban areas. Urban areas with less vegetation experience lesser evaporative cooling. Surface runoff increases with an increase in surface sealing. The global climate change is certain to intensify these features. Data on annual rainfall and average temperature during the period 1980-2016 in India are presented to emphasize the point that the average rainfall pan-India is quite significant though varying inter-annually.

Urban sanitation systems must be of high hygienic standards to prevent the spread of diseases (Eslamian, 2016). The World Bank predicts that over the next two decades, the greatest challenge in achieving adequate water and sanitation level would be the implementation of low-cost, rapid and efficient sewage treatment technology (Eslamian, 2016). At the same time, this treatment option must "permit selective reuse of treated effluents for agricultural and industrial purposes" (Eslamian, 2016). In addition, the recovery of nutrient and water resources is necessary for reuse in urban green space creation and agricultural production to ease the overall user-demand for water resources. With increasing population and economic growth, it is evident that treatment and safe disposal of wastewater is essential for preserving public health and reducing intolerable levels of environmental degradation. In addition, adequate wastewater management is also required for preventing contamination of water bodies for preserving the sources of clean water.

2.6 Solution strategies

2.6.1 Provisioning and creation of urban green spaces

For urban development to be sustainable, it must be environmentally, socially, and economically beneficial. In this context, urban green spaces are an important component of sustainable development (Elgizawy, 2014). The environmental benefits through green spaces include mitigation of climate change by sequestering carbon emissions and reduction in air pollution (Rakhshandehroo, Mohd Yusof, et al., 2017). Economic benefits include an appreciation of real estate value (Arvanitidis et al., 2009). Social benefits include job creation, recreation zones, and better health (Zhou & Rana, 2012). Plants provide important ecosystem functions such as shading and cooling through evapotranspiration.

Growing plants in open areas free from concrete pavements and other locations of cities is a desirable step forward to cut down on the impact on climate. This is because impervious urban surfaces differ significantly from those of vegetated countryside areas in terms of being cooler (Gill et al., 2007). According to Bonan (2015) and Gill et al. (2007), "This less effective rainwater interception and storage generates more runoff and reduces evapotranspiration in urban areas." Urban green spaces can synergistically add up in mitigating climate change by sequestering sizable volumes of carbon emissions. Citing Greater Manchester as a case study site, Gill et al. (2007) recognize the important roles the green infrastructure -the green space network- plays in adapting for climate change. They highlighted that their surface temperature and surface runoff in relation to the green infrastructure model study calls for an adaptation strategy to climate change in the urban environment.

2.6.2 Water management for urban green spaces

Green space is a much sought-after facility even in chaotic, traffic busy urban sites. In order that the green spaces are healthy and enabled for growing normally, the regular supplement of water, nutrients, periodic de-weeding, pruning, spraying, and replacing may be essential. Among these, the vital and frequent requirement is water. As highlighted earlier, this finite resource is becoming deficit, largely due to population growth and injudicious allocation of natural supplies as well as due to a lot of mismanagement. Groundwater is one of the natural resources essential for the upkeep of biodiversity. However, the escalating urbanization trend and climate change have a severe effect on groundwater availability. As groundwater resources are also getting depleted rapidly, it is crucial to recycle wastewater, purify, and reuse for various purposes, including drinking and, most importantly, for the regular watering and irrigation of urban green spaces such as parks and gardens.

The domestic wastewater that is generated in millions of liters daily (MLD) is a resource that is both easy to collect, treat, and reuse in urban areas. One of the strategies for the maintenance of urban green spaces is regular irrigation. Irrigation of urban green spaces such as parks, gardens, and roadside plants is often done by drip irrigation. The major irrigation method of roadside plants in India are flooding of the plant areas from a pipeline mounted to trucks. In the parks, flood irrigation, sprinkler irrigation, as well as drip irrigation are in practice. Drip irrigation is an efficient, water-saving technology that reduces losses from evapotranspiration (Ramaiah, 2015). Suitable treatment of several 100-million liters of wastewater generated daily across the cities is not yet considered for use in UGS programs.

2.6.3 Wastewater treatment and use for urban green spaces

In developing countries, there is still a persisting aversion to reuse treated wastewater. However, this cannot go on, or as Jhansi & Mishra (2013) highlight, "cannot be assumed that the current low percentage of the coverage of wastewater treatment in these countries will increase in the future unless a new, innovative strategy is adopted and affordable wastewater treatment options are used." According to them, "a key component in any strategy aimed at increasing the coverage of wastewater treatment should be the application of appropriate wastewater treatment technologies that are effective, simple to operate, and low cost in investment and especially in operation and maintenance" (Jhansi & Mishra, 2013). Further, there is a need for appropriate technology processes that are very eco-friendly by being energy efficient and able to facilitate efforts to mitigate the effects of climate change. The appropriate technology unit processes are listed by Jhansi & Mishra (2013) are as follows.

- Preliminary treatment by rotating micro screens
- Vortex grit chambers
- Lagoons treatment (anaerobic, facultative and polishing), including recent developments in improving lagoons performance
- Anaerobic treatment processes viz. anaerobic lagoons, up-flow anaerobic sludge blanket reactors, anaerobic filters, and anaerobic piston reactor
- Physicochemical processes such as chemically enhanced primary treatment
- Constructed wetlands
- Stabilization reservoirs for wastewater reuse and other purposes
- Overland flow
- Infiltration-percolation
- Septic tanks
- Submarine and large rivers outfalls

From the processes and various technical details listed above, it is possible that various combinations can be set up, including sand filtration and dissolved air floatation together.

2.7 Carbon sequestration

In the carbon sequestration process, carbon dioxide (CO_2) and other forms of carbon are stored (Ugle et al., 2010). The capture of CO_2 from the atmosphere through biological, chemical, and physical processes mitigates global warming (Ugle et al., 2010). Other benefits provided by carbon sequestration helps in mitigating the effect of greenhouse gases in the atmosphere (Ugle et al., 2010). During the photosynthesis process, trees convert water and carbon dioxide into oxygen and sugar molecules. A part of the sugar gets stored, while most of it gets used by the tree for many other purposes such as energy and structure (Ugle et al., 2010).

2.7.1 Carbon sequestration potential

Almost all plant species contribute to carbon sequestration in varying quantities depending on the availability of water, inorganic nutrients, and adequate sunlight. According to Misni et al. (2015) in the paper "Carbon Sequestration Through Urban Green Reserve and Open Space", the tree species that have the highest carbon sequestration potential include *Khaya senegalensis* (Khaya), *Alstonia angustiloba* (Pulai), *Pterocarpus indicus* (Angsana), *Sandoricum koetjape* (Sentul), *Mimusops elengi* (Tanjung), and *Samanea saman* (Hujan-hujan). According to Chandrashekhar (2019), "A study in Varanasi found that native species like fig (*Ficus carica*), banyan (*Ficus benghalensis*), mango (*Mangifera indica*), and Ashoka (*Saraca asoca*), with their large thick leaves, withstood air pollution better and were more suited to planting in that urban area." According to Bhalla & Bhattacharya (2015), the all-India urban tree cover area is 16.40% of the total urban area. With a green cover of approximately 20% of the urban area, the Municipal Corporation of Delhi has a record of 18,000 parks that is further planned to be increased to 33% in coming years. According to the study by Terakunpisut et al. (2007), tropical rain forests have the greatest carbon sequestration potential (137.73 ton C/ha) followed by dry evergreen forest (70.29 ton C/ha) and mixed deciduous forest (48.14 ton C/ha). Relevant literature is also added in chapters 4, 5, and 6.

2.7.2 Carbon sequestration potential of main plants grown in Indian cities

Increasing atmospheric CO_2 levels are identified unequivocally as the predominant cause of global change (Dhyani et al., 2020). Though agricultural and forestry practices are believed to partially mitigate increasing CO_2 concentration (Kirby & Potvin, 2007), the role of UGS in aiding sequestering carbon is yet to be fully acknowledged and our understanding on this aspect is still frail. Ever since the Kyoto Protocol has become effective, there is increased attention on strategies for carbon sequestration. More impetus is acquired to the climate change mitigation and adaptation measures following The Paris Agreement. In essence, by planting trees in urban and/or suburban areas, and by improved management/maintenance of already existing green spaces, opportunities abound for reducing many ill effects. Depending on locations, the plant species grown in major cities of India vary quite widely. The percentage of green space and main plants grown in major cities of India are listed in Table 2.3.

Table 2.3: Green spaces and plant species grown in major cities of India (*Status of Tree Cover in Urban Areas of Gujarat*, n.d.)

City	Green space (%)	Major plant species (indicative)
New Delhi	11.90	Banyan tree, Peepal tree, Bael, Jamun, Ber, Arjun
Mumbai	6.20	Bhendi tree, Banyan trees, Tamarind tree, Coconut palm, Paral tree, Padauk trees, Mahogany tree, Cajuput tree, Baobab tree, Star Apple, Baobab tree, Peltophorum tree, Gulmohar tree
Chennai	7.50	Sansiveria, Dieffenbachia, Dracaena, Spider plant, Earth star, Money plant, Pothos, Syngonium
Hyderabad	1.66	Bougainvillea, Neerium, Adeneum, Lantana, Euphorbia russelia
Bengaluru	2.96	Australian wattle, Butterfly tree, Red silk-cotton tree, Popcorn bush cedar, Coconut palm, Gulmohur, Indian cork tree, Indian elm, Teak, Silver oak, Orange champak
Kolkata	7.30	Neem, Peepal, Banyan, Radhachura, Krishnachura, Tamarind, Coconut, Betelnut tree
Pune	1.40	Cadamb, Tetu, Awala, Chandan, Tamhan, Muchkund, Cadamb, Kanchan, Putranjiva, Semla Kanchan, Kapila, Murudsheng Ritha, Undi
Panaji	9.6	Casuarina, Peltophorum, Badam, Coconut, Bottle palm, Mango, Rain tree

Panaji city in the state of Goa is one of the cities chosen for the Smart Cities Mission initiated by the Government of India. In Goa state, the total forest cover is 60.21% with an area of 2229 sq. km. as per the 2017 FSI report (Team Herald, 2018). The state's forest cover has increased by 5% between 2015 and 2018 due to the increase in mangroves (TNN, 2018). In Panaji city, the approximate green space area is 80 hectares. The city aims to be clean, environmentally friendly, and ecologically sustainable with a focus on improving the urban infrastructure facilities and tourist infrastructure, along with conserving the natural elements and heritage structures by adopting eco-friendly alternatives and techniques.

In the case study conducted by Kaul et al. (2010), it was found that "long-term total carbon storage ranges from 101 to 156 Mg C ha^{-1}, with the largest carbon stock in the living biomass of long rotation sal forests (82 Mg C ha^{-1}). The net annual carbon sequestration rates were achieved for fast-growing short-rotation poplar (8 Mg C ha^{-1} yr^{-1}) and Eucalyptus (6 Mg C ha^{-1} yr^{-1}) plantations, followed by moderate growing teak forests (2 Mg C ha^{-1} yr^{-1}) and slow-growing long rotation sal forests (1 Mg C ha^{-1} yr^{-1}). Due to the fast growth rate and adaptability to a range of environments, short rotation plantations, in addition to carbon storage, rapidly produce biomass for energy and contribute to reduced greenhouse gas emissions." Native trees like *Azadirachta indica* (Neem), *Tamarindus indica* (Tamarind), *Ficus religiosa* (Peepal), and *Madhuca latifolia* are considered ecologically beneficial as they have relatively high efficiency of carbon fixation; these species may be suitable for checking urban pollution and may provide a good option for maximum carbon fixation (Ugle et al., 2010). While a variety of short-term and long-lived plants/trees are grown in different cities in India, the overall data is lacking on the carbon sequestration potential of different plants species.

2.7.3 Regulatory ecosystem services of UGS

The two climate-regulating services of carbon sequestration involve direct removal of carbon dioxide from the atmosphere and indirect effects of vegetation on local cooling through shading and transpiration in warm climates (see Ravindranath & Ostwald (2008) for the overview). As recognized by Pataki et al. (2011), the coupling of carbon, water (much better if it is recycled and reused: (United Nations, 2018b)), and energy cycles is integral to impacts of urban vegetation on climate. In the words of Pataki et al. (2011), the UGS are "purported to offset greenhouse-gas (GHG) emissions, remove air and water pollutants, cool local climate, and improve public health." Thus, making use of these services, the municipalities in the cities aspiring to be "smart" especially in India have to focus efforts on designing and implementing ecosystem-services-based "green infrastructure" in urban environments. These aspects are included in Chapter 6, which is developed for showcasing the importance of treated water in the sustainable management of UGS in three different Indian cities. While in some cases, the environmental benefits of this infrastructure have been well documented, but they are often unclear, unquantified, and/or outweighed by potential costs.

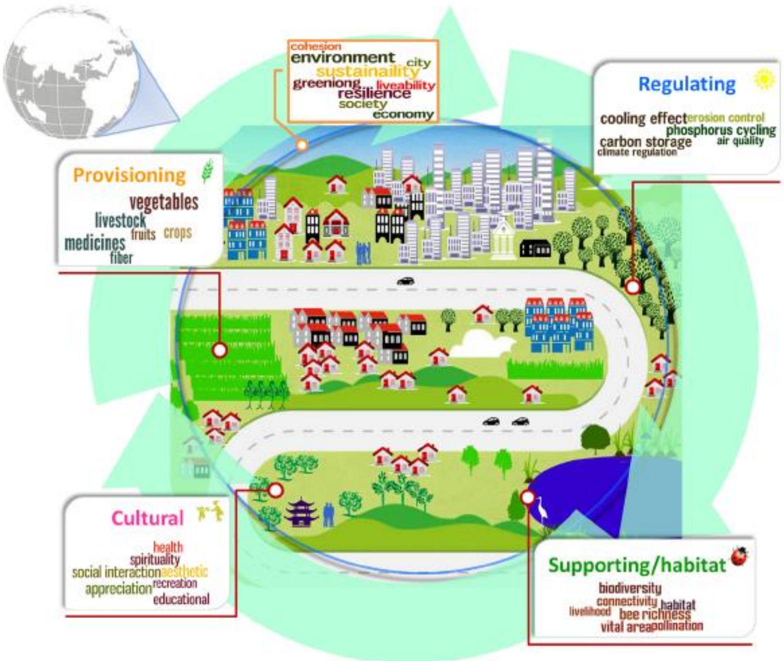


Figure 2.5: Ecosystem services provided at urban level. Examples are illustrative, not exhaustive (figure taken from Pulighe et al. (2016))

2.8 Role of wastewater management in urban green spaces

Urban green spaces can enable sustainable, environmentally-friendly urbanization, and can also be highly effective in mitigating climate change (Haaland & van den Bosch, 2015). However, under the present trend of urbanization in developing countries, urbanization and deforestation are occurring in parallel (Richards & VanWey, 2015). As urbanization increases, the problem of climate change is intensifying due to many factors, mainly, the increased carbon emissions resulting from excessive use of automobiles and deforestation for enabling new urbanization projects (Padigala, 2012). According to Padigala (2012), "haphazard urbanization" occurring in developing countries threatens vegetation. As a result, urban settlements become a major source of greenhouse gas emissions, and at the same time, more vulnerable to global environmental change impacts (Padigala, 2012; Taylor & Hochuli, 2017). Green areas in cities in any shape, form, function, and purpose can consist of open spaces, covered with either natural or planted vegetation (Rakhshandehroo Afshin, et al., 2017). They can be public and private open spaces available for all urban users (Baycan-Levent et al., 2009). In India, there are pockets of green cover in urban areas such as neighborhood parks, roadside plants, and trees (Chaudhary et al., 2011). However, the problem is that of maintenance (Singh et al., 2010).

The main maintenance-related problem is that of irregular watering (Singh et al., 2010). One main objective of this review was to also recognize the importance of planning well and ahead by taking urban green spaces into statutory consideration to be 'smart' as in the smart city concept that was initiated during 2014. A lack therein of suitable planning and provision for urban green spaces can be detrimental to the city's overall wellbeing and being eco-friendly. Using the available information on UGS across different parts of the world, it was also the intent of this review to list a set of possible solutions that lead to sustainable smart cities from the perspectives of being economical, environmentally friendly, and aimed at mitigating climate change impacts.

2.8.1 Treatment and non-potable reuse of wastewater

Water is the world's most precious, life-sustaining resource. This valuable resource is under severe and perpetual threat due to climate change and resulting drought, explosive population growth, and more notably, wastage in many parts of India. As shown in Table 4, the wastewater generated daily in millions of liters is one "cheap" resource waiting to be harnessed. It is easy to see that even if 60 to 75% is treated and reused, the hardship on water demand will be receding several folds. Reclamation and reuse of industrial and municipal wastewater are very promising to stem the water crisis across India. Jhansi & Mishra (2013) have covered many details on the appropriate technologies for wastewater treatment and the benefits of wastewater treatment. The natural water which is subject to purification for potable purposes is currently used in almost every city (except Mumbai where treated wastewater is used for maintaining greenery in some parts of the city. This is one example of treated wastewater used for maintaining the urban green spaces).

The Water Reuse Association defines reused, recycled, or reclaimed water as "water that is used more than one time before it passes back into the natural water cycle" (Jhansi & Mishra, 2013). Recycling or reusing of treated wastewater for agricultural and landscape irrigation, industrial processes, and replenishing a groundwater basin (referred to as groundwater recharge) is the essential requirement in India. Wastewater reuse allows communities to become less dependent on groundwater and surface water sources. This 'renewed' water can be useful by rejuvenating severely overdrawn groundwater resources (Jhansi & Mishra, 2013). Wastewater reuse can decrease the diversion of water from sensitive ecosystems. Such reuse, in particular for irrigating plants and crops, can prevent pollution by siphoning off the nutrient loads from wastewater.

2.8.2 Outlook for urban green spaces through reuse of treated wastewater

The urban areas of many developing countries, including India, are growing rapidly. Thus, the adverse consequences are an ecological imbalance if wastewater treatment and suitable sanitation systems to be implemented are lacking. India has a greater opportunity under the Clean India Mission to achieve self-sufficiency in water supplies to green spaces, a variety of agricultural uses, and for recharging the lost resource of precious groundwater. In doing so, the country can attain adequate sanitation, which can cater to Healthy India, another pan-India Mission. The importance of reusing wastewater in a developing urban society lies in the fact that the wastewater generation usually averages 30-70 cubic meters per person per year. In this arithmetic, reprocessing of wastewater from a city with one million people would be enough to irrigate approximately 1500-3500 hectares of urban green space and farmland. Needless to overly emphasize, a major need exists to harness this "reliable urban resource" advantageously. There is a crucial need for India's current urban development policies to address climate adaptation strategies (Mundhe & Jaybhaye, 2014; Sharma & Tomar, 2010).

Green spaces can significantly contribute to social and environmental urban sustainability, and also to cost-effective climate adaptation and mitigation. There is an urgent need in India to realize these potentials of green spaces. Instead of making efforts to retain the land as an open space, the short-term economic benefits of land conversion are more sought-after, thus leading to short-sighted vision in urban planning in the country (Govindarajulu, 2014). Limited efforts are underway to protect sensitive areas from excessive urban development and make adequate provisions for open spaces.

The Ministry of Urban Development, Government of India, has issued guidelines on Urban and Regional Development Plans Formulation and Implementation to protect environmentally sensitive areas from urban development and provide an adequate network for open spaces. In almost all Indian cities, the public works departments (PWDs) are responsible, among other activities, for handling water supply, sewage collection and treatment/disposal, electricity supply, and road construction and maintenance. The forest and horticulture departments are mostly tasked with all aspects of green spaces in cities. While a lot needs to be advanced in wastewater handling and treatment skills and technologies, efforts to manage this year-round resource of wastewater are afoot under the smart city idea in India. Networking and cooperation between different departments is also to be in place. As highlighted above, there is a much larger scope for treating several more million liters of domestic sewage and ensuring the reuse of treated water for green spacing to bring many benefits.

2.9 Perspectives of green spaces in 'smart cities' of India

Cities in India with populations exceeding 100,000 people can plan and implement all criteria essential for being qualified as a smart city. It is reiterated here that there are parks in all the district headquarters in India, which number over 550. Also, many townships with lesser population counts possess parks, pavement, and avenue plantation. The data on these areas must be collected, pooled, and a comparative assessment of the carbon sequestration potential of all these cities those aspiring to be smart cities soon. In this regard, an estimate of the green spaces available in eight Indian cities and the major types of plants grown are furnished in Table 2.4. Green space includes vegetated areas with trees, shrubs, and grasses. Having realized the effectiveness of vegetation in reducing air pollution, past urban forestry projects in Kuala Lumpur and Manila aimed to increase the area of planted vegetation (Kuchelmeister, 1998).

The civic administrators in India should recognize that the benefits provided by green spaces in cities include reduced energy requirements for cooling and heating in the summer and winter seasons, respectively. Green spaces significantly contribute to enhanced biodiversity of flora and fauna in cities. Fam et al., (2008) highlight that the economic benefits of green open space include income generated from festivals, sporting events, and appreciation of property value. In Indian cities, systematic record-keeping of all the species of plants and the area of urban green spaces, preferably by horticulture departments, is essential not only from the perspective of upholding the healthy-city status but also from showcasing the efforts in place for pollution mitigation and carbon sequestration. It is noteworthy here that some urban forestry projects received finances under carbon sequestration projects (Akbari et al., 1992; Mcpherson & Rowntree, 1993) in several cities in the United States.

A part of Jal Jeevan Mission (urban) is designed to provide a complete cover of urban water supply to all households of 4378 towns in India (Ministry of Housing & Urban Affairs, 2021) in accordance with SDG 6. In addition, sewage/septage management is underway in about 500 towns. These efforts can also help establish and maintain the UGS. The benefits of urban green spaces are not just environmental (Kuchelmeister, 2000). They also encompass the provision of employment, and by cleaning and cooling, improvement of the urban air quality. Strategic tree planting following a well thought out landscaping can aid in saving energy and maintaining ‘cool-comfort’. Since urban trees reduce the need for burning fossil energy, they are a cost-efficient investment for mitigation of greenhouse effects.

Furthermore, urban development agencies of many metropolitan cities have framed several policies and strategies for the protection of open spaces during urban development projects. It is highly essential to develop rules and regulations to set some minimum green space per capita in major cities of India. It is also necessary to have guidelines for improving the green spaces by encouraging the maximum utilization of the available area for ecological and social needs as well as for reducing food miles wherever appropriate by encouraging urban agriculture/farming. At present, more green spaces are being included in future urban development plans in India by the metropolitan development authorities. The several social and urban forestry schemes aim at improving urban green spaces (Govindarajulu, 2014).

The urban forest can play a significant role in making the towns and cities more liveable and better adapted to the rigors we expect from a changing climate. But to do this, and to make it a policy, planning, and public reality, urban forest research needs to embrace transdisciplinary approaches and find ways to better communicate the scientific evidence to a nonscientific audience.

There are continued efforts on developing models that can quantify the role of urban vegetation in removing pollutants from the atmosphere (Nowak & Crane, 2002) around the world. Further, carbon inventory can be used to assess the impact of a land development project on employment, income, and livelihoods through enhanced biomass production, regulatory services, educational and recreational opportunities from the UGS. Making carbon inventories could be helpful for estimating and monitoring the biomass stock or production and soil organic matter. Much more data is essential to have useful models by considering the recent expansion of urban areas.

A key and substantial role in reducing atmospheric concentration of CO_2 can be ascribed UGS too as they do store carbon in above and belowground biomass identical to trees in a forest or in any agroforest. By attaching similar importance as it is for agroforestry practices, the UGS have great potential to add to carbon stocks. For instance, green cover in New York City is reported to annually sequester 22.8 million tons and, store a staggering 700 million tons of carbon (Nowak & Crane, 2002). However, estimates of carbon sequestration potential (CSP) even for the widely investigated agroforestry vary substantially. Due to lack of information, an estimation on how much is the carbon biomass in the trees in city’s UGS and how much is their carbon sequestration potential was attempted in this study.

2.10 Conclusion

Millions of urban inhabitants are still deprived of access to clean drinking water and adequate sanitation services. It is quite common to see wastewater flowing in the streets in many slum and peri-urban areas. The insufficient quantity and substandard quality of water and sanitation services are the major causes for the spread of diseases in developing countries. A large portion of the entire population still lacks access to services such as collection and transportation of wastewater out of urban neighborhoods. Urban green spaces significantly affect the regional micro-climate. They contribute significantly to modulation of climatic extremes, improvement of the hydrological cycle, as well as plant health, etc. The creation of green spaces in urban areas requires supportive policies. Furthermore, education on the important contributions of green spaces needs to be provided on a large scale to facilitate their implementation and funding. It is highly crucial to recycle and reuse wastewater to deal with the problem of depleting groundwater resources. In addition, regular watering of parks, gardens, and roadside vegetation is required to maintain many of these beneficial characteristics of urban green spaces, particularly during drought years. Irrigation of UGS can be conducted through simple yet effective technologies such as drip irrigation. As can be recognized from the foregoing account, there is an urgent need for adequate treatment of wastewater from a larger proportion of the population. Some programs like Smart Cities and AMRUT are aiming to provide ample job opportunities with the support of efficient service infrastructure. The missions such as Smart Cities Mission, Clean India, and Healthy India would become successful when the civic bodies prepare guidelines, implement all mandatory regulations, and administer proactively and efficiently to not only create much needed urban green spaces but also to treat and use multiple times the cheap and mega resource of wastewater to solve many problems including the reduction of carbon footprint due to urbanization.

Chapter 3

Analysis of Land Cover Influences on LST by Using Spectral Indices

3.1 Introduction

Rapidly expanding urbanization taking place in an unplanned manner necessitates knowledge of the extent and shape of the settlement and ecological features (Koomen et al., 2009; Estoque et al., 2015) from the sustainability perspective. The concept of environmentally and ecologically vibrant city development emerged in the early 1970 (Wheeler, 2004). However, the relationship between urban landscape patterns and microclimate needs to be sufficiently understood (Hua & Ping, 2018) for developing urban areas more efficiently. In this regard, information on diverse patterns of land use intensity or spatial growth is essential to delineate both beneficial and adverse impacts on the urban environment. Unplanned spatial growth of cities brings numerous environmental problems, among which the "urban heat island" (UHI) effect is a well-documented climatological effect of human activities on the urban environment (Hua & Ping, 2018). The urban heat islands (UHI) result from the increased heat storage capacity of urban surfaces (Tran et al., 2017). Typically, the concentric urban expansion patterns lead to intensive UHI. To a large extent, the UHIs result from the formation of urban microclimates due to built-up areas, concrete zones, and high concentrations of various human activities. Within the UHIs, the built-up areas are hotter than adjacent/rural areas (Rizwan et al., 2008), causing a local difference in temperatures, which hampers air quality and impacts the environment, thermal comfort, and human health. It also leads to increased energy consumption (Plocoste et al., 2014) for cooling homes and offices. UHIs trap atmospheric pollutants, contribute to increased urban smog formation, and generate socio-economic impacts affecting the quality of urban life. Since urbanization transforms the land use/land cover (LULC) pattern by increasing the built-up areas, the energy balance gets modified resulting in urban areas becoming warmer than the surrounding rural/less-urban areas. Factors that contribute to increased UHI phenomenon include high building density, reduction in UGS, and increases in built-up spaces (Lilly Rose & Devadas, 2009).

The ecological features, such as vegetation and water bodies, are highly sensitive to LST (Feizizadeh & Blaschke, 2013; Sannigrahi et al., 2018; Sinha et al., 2014; Weng et al., 2007). Hua & Ping (2018) demonstrated that LST increases with a decrease in vegetation and an increase in non-evaporative surfaces. The United States Environmental Protection Agency reported that some serious health hazards such as general discomfort, respiratory difficulties, heat cramps, non-fatal heat stroke, and heat-related mortality are rising with the increase of thermal surfaces and a corresponding decrease in cooling surfaces (USEPA, 2017). The Agency suggested that it is possible to reduce UHIs by increasing trees and vegetative cover and by installing green roofs. The increase of vegetation cover and water bodies or decrease in impervious surfaces can help to strengthen Green space Cool Island (GCI) effects (Du et al., 2017; Yu et al., 2018).

The research community can characterize and examine the UHI-landscape relationship due to advances in thermal remote sensing, geographical information systems (GIS), and statistical methods. Policy-makers and researchers have received valuable feedback from several studies carried out dealing with UHI analysis (Tran et al., 2017). Besides air temperature, land surface temperature (LST) derived from remote sensing data is essential and highly reliable in identifying surface UHIs (Imhoff et al., 2010). Nichol & To (2012) reported that between the temperature data collected from urban weather stations (usually within/near a park/shading trees) and the LST derived from remote sensing, the latter can reliably spot the hottest and coolest areas. For inferring the impacts of rapid and/or unplanned urbanization, information on land use intensity in terms of built-up area or bare land in relation to the vegetation cover and water spread area is especially useful and helps to recognize adverse impacts or useful outcomes due to planned urban land use patterns. Analyses of remote sensing data and GIS-based derivation of relevant indices have proven useful in recognizing the changes in land use/land cover (LULC) and deriving variations in LST.

It is vital to investigate the crucial land dynamic processes which significantly contribute to the increase in LST and aggravation of the UHI effect (Yu et al., 2018b). In the absence of ground-based meteorological stations, the spatiotemporal assessment of LST using thermal remote sensing data can help to assess the LST changes and support the policy-makers for eco-sensitive city development (Feizizadeh & Blaschke, 2013; Weng, 2001). As is widely known, remote sensing techniques can also aid in investigating the complex relationship between spatial parameters and thermal conditions over large areas, along with updated spatial information in cost-effective ways. The use of remote sensing indices for earth observation has been well acknowledged by remote sensing professionals. They are widely used for various applications such as detecting environmental changes (Xu, 2006), monitoring urban expansion (Yang et al., 2003), monitoring vegetation and water bodies and their impact on LST (Eswar et al., 2016; Gascon et al., 2016; McFeeters, 1996; Saini et al., 2016; Yengoh et al., 2015). However, there are no comparative assessments of different geographical locations and relationships of UGS, built-up area, and water bodies with LST. The predicted rate and intensity of climate change and higher temperatures in UHIs leading to reduced thermal comfort and increase in energy consumption call for urgently planning, developing, and maintaining the UGS as a major strategy "to adapt to and mitigate the expected continual increase in temperature" (Bowler et al., 2010). Thus, the role of urban greenspace in moderating urban climates is vital. Back in the 1990s itself, Semrau (1992) and Rosenfeld et al. (1998) emphasized that an effective way to reduce or alleviate the effects of UHIs is to increase tree cover area and density.

With the above background, the purpose of this study was to assess the quantitative relationship of urban factors (built-up areas, vegetation cover, and water bodies) with LST using multivariate statistical analysis for two geographically disparate Indian cities: Tumkur and Panaji. As such, the smart city development objectives in both cities do not showcase how land cover changes could affect the LST, UHIs formation, or living conditions. As per the information posted on the Tumkur Smart City website (*Tumakuru Smart City*, n.d.), in Tumkur city, approximately only 37% of the 'smart city' work is completed. Similarly, only ~40% of such work packages are completed in Panaji (personal information).

The developmental plans in both cities do not mention either LST or UHI as features of importance in the expansion and upkeep of smart cities. In this regard, this research is hoped to provide input for inclusion and improving urban planning. Thus, in both cities, much of the developmental work needs to be done not only to consider the impact of increasing LST and UHI effects but also on the maintenance and creation of additional UGS. In view of this, this study aimed to examine how the land cover features affect the LST, which in turn is to be factored in for improving and sustaining the living comfort. The findings of this study are useful to recognize the sensitivity of urban ecological features (green spaces and water bodies) and their influence on LST. By assessing the ecologically and environmentally vibrant cities, which are also proposed to be future smart cities, this study hopes to contribute to the formulation of policy frameworks for sustainable and livable community development (SDG 11) (Avtar et al., 2019). It would also provide information for prioritizing the action plans to mitigate the adverse impact of the destruction of ecological features due to the rapid growth of many cities in developing countries.

3.2 Study Area

Panaji and Tumkur cities were chosen for this study by considering several factors, such as their geographic location, population, and green space cover. Apart from the disparate geographical locations of Panaji (a coastal city) and Tumkur (an interior city), various other factors such as population size, gross domestic product (GDP), and climatic factors were considered. In 2015, both these cities were designated to be developed as smart cities under the National Smart Cities Mission (Ministry of Urban Development, Government of India, 2016). Panaji, as a coastal city, is highly vulnerable to sea-level rise issues via climate change impacts. Located in the interior part of India, Tumkur city is rapidly industrializing and recognized as an important National Investment and Manufacturing Zone (NIMZ) by the Government of India. Panaji city is the capital of Goa state and located at a latitude of 15° 29' 48.3972" N and a longitude of 73° 49' 40.1772" E. Tumkur city is located in the southeastern part of Karnataka state at a latitude of 13° 20' 17.7468" N and a longitude of 77° 6' 5.0760" E. Figure 3.1 illustrates the locations of the Panaji and Tumkur cities in India.

In Panaji city (Ministry of Urban Development, Government of India, n.d.), despite its strength of compact form and mixed land-use, the most noted weakness listed is the lack of adequate and reliable public transport facilities, both within Panaji and for connecting outgrowth areas to Panaji. The main opportunity is the use of mangroves and a network of creeks as natural resources. These blue-green infrastructures can provide ecosystem services to help mitigate the impacts of threats of urban development and climate change events like sea-level rise. Due to rapid urbanization, the city's environmental resources are noted to get adversely impacted, potentially lowering the city's resilience to various natural disasters. Notably, there are serious concerns of heavy losses as well as unsustainable and chaotic situations due to many parameters (impending sea level rise, severe traffic congestion, troubled pedestrian mobility, increased population and vehicles, citizens' health, and livability, and resulting air/noise pollution). It is cautioned that the eventual collapse of the existing infrastructure network will occur if appropriate measures are not taken. However, there is no mention in the city development plan on what the LULC changes can bring about or how the new developments would create UHIs or affect the LST.

The coastal city of Panaji experiences tropical climate with the annual average temperature being 27.4°C (*Panaji Climate: Average Temperature, Weather by Month, Panaji Weather Averages*, n.d.). Temperatures start rising from January to a peak of around 34 °C in April, the hottest month (Fig 3.2a). Thereafter, it declines during the monsoon months of June-September. The average annual rainfall of Panaji is 2,774mm. The city receives over 85% of the total rainfall during June-September. January is the coldest month with a temperature below 26°C. The predominant climate in Tumkur is defined as a local steppe climate, with very little rainfall throughout the year (*Tumakuru Climate: Average Temperature, Weather by Month, Tumakuru Weather Averages*, n.d.) and an annual mean temperature of 24.4°C (Fig 3.2b). The average annual rainfall is 630 mm in Tumkur and October is the wettest month with 140mm precipitation (*Tumakuru Climate: Average Temperature, Weather by Month, Tumakuru Weather Averages*, n.d.). A comparative account of the major features of these cities is furnished in Table 3.1.

Table 3.1: Details of different demographic, meteorological and other parameters from Panaji and Tumkur cities proposed to be developed as smart cities (Ministry of Urban Development, Government of India, 2016)

Parameters	**Panaji**	**Tumkur**
City area (km^2)	21.60	48.60
Geographic location	Coastal	Interior
Land scape	Heterogenous	Majorly plain
Population (2018 estimate)	255,381	512,000
City GDP (Billion US$)	9.22 (2016)	1.14 (2014)
Domestic water supply (MLD)	26	32
Domestic sewage generated (treated)MLD	14-16 (14-16)	26 (0)

With 17 parks in the city limits maintained by the Corporation of the City of Panaji (CCP) and the Forest Department, Panaji city (excluding the areas under the CCP) has about 0.80 km^2 under green cover (Corporation of the City of Panaji & CRISIL Risk and Infrastructure Solutions Limited, 2015). The natural marshy lands and mangroves along the waterfront add to natural, non-curated green areas and act as barriers to prevent monsoonal flooding. The Bhagwan Mahaveer Park maintained by the Forest Department, is the largest green patch in the city. The other 16, mostly small-sized parks plus public gardens, including the forest nursery and roadside plants, add up to about 5% of the green cover.

In Tumkur city, under the Smart City Initiative, there are plans to increase the number (/area) of green spaces. There are four large-sized parks ($\geq$ 5 hectares ($\geq$ 0.05 km^2)) in the city maintained by Tumkur Urban Development Authority (TUDA). A 10 hectare (ha) (0.1 km^2) newly developed Amanikere Park on the area recovered by landfilling the Amanikere irrigation tank. Further, new roads being laid under the Smart City Development Initiative have walk paths, and divider lanes. Suitable plantations on both sides of, and on, the divider in the middle are being made. Unlike the coastal city of Panaji where the monsoonal rains help the green spaces to sustain for quite long periods with once a fortnight watering, Tumkur city in the interior region receives insufficient rainfall. As a result, the existing UGS need watering at least once every week in sufficient quantities to meet up losses, including those occurring through dispersals into the soil.

Panaji and Tumkur are part of the National Smart Cities Mission by the Government of India to make them citizen-friendly and sustainable (Ministry of Urban Development, Government of India, 2016). The Smart Cities Mission initiated in 2015 has inclusive aims by considering all factors essential for sustainable urban development (Prakash, 2017). Necessary infrastructure elements in a smart city listed by Prakash (2017) include adequate water supply, stable assured electricity supply, sanitation (including solid waste and wastewater management), efficient public transport, ease of urban mobility, affordable housing, IT connectivity and digitalization, good governance, sustainable environment, safety and security of citizens, good healthcare, and education/employment opportunities.

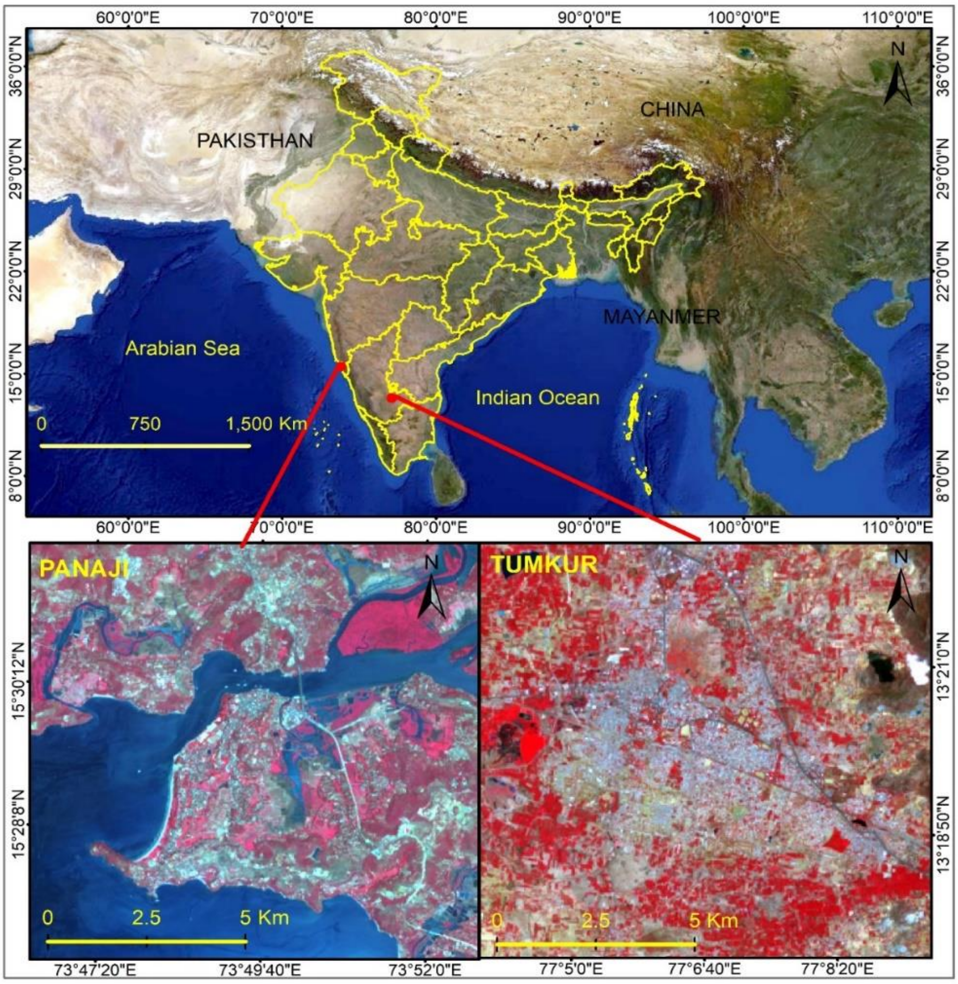
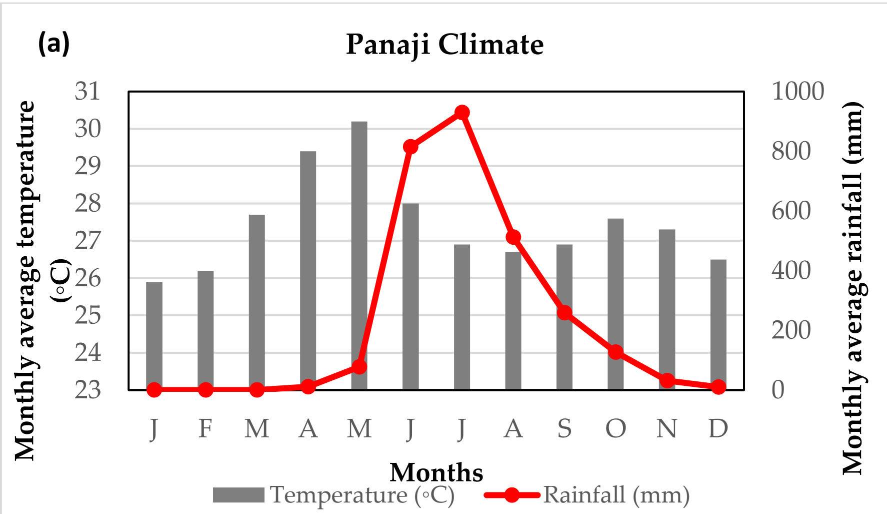


Figure 3.1: Map showing the city areas of Panaji and Tumkur considered for this study.



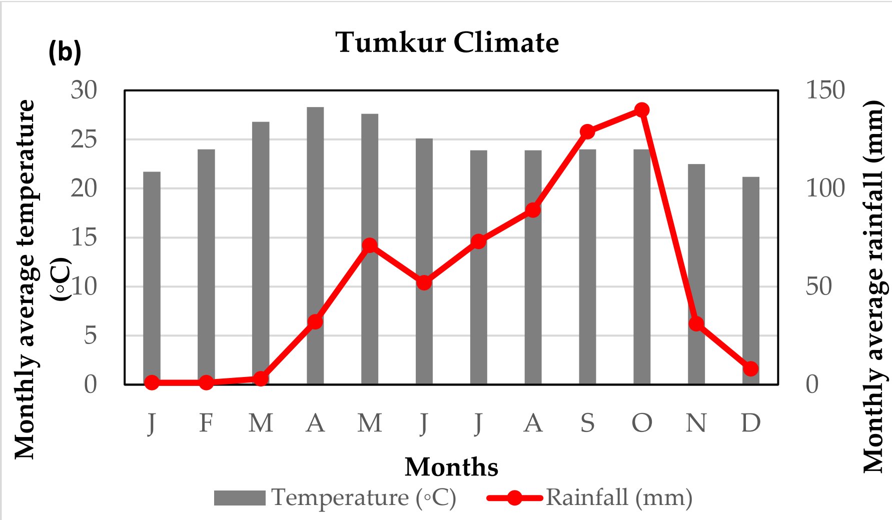


Figure 3.2: Monthly averages of temperature and rainfall data of (a) Panaji and (b) Tumkur.

3.3 Data and Methods

With the introduction of thermal remote sensing, LST information is available from a series of satellite sensors (such as Landsat, MODIS, and ASTER) that cover a wide range of the Earth's surface. Compared to air temperatures collected from weather stations, thermal imagery provides full spatial coverage at various temporal scales (Myint et al., 2013). Figure 3.3 shows the flowchart of the methodology adopted in this study.

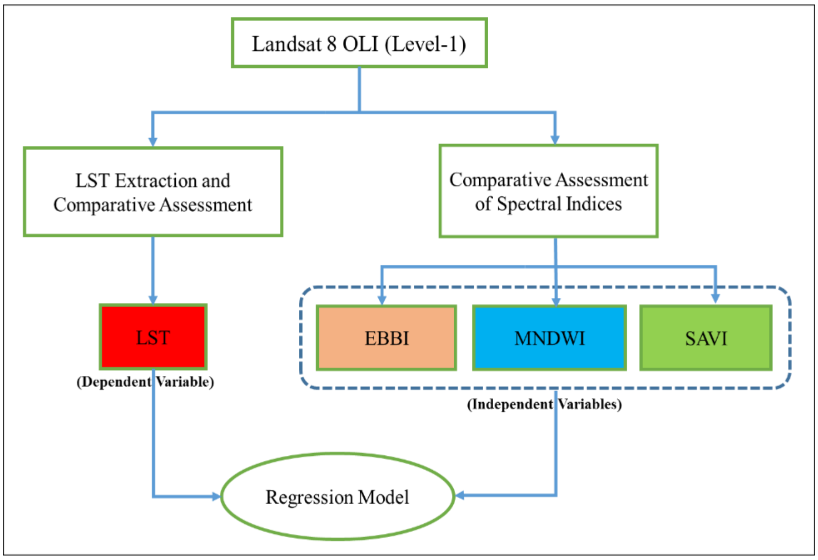


Figure 3.3: Flow chart of the methodology used in this study.

3.3.1 Satellite Data

Landsat-8 satellite data was used to evaluate the response of different land covers on LST. Landsat 8 satellite has Operational Land Imager (OLI) and Thermal Infrared Sensor (TIR). There are nine spectral bands from bands 1 to 9 and two spectral bands from bands 10 to 11 in OLI and TIRS sensors, respectively. Bands 10 and 11 provide atmospheric rectifications for the thermal inferred data (Zhang et al., 2015). Two Landsat-8 OLI/TIRS data of the Tumkur and Panaji areas in 2019 were acquired from https://earthexplorer.usgs.gov/ (*EarthExplorer*, n.d.). Table 3.2 provides details of Landsat-8 data used in this study.

Table 3.2: Path and acquisition details of Landsat-8 data from the study areas

Path/Tiles	Time	Acquisition Date	Cloud coverage	Location
144/51	11:10:20.54 AM	2019-04-14	3%	Tumkur
147/49	11:28:12.31 AM	2019-03-18	1%	Panaji

3.3.2 Field Data

In this study, field surveys were conducted from January - February 2019 to collect ground-truth data for the LULC classification and validation. In the field survey locations of the UGS, built-up areas were marked with the help of a Global Positioning System (GPS) device (Gamin 60x). Various city development offices were also visited to collect secondary information about the landscape, UGS, and city plans. Field surveys were aimed to understand the problems related to LULC patterns in these urban areas and management plans in place to address these problems in both upcoming smart cities.

3.3.3 Methodology

3.3.3.1 Image Pre-processing

The analysis in this study only included the ~98km^2 buffer area from both city centers and Landsat data were clipped for further analysis. Atmospheric correction was done prior to image processing. The aim of atmospheric correction was to derive a good estimate of the true at-ground upwelling radiance (Sonka et al., 1993). The FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubus) model was implemented in ENVI 5.3 platform provided by Harris Corporation in Melbourne, FL, USA.

3.3.3.2 Enhanced Built-Up and Bareness Index (EBBI)

Remote sensing techniques provide an efficient and cost-effective approach to monitor the expansion of the built-up area, in comparison to other traditional approaches (Yang et al., 2003). Previous studies used different indices for the extraction of desired land features. For example, the Normalized Difference Built-up Index (NDBI) was proposed by Zha et al. (2003) for Landsat Thematic Mapper (TM) images, Built-up Area Extraction Index (BAEI) was proposed by Bouzekri et al. (2015) for highlighting built-up areas in Landsat-8 image, improved NDBI was proposed by He et al. (2010) as a semi-automatic approach to extract built-up area, and Enhanced Built-Up and Bareness Index (EBBI) for highlighting built-up land and bare land was proposed by As-syakur et al. (2012). Application of the indices depends on the study purpose, surface characteristics, accuracy level, and satellite image physiognomies. In this study, we used EBBI index for extracting built-up and bare land areas.

A recent study by Li et al. (2017) revealed that EBBI is an effective method for extracting built-up area and bare land cover. In view of this, to distinguish the effect of LST on vegetation cover from the land cover altered due to human-induced activities (built-up) and bare land together, we used the EBBI index for extracting built-up and bare land. Hence, both bare land and built-up area were resulting from urban activities. EBBI is derived using the following equation:

$$EBBI = \frac{(SWIR1 - NIR)}{(10 * root(SWIR1 + TIR))} \quad (1)$$

where SWIR1, NIR, and TIR represent the band-6, band-5, and band-10 of Landsat-8 data, respectively.

3.3.3.3 Modified Normalized difference water index (MNDWI)

Waterbodies can be extracted by using the spectral information of satellite images. Compared to other surface objects, water bodies show a weak spectral reflectance in most of the wavelengths. In this research, we used the band threshold method using band-3 (Green) and band-6 (Mid–Infrared/SWIR1) of Landsat-8 images proposed by Xu (2006) which is the modified index of NDWI proposed by McFeeters (1996) for highlighting water bodies (Xu, 2006), who suggested that water information using the NDWI is often mixed with built-up land noise resulting in an overestimation of extracted water bodies' areas. MNDWI can provide better results as compared to NDWI. Therefore, MNDWI was used in this study. MNDWI is derived from the following equation:

$$MNDWI = \frac{(Green - SWIR1)}{(Green + SWIR1)} \quad (2)$$

3.3.3.4 Soil Adjusted Vegetation Index (SAVI)

The Soil Adjusted Vegetation Index (SAVI) is a useful index for extracting urban area vegetation information. It was proposed by Huete (1988), takes into account the optical soil properties on the plant canopy reflectance, and gathers information for a small amount of vegetation. The use of SAVI is an approach by which spectral indices are calibrated, so that soil substrate variations are effectively normalized without influencing vegetation measures (Huete, 1988). An understanding of soft surface spectral properties, as well as their behavior and interactions with plant life and water, is crucial to development (Qi et al., 1994). Therefore an 'adjustment factor' is used for measuring SAVI with varying vegetation density. A single adjustment factor (L= 0.5) was adopted in this analysis to shrink soft (moisture, organic inputs, erosion, and cultivation) noise considerably throughout the range in vegetation densities. SAVI, involving a constant L to the NDVI equation with a range of -1 to +1, is expressed as follows:

$$SAVI = \left(\frac{NIR - Red}{(NIR + Red + L)}\right) * (1 + L) \quad (3)$$

Two or three optimal adjustments for L constant (L=1 for low vegetation densities; L=0.5 for intermediate vegetation densities; L= 0.35 for higher densities) were suggested by Huete (1988) wherein NIR and Red represent the band-5 and band-4 of Landsat-8 data, respectively.

3.3.3.5 Land Surface Temperature (LST)

The land surface temperature was calculated using the standard methodology. Based on Weng et al. (2004), a two-step process was followed to derive the brightness temperature of the land. The DN values of each Landsat image band were scaled from the total radiance calculated to byte values before media output using the gain and bias (offset) values given for each group. The DN values can be transformed back to the radiance units using the following formula:

$$\text{Radiance } (L\gamma) = M_L\text{*Band } 10 + A_L \quad (4)$$

where, M_L represents the band-specific multiplicative rescaling factor and AL represents the band-specific additive rescaling factor. ML and AL can be obtained from the header file of the satellite data.

Once the DN was converted to radiance values, we calculated the brightness temperature (Bt) using the following equation:

$$Bt = \left(\frac{k2}{\ln \left(\frac{k1}{L\gamma}\right.} + 1 \right) - 273.15 \quad (5)$$

where K1= Band-specific thermal conversion constant (K1_CONSTANT_BAND_10) and K2 = Band-specific thermal conversion constant (K2_CONSTANT_BAND_10), we can find the constant from the image header file.

Thereafter, the Surface emissivity (ε) was calculated using the proportion of vegetation coverage (P_V). The following two equations were used:

$$Pv = square\left(\frac{SAVI - SAVI\_min}{SAVI_{max} - SAVI\_min}\right) \quad (6)$$

Surface emissivity $\varepsilon = .004 * Pv + 0.986$

where, 0.004 and 0.986 are the correlation values of surface emissivity. After calculating the brightness temperature and surface emissivity, the LST was calculated by using the following equation:

$$LST = \left(\frac{Bt}{1 + .00115 * \frac{Bt}{1.4388}} \right) * Ln(\varepsilon) \quad (7)$$

where, 0.00115 and 1.4388 are the correlation values of LST.

3.3.4 Statistical Analysis

To find out the significance of changing urban green cover and the impact on urban microclimate, we developed a regression model. Regression analysis is a form of predictive modelling technique that investigates the relationship between a dependent (target) and independent variable (s) (predictor) (Tirta et al., 2017). It expresses the strength of the impact of multiple independent variables on a dependent variable (Dobson, 2013). In this study, “Stepwise Regression” model was used. The selection of multiple independent variables was done with the help of an automatic process without human intervention. This technique basically fits the regression model by adding/dropping co-variates, one at a time, based on a specified criterion. In this study, LST was the dependent variable; while EBBI, MNDWI, and SAVI were the independent variables. The aim of this modelling was to investigate the significance of the presence of built-up area, water bodies, and vegetation on LST in the urban area. Equation 8 illustrates the regression model.

$$LST = \alpha o + \beta 1 x 1 + \beta 2 x 2 + \beta 3 x 3 + e \quad (8)$$

where, α_o, β, x, and e stand for constant, coefficient, variables, and significant error, respectively.

3.4 Results

The widely employed Spectral Indices is a reliable indicator for closely observing Earth surfaces using remote sensing technology. The EBBI is the built-up and bare land index that applies near-infrared (NIR), short wave infrared (SWIR), and thermal infrared (TIR) channels simultaneously (As-syakur et al., 2012). Vegetation has a high reflectance in NIR, but the reflectance of built-up or bare land is low. In contrast, TIR has high reflectance to detect built-up areas as compared to vegetated areas, thus making it effective for built-up areas mapping (Herold et al., 2003).

3.4.1 Comparative analyses of various indices

Spectral Indices utilize spectral reflectance properties to distinguish different LULC classes present in the study area. EBBI, MNDWI, and SAVI indices as discussed in Section 3.3 were calculated using Landsat-8 data. Later, a non-parametric support vector machine (SVM) classifier was used to extract LULC to validate the findings of indices. Figure 3.4 shows the EBBI, MNDWI, and SAVI indices for both Panaji and Tumkur cities.

Visual interpretation of extracted spectral indices for EBBI is useful to recognize lower reflectance in Panaji (Fig. 3.4a) than Tumkur (Fig. 3.4b). It can, therefore, be inferred from the images that EBBI is high for the Tumkur area, indicating that the percentage of the built-up and bare land area is more than twice that of Panaji. The MNDWI also depicts a much higher waterbody coverage area in Panaji (Figure 3.4c) than in Tumkur (Figure 3.4d). Most of the area in Panaji is surrounded by water bodies compared to that of Tumkur (Figure 4c). Similarly, the SAVI is quite high for Panaji (Fig. 3.4e) compared to Tumkur (Fig. 3.4f). In Panaji, the vegetation is distributed evenly within the city area. Besides, the higher reflectance value of SAVI is witnessed in the Panaji area than Tumkur. Panaji city has much more, evenly spread green areas than can be visualized for Tumkur city where green areas are distributed rather sparsely, unevenly, and mostly in the peripheral parts of the city. A clear gradient from the city core to the peripheral area is discernible (Fig. 3.4f). There is a tradeoff between urban ecological features (green spaces and water bodies) and built-up areas. Therefore, Tumkur city needs a better urban green space management plan for smart city development to improve the ecosystem services.

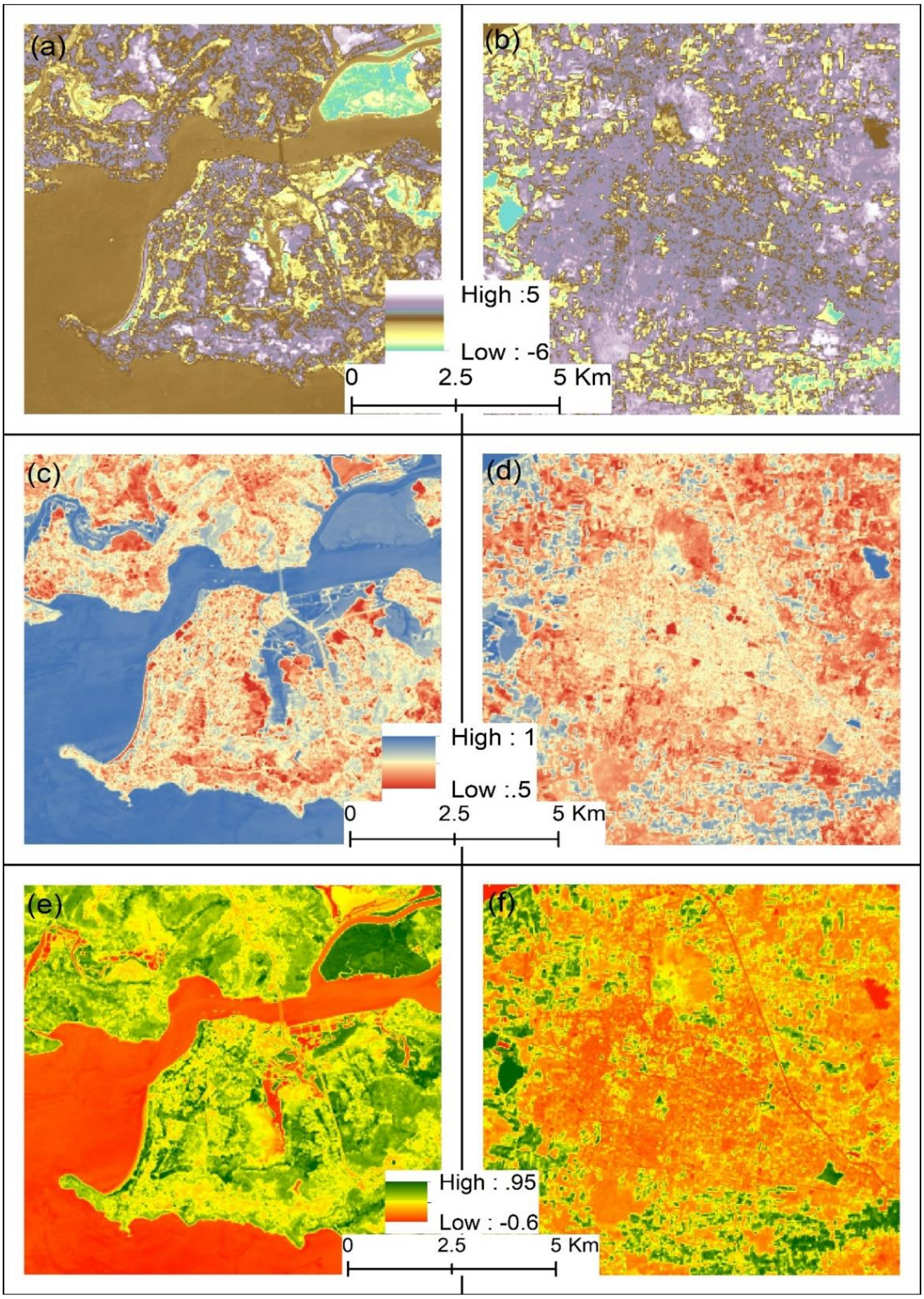


Figure 3.4: Images of EBBI for Panaji (a) and Tumkur (b); MNDWI for Panaji (c) and Tumkur (d) and SAVI for Panaji (e) and Tumkur (f)

3.4.2 Land Use Land Cover (LULC)

To examine the spatial pattern of LULC in Panaji and Tumkur, SVM classification was performed in ENVI for 2019. The LULC map was cross-checked with recent Google images. A total of 179 and 251 training samples were taken for Panaji and Tumkur, respectively. For the validation of LULC map, 120 and 95 samples were used to validate the results in Panaji and Tumkur, respectively. The classified images showed an overall accuracy of 90.31% and a Kappa coefficient of 0.83 for Panaji and overall accuracy of 89.78% with Kappa coefficient of 0.79 for Tumkur city. Figure 3.5 illustrates the LULC pattern of the Panaji and Tumkur cities. An accuracy assessment of classified maps was done using a confusion matrix. Appendix A1 and A2 illustrate the overall accuracy of LULC maps and Kappa coefficient based on the confusion matrix. In Tumkur, the built-up class was the most dominant land cover type in 2019, representing 41% of the total area; followed by bare land (33%), vegetation (30%), and water bodies (1%). In Panaji, 32% of the land area is covered with water bodies class; followed by built-up (32%), vegetation (24%), and bare land (12.49%). Table 3.3 shows the area of various LULC classes in the study area. Most of the area of Panaji is covered by water bodies and vegetation, whereas Tumkur is covered by built-up and bare land. Therefore, the functional characteristic of LULC is completely opposite for the two cities. Tumkur is dominated by the LULC of urban activities, while Panaji, by urban ecological features.

Table 3.3: Percentage of satellite derived LULC for Panaji and Tumkur areas covered for this study.

LULC	**Panaji area in km^2**		**Tumkur area in km^2**	
Built-up area	31.65	32%	40.01	41%
Bare land	12.49	13%	32.20	33%
Water bodies	30.17	31%	0.97	1%
Vegetation/agriculture	23.78	24%	24.4	25%

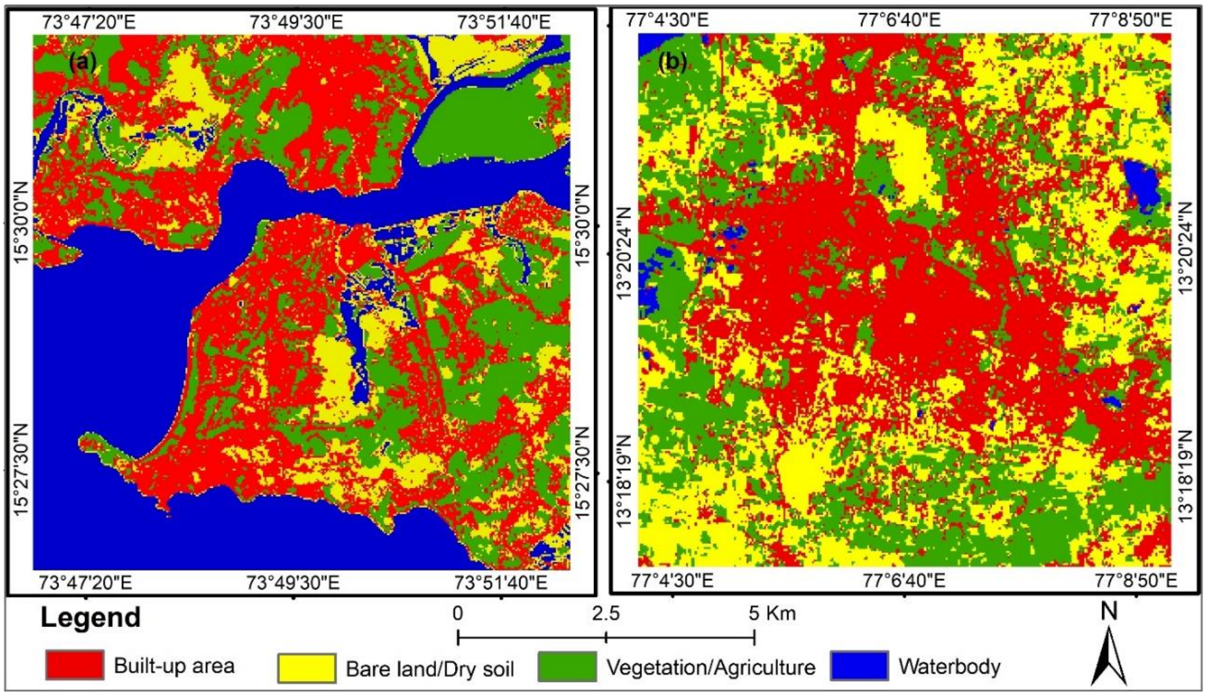


Figure 3.5: Land use/land cover profile of Panaji (a) and Tumkur (b)

3.4.3 Land Surface Temperature (LST)

The LST estimated by using the radiative transfer equation algorithm using TIR-band is effective for deducing surface emissivity in the urban landscape (Rahman et al., 2020). This technique is used to recognize the response of different thermal properties on the Earth's surface. The response of such thermal properties varies with different landscape patterns, different geographical locations, and climatic conditions such as rainfall, wind speed, etc. Also, the land cover dynamics *viz*, agriculture/vegetation, waterbody, built-up area, bare land, etc. seriously affect the LST variations (Rahman et al., 2020). The LST images for Panaji and Tumkur (Figure 3.6a and 3.6b) indicate a temperature range of 34 -

38℃ in most area of Panaji and 42 - 46℃ for the most area of Tumkur city. Largely, the LST pattern in Panaji is mostly homogeneous, unlike the quite heterogeneous one of Tumkur. In Panaji, about 35% of the area is covered by water bodies and experiences temperatures <30℃. In Tumkur, only a few places close to water bodies and vegetation experience <30℃. The maximum LST of (≥) 46℃ is observed in approximately 4% of the land area of Tumkur city. On the other hand, in Panaji, the LST maximum of 42℃ to 46℃ is in <1% of the land area. The maximum and minimum LST differences are lower in Panaji (12℃) and more in Tumkur (16℃).

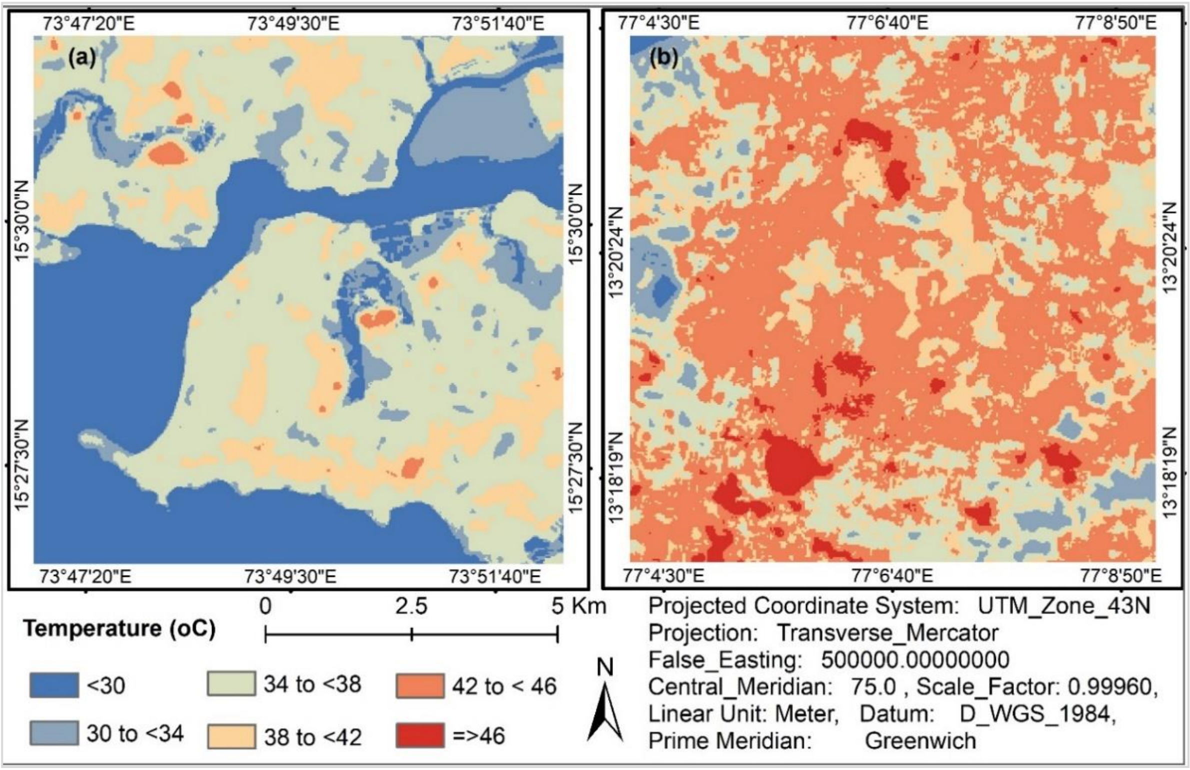


Figure 3.6: Land Surface Temperature profile of Panaji (a) and Tumkur (b)

3.4.4 Relationship of LST and EBBI, MNDWI, and SAVI

Figure 3.7 illustrates the non-parametric test with indices of urban features and LST. Generally, LST bears a negative relationship with SAVI and MNDWI, and a positive relationship with EBBI. The 30m×30m pixel-based correlation coefficient values between LST and SAVI, MNDWI and EBBI were significant (P<0.01). The EBBI had a strong positive correlation with LST among these three indices for both cities (Figure 3.7a, 3.7d). This implies that both bare land and built-up are causes of high LST in both cities. The SAVI and MNDWI indicate a strong negative correlation with LST for both cities (Figure 3.7b, 3.7e, 3.7c, and 3.7f). A weak correlation of -0.37 between LST and SAVI is seen for Panaji compared to Tumkur with a strong correlation of -0.75. This may be due to a low UHI effect in Panaji compared to Tumkur. Besides, Panaji city being located near the seashore and interspersed by water channels, experiences minimal LST differences.

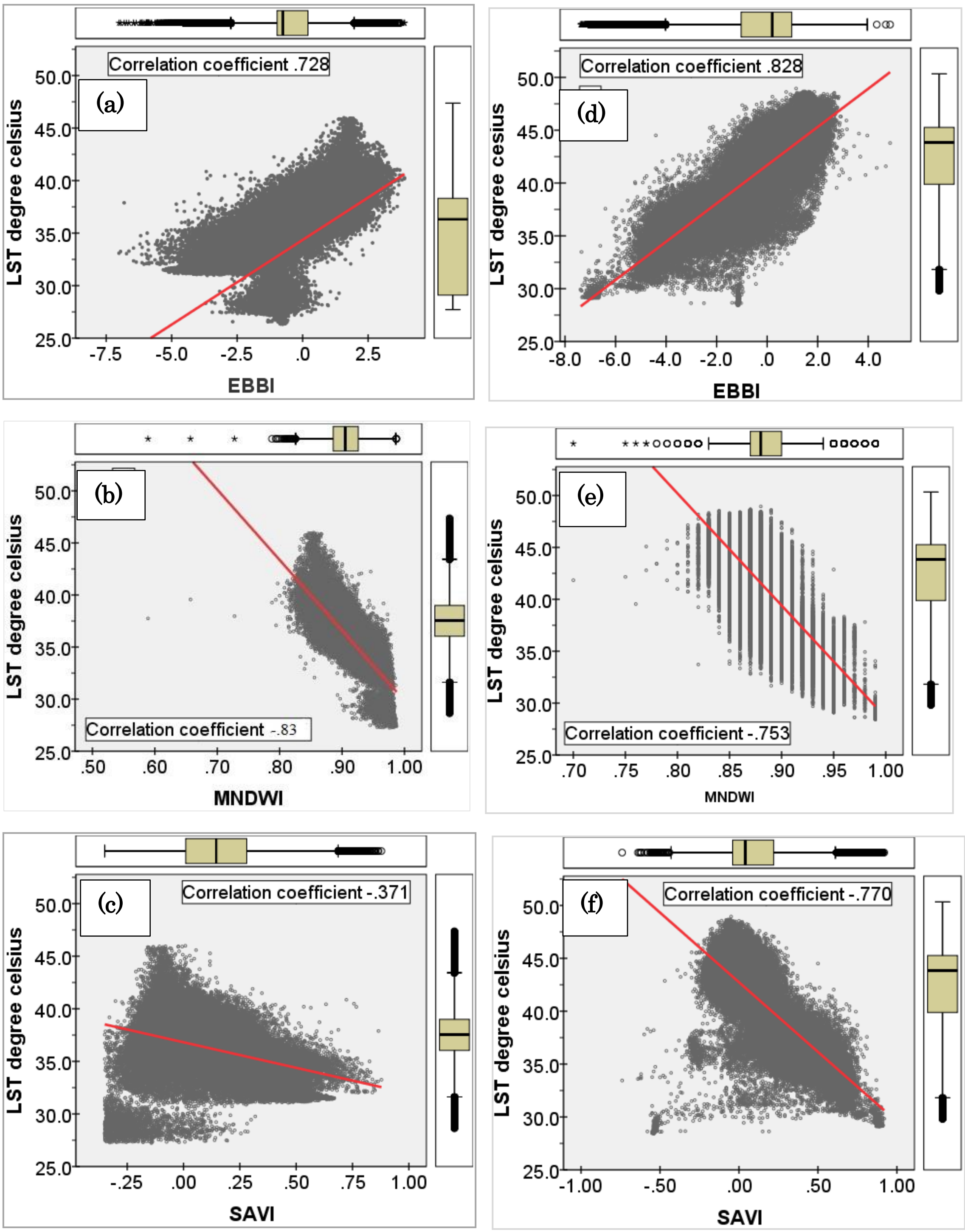


Figure 3.7: Correlation coefficient values between LST (dependent variable) and other indices (independent variables) obtained through the analyses of data from Landsat OLI for Panaji (a, b, c) and Tumkur (d, e, f).

3.4.5 Regression Model

The multivariate regression model derived in this analysis is useful to denote the relationship between LST and EBBI, MNDWI, and SAVI. LST being the dependent variable, is affected by EBBI, MNDWI, and SAVI (the independent variables). The adjusted R^2 in the linear regression model is 0.698 (with standard error 1.407) for Panaji city. A high 0.582 Durbin-Watson d (within the two critical values of $0 < d < 2$) signifies a strong linear autocorrelation. Like Tumkur, the highly significant F-test ($P<0.0001$) ascertains that the model explains a significant amount of the variance in LST. By subjecting all variables to multiple linear regression, it is inferred that SAVI, MNDWI, and even EBBI serve as significant predictors as there was a high level of significance ($P<0.0001$) between LST and all three independent variables. The significance level for SAVI, MNDWI, and EBBI is less than 0.0001. We also observe that the impact of EBBI and MNDWI is higher than SAVI by comparing the standardized coefficients (beta coefficient for SAVI = -0.168, MNDWI= -1.06 and EBBI= 0.00338). From the multiple linear regression model, the following relationship is predicted among LST and EBBI, MNDWI, and SAVI for Panaji city with unstandardized coefficient of the variables.

$$\text{LST (Panaji)} = 114.531 + 0.563\ \text{EBBI} - 86.349\ \text{MNDWI} - 2.206\ \text{SAVI} \quad (9)$$

For Tumkur city, the adjusted R^2 value is 0.716 (with a standard error of 1.97). The Durbin-Watson *d* being 0.578 brings forth a strong linear autocorrelation between different variables used for multiple linear regression analyses. With the F-test revealing a highly significant ($P<0.0001$) relationship, it is confirmatory that this model explains a significant amount of the variance in LST for Tumkur city. By forcing all variables into the multiple linear regression, it can be discerned that both SAVI and MNDWI are significant predictors. The level of significance for SAVI and MNDWI is a high of < 0.001, while for EBBI, it is low of 0.058. We also observe that the impact of SAVI and MNDWI is higher than EBBI by comparing the standardized coefficients (beta coefficient for SAVI = -0.483, MNDWI= -0.439 and EBBI= 0.016**).** From this multiple linear regression model, the following relationship among LST and EBBI, MNDWI, and SAVI is predicted for Tumkur city with an unstandardized coefficient of variables.

$$\text{LST (Tumkur)} = 97.80 + 0.036\ \text{EBBI} - 62.987\ \text{MNDWI} - 8.272\ \text{SAVI} \quad (10)$$

From checking for normality of residuals with a normal P-P plot (Fig. 8), it can be inferred that the points generally follow the normal –diagonal- line with no strong deviations indicating a normal distribution of residuals for both cities. Apparently, the regression model developed in this analysis is applicable only for these cities. Owing to geomorphological heterogeneity of different cities, future studies can consider inputs of land cover variations using this strategy.

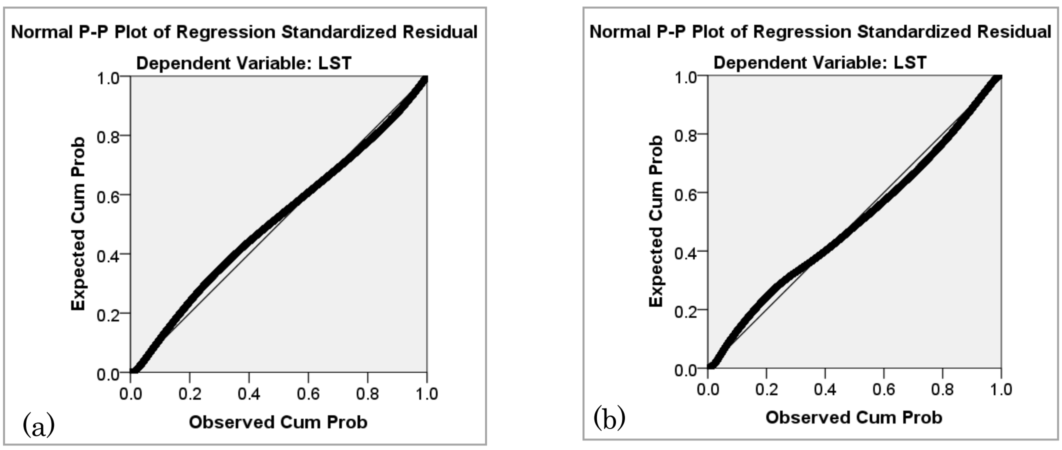


Figure 3.8: Expected cumulative probability *vs* Observed cumulative probability plots (P-P plot) for Panaji (a) and Tumkur (b)

3.5 Discussion

This comparative study focused on spectral indices and their influence on LST in the coastal city of Panaji and the interior city of Tumkur slated for development as smart cities. Low urban landscape patterns in Panaji are mixed with built-up areas and vegetation. There is a possibility of confusion to extract built-up areas using EBBI approach. Ahmed et al. (2014) reported that the tremendous pressure of urbanization on the peripheral area of a city leads to the conversion of non-built-up areas (green area, agriculture land, waterbody) to built-up areas. The first step of such a conversion process is ecosystem sensitive land cover to bare land and finally, it is replaced by built-up area (Alam, 2018). In this context, Tumkur is environmentally more vulnerable as compared to Panaji due to the presence of more bare land.

3.5.1 Land Use Land Cover (LULC) Influences on Land Surface Temperature (LST)

MNDWI can extract the water information efficiently from both built-up and non-built-up areas. It can dampen the built-up land information effectively while highlighting water information and can accurately extract the water bodies information (Xu, 2006). Although, from a statistical perspective, when most land cover types differ from each other, the MNDWI's efficiency in identifying water, saturated soil, or different water content of the vegetation can lead to misclassification. Biggs et al. (2016) emphasized that the presence of water bodies (ponds, small lakes, low-order streams, ditches or springs) are critical for freshwater biodiversity and are increasingly recognised for their role in a variety of ecosystem services as well as the aquatic ecosystem. Jackson et al. (2004) reported that MNDWI is positively correlated with vegetation water content and useful for assessing the extent of strains of drought in any area. In Tumkur, where the availability of water bodies is minimal, it can be suggested that the functioning of urban ecosystem services is negatively affected, and vegetative areas might experience water stress during summer. The high value of MNDWI in Panaji is related to high vegetation water content and it might help vegetation to have less water stress during summer.

SAVI is the measuring index for vegetation or green spaces which has more functional value for the urban ecosystem. The significant coefficient of the regression model illustrates that MNDWI and SAVI are accountable for combatting LST. Although the percent share of SAVI and MNDWI is higher than that of built-up and bare land, MNDWI was the most significant predictor for controlling LST in Panaji, while SAVI was the important predictor for Tumkur.

Surface temperature also has a direct interaction with LULC characteristics (Quattrochi & Luvall, 1999). Therefore, the analysis of the relationship between LULC and LST is crucial to understand the effects of LULC on UHI. The land cover dynamics are accountable for elevated or decreased LST. Higher/significant correlation coefficient values between LST and EBBI, MNDWI, and SAVI for Panaji and Tumkur cities clearly reflect that both bare land and built-up area cause, accelerate, and sustain higher LSTs. It can be inferred that the existing coverage of water bodies in Panaji seems to dampen the LST to a greater extent when compared to Tumkur. Both LULC and spectral indices, as well as the observed higher LST in Tumkur, signify inefficient ecosystem services than a better service possible in Panaji city. With much lower vegetation cover in Tumkur, the degree of absorption of solar radiation by built-up and dry soil drastically elevates the LST and alters the conditions of the near-surface atmosphere (Mallick et al., 2008) over Tumkur city.

Tran et al. (2017) inferred that absolute LST is useful in characterizing UHIs on a short-term basis (particular date) but not effective in comparing spatial patterns of UHI through time. To ensure that LST values retrieved from different images are comparable, Walawender et al. (2014) had proposed the use of normalized LST to investigate the LST spatial distribution in relation to LULC. Many earlier studies (Yuan & Bauer, 2007; Adams & Smith, 2014; Rotem-Mindali et al., 2015) had emphasized that the simulation of future LST, based on LULC, helps in mitigating UHIs effects and in adopting new strategies and policies in land use planning and urban design to reduce/control the UHIs effect. In view of such possibilities, it can be inferred from our analyses that both the cities are prone to increased LST for reasons mentioned earlier. Further, as Guo et al. (2015) and Guo et al. (2016) recommend, these cities would be better placed for LST prediction by taking into account the complex landscape structure and urban morphology heterogeneity. Results of this study showcase the effectiveness of the spectral indices derived in identifying the LST differences within the study area and in marking UHIs. These could provide crucial feedback to planners and policymakers for the inclusion of UHIs mitigation measures.

In general, LST is negatively correlated with SAVI and MNDWI and positively correlated with EBBI. But, these relationships tend to change with UHI (Alam, 2018). With both SAVI and MNDWI bearing a stronger correlation with LST in both the cities, it can be suggested that the impact of UHI is strong in at least over 50% of the areas. Guha et al. (2020) reported that vegetation areas have a much better negative correlation with LST, but these relationships gradually weaken with the increase of the heterogeneous surface features. Although Panaji has a smaller urban area compared to Tumkur, the large water body, forest cover, and hilly features render Panaji city as a heterogeneous surface than Tumkur city located in the plains of India's interior. A weak correlation (R^2= 0.37) in Panaji city and a significant correlation (R^2= 0.75) between LST and SAVI in Tumkur city can be taken to suggest that there is lower UHI effect in Panaji city than in Tumkur city, a fact that can be confirmed through visual analyses of the images (Fig. 5). In Panaji city located near the sea, the water channels surrounding the city area are minimizing the LST differences

Though there is more green cover in Panaji, it is inadequate according to the Urban and Regional Development Plans Formulation & Implementation (URDPFI) guidelines (Corporation of the City of Panaji & CRISIL Risk and Infrastructure Solutions Limited, 2015). Currently, existing roadside plants and 17 parks are irrigated by the Public Works Department (PWD) by diverting an unspecified volume of urban drinking water supplies. While over 70% of domestic sewage is claimed to be treated, all the treated water from Tonca sewage treatment plant (STP) is drained into an adjacent polluted creek 'to improve its water quality' (Appendix A1 and A2).

In Tumkur, under the Smart City Initiative (Sharma, 2018), there are plans to increase the number(/area) of green spaces. Unlike in Panaji where the monsoonal rains help sustain green spaces for quite long periods (with once a fortnight watering), Tumkur, located in the interior region, receives less rainfall. Thus, a 150 km-long canal is planned for potable water supply from River Hemavathi to this rapidly urbanizing, water-scarce city. Besides meeting drinking water demand, the canal is expected to help meet water requirements for existing and planned parks and roadside vegetation. To provide respite from unhealthy LST and UHI impacts, maintenance of existing parks, adding many more new ones, and roadside trees to increase the green cover are vital steps. The fact that urban greening would help overcome the adverse effects of elevated LST (Estoque & Murayama, 2017; Zhang et al., 2017; Estoque et al., 2017) ought to sensitize the development of both Panaji and Tumkur as smart cities. Further, as Thapa & Murayama (2009) and Ramaiah & Avtar (2019) suggest, green areas must be considered. As reported from Dhaka (Mustafizur et al., 2019), with the percent share of urban green areas getting reduced due to unplanned urban activities and weak land-use zoning regulations, Tumkur city needs a sound urban green space management strategy.

While some alternative options exist for surface water (such as groundwater, water supply from outside the urban areas, treated urban wastewater), there are no alternatives for green spaces and their services. Green spaces not only control LST; they also provide recreational facilities, beautify the city, contribute to atmospheric oxygen, purify the air for maintaining ecological balance and for the upkeep of biodiversity (Niemelä et al., 2010). From a significant positive spatial autocorrelation observed between LST and greenspace area within the chosen section/s of expansive Beijing, Li et al. (2012) suggested that green spaces bring down summertime LST by 5 °C.

In Tumkur city in particular, UGS can reduce temperatures through direct shading and evapotranspiration, and as Tyrväinen et al. (2005) recommended, they can create a local cool island within this sprawling urban area. With proper maintenance practices, including the use of treated wastewater, the existing vegetation in its 400 plus listed parks in addition to new ones (including roadside plantation) can also achieve many other environmental benefits such as reduced rainwater runoff, greater urban biodiversity, and improved aesthetics (Kong et al., 2007; Kong et al., 2010). Although there may not be a linear relationship between the cooling effect and the size of greenspace (Cao et al., 2010), there would be discernible cooling effects in specific locations with denser vegetation. These desirable services are necessary for a high-quality living environment. The use of advanced remote sensing techniques can help in the development and maintenance of UGS as part of the smart city programs and implementation of SDGs 11.

3.5.2 Treated wastewater for trees as an option for urban heat (LST) balancing

The urban heat island is indeed an acknowledged real phenomenon. Increased exposure to it discomforts urban life leading to health problems. The UHI in towns and cities can be hazardous due to heat stress, with a potential of heat stroke (USEPA, 2020). Invariably, the UHIs lead to increased energy use for building space cooling. Several investigations and sophisticated climatic and physiological models. For instance, Bolund & Hunhammar (1999) and Ballinas & Barradas (2016) have helped recognize the potential of urban forests in mitigating heat island effects by reducing the LST. These studies are useful to note substantial cooling and shading benefits from the daily rates of evapotranspiration both by individual trees and other plants in a social urban forest. Thus, the regional evapotranspiration rates derived in this study for Panaji and Tumkur cities can help to discern the importance of UGS in achieving urban heat balance.

It was learnt during the survey that there are many parks in these cities that are hardly watered during April-June, the intense summer months in India due mainly to dried up borewells, and to a shortage of drinking water supply to many/some city-areas. The absence of watering leads to wilting of some -and drying up of many- plants. During these times of raised LST, there is discomfort for urban pedestrians, toiling peoples, and commuters, among others.

Perhaps, a comparison of LST of Panaji and Tumkur cities is contextual here. From the recent study of Ramaiah et al. (2020), it was evidenced that the coastal city of Panaji experiences annual LST variations in 38-42 °C ranges with fewer least UHIs. The city is built on a quite heterogeneous landscape, receives higher rainfall, has large water spreads, and maintains a near-optimal percent of green cover. Unlike this, Tumkur city in the interior region experiences far higher LST varying between 42 and 48 ◦C with higher numbers of UHIs. Plain landscape, arid zone, suboptimal green cover area, sparse water spread, sizable industrial activity, and continuously intense traffic on the 15 km-length of national highways passing through the city render the city vulnerable to higher LST.

3.6 Conclusion

Any existing urban fabric would lead to rapid changes in the urban environment whenever altered. This, in turn leads to deviations in urban settings in a variety of ways. Thus, urban settlements ought to plan and create facilities/amenities that are ergonomic, long-lasting, and encompassing. This study compares two upcoming smart cities (Panaji and Tumkur) in India using landscape sensitivity analysis and its influence on LST. The urban factors such as EBBI, SAVI, and MNDWI influence the LST in both cities. The study reveals that water bodies and green spaces are actively responsible for dampening LST. The performances of LST dampening depends on the maximum share of cooling surfaces (water bodies and green spaces) in the study area. In the Panaji, the correlation coefficient between EBBI, SAVI, and MNDWI with LST is about 0.72, -0.37 and -0.83, respectively. On the other hand, in the Tumkur, the correlation coefficient between EBBI, SAVI, and MNDWI with LST is about 0.829, -0.77 and -0.753, respectively. The multivariate regression model reveals that in the Tumkur, the adjusted R^2 of the developed model is 0.716 with the standard error 1.97 and in the Panaji, the adjusted R^2 of the developed model is 0.698 with the standard error 1.407. This study did not consider the local climate issues such as wind speed, rainfall, topography, and functional activities of the urban area (eg., industrial and economic activities, building densities, transportation) may reinforce the findings. Therefore, there is a need to consider these limitations open for further investigations. The use of advanced remote sensing techniques can help to maintain urban green spaces for healthy and livable city development. The analyses of this study would serve as guidelines for an in-depth investigation of the significance of urban green spaces in controlling/reducing urban heat island effects.

Chapter 4

Water Requirements of Trees, Hedge Plants and Lawns in UGS

4.1 Introduction

The importance of vegetation within and around the urban areas is recognized variously. These urban green spaces (UGS) can be regarded as "lungs of city" and reservoirs of "carbon stock" for removing CO_2 from the atmosphere and giving out oxygen. Offering a broad range of benefits, their major ecosystem services of sequestering and storing large amounts of carbon (Pereira et al., 2012) contribute to mitigation of climate change. With expanding urbanization globally, even the smaller share of carbon sink from the urban vegetation is vital and must be facilitated by proper maintenance. Further, creating newer UGS for mitigating the increased land surface temperature (LST) and urban heat islands (UHI) improves the urban living comfort.

Water requirement of plants is overly complex to predict in practice (Nouri et al., 2013). To achieve "good vegetation appeal" in the UGS, irrigation and/or rainfall should substitute the total water lost through evapotranspiration (ET_o). This ET_o is the sum of water lost through natural evaporation and plant transpiration. Evapotranspiration has great ecological relevance. For instance, with growing populations, there is an increasing demand for water resources (Govindarajulu, 2014). For minimizing or, avoiding competition for limited water resources, utilizing water efficiently is important for both landscape and agricultural irrigation. An estimate of evapotranspiration is essential for water management for a good upkeep of landscaped plots in urban areas (Pereira et al., 2012), which offer a variety of ecological and societal services.

Estimating landscape irrigation requirements and ET_o can be problematic due to mixtures of plants, small plots of vegetation, and multiple microclimates (Nouri et al., 2013). To arrive at a helpful process for landscape water management practices, several approaches have been tried. Among them, the Landscape Irrigation Management Program (LIMP) (Romero & Dukes, 2010), the Water Use Classification of Landscape Species (WUCOLS) (Costello et al., 2000), and Simplified Landscape Irrigation Demand Estimation (SLIDE) Rules (Kjelgren et al., 2016) rely on deriving appropriate coefficients for estimating landscape evapotranspiration to help the landscape managers in defining programs to improve landscape irrigation requirement (Snyder et al., 2015). Ideally, it would be better to calculate water requirements based on local ET_L or local reference evapotranspiration (ET_{oL}). This ET_{oL} is an estimate of the ET_o for the local climate "if it were possible to measure weather data over a well-watered grass surface to determine ET_o in the local climate" (Snyder et al., 2015).

Worldwide, the estimated ET_{oL} (or those evolved by the FAO calculated based on local microclimate data) are adapted for working out the plant water requirements. In these efforts, the same standardized reference ET_o equations are used for deriving the regional ET_o. Since no study hitherto has provided ET_o-based daily water requirements for the UGS in almost all cities of India or in many Asian cities, one of the objectives was to derive ET_{oL} for Panaji and Tumkur cities chosen for this study. This approach was to provide a basis for estimating the daily water requirement (DWR) in a select few parks surveyed from Panaji (Sep-Oct 2020) and from Tumkur (Jan 2019). As detailed later in Chapter 6, the other objective was to examine the feasibility of whether treated wastewater (=recycled water) available regularly would be considered for irrigating the parks and gardens.

4.2 Methods and Data

4.2.1 Data Collection from Urban Green Spaces

A set of key informant survey questionnaires was prepared to collect the required information from different gardens/parks, sewage treatment plants, and city development agencies (smart city office, Planning and Development Authority, urban planning). The data were collected by visiting the sites on different days during January – February 2019 and again during August – October 2020. The questionnaires prepared for obtaining information from parks, gardens, and STP are included in Appendix Tables A6 to A8. In addition to collecting the on-site data, details obtained through interactive discussions with the garden staff and officers in charge were collated. Main details of these parks (sometimes referred to as Panaji city UGS) are compiled into Table 4.1.

4.2.2 Study area details

Various climatological details of Panaji and Tumkur cities are available in Ramaiah et al. (2020). In addition to metadata presented in chapter 3, seven different parks/gardens (social forests) within Panaji city were also covered for this study. Many essential details from these parks were collected through at-the-site (Fig A1- A9) guidance from garden staff and interactions with them. The details for the total area of the parks/gardens, species and numbers of trees, and ornamental/edge plants were noted (Table 4.1).

Information on the source and amount of water used daily in these parks was also collected. The general practice of watering the gardens in the parks included for this study is that there is no watering during the monsoon months of mid-June to mid-October. There have been instances of acute water shortage, during mid-February till the onset of monsoon/pre-monsoon showers (sometime during late May/early June). During this mostly hot and humid period, the plants, in particular the ornamental plants and the lawn cover, suffer from water deficiency.

Table 4.1: Important details of seven different parks surveyed for this study

Park	Area (m^2)	No of species		Grass cover (m^2)	Source of water	Daily water used (L)	Annual litter fall (tons)	#of staff
		Trees (Total number)	Ornamental (hedge length; m)					
Kala Academy	10630	21 (300)	6 (400)	2675	Borewell	10000	15	6
North Goa Range Forest Park	5000	18 (390)	6 (200)	2250	Borewell	4800	10	3
South Goa Range Forest Park	6500	9 (200)	52 medicinal	1625	Borewell	8400	6*	5
Mahavir Park	18312	27 (3130)	17 (3000)	6410	Borewell	15000	60	22
Art Park	18999		0	0	Not watered	0	30	
Garcia da Orta Garden	4000	12 (180)	6 (450)	1500	Corporation water + Borewell	4000	6	5
Ambedkar Park	10000	15 (400)	17 (1800)	6500	Treated wastewater	16000	25	12
Joggers Park	11500	8 (400)	12 (2600)	6900	Borewell	36000	12	22

*total number of trees in Mahavir Park and Art Park as per lists provided by the Park Offices

Except for Joggers Park, the soil is mostly sandy in all the gardens adjacent to, and including, Mahavir Park. Garcia da Orta garden has sandy: silty (66%:33%) soil. The levelled laterite base of the Joggers' Park is topped with soil from elsewhere to grow hedge plants and to support nutrients to existing vegetation. Ambedkar Park (established 1992) exclusively uses treated wastewater of 16000 liters every day during non-rainy period from October 15 to June 15 for maintaining the grass-cover and long hedge rows in the garden of ca 11000 m^2 total area.

Most other parks sourcing borewell water, have drilled bores of varying lengths. The length of the bore in most of these parks is less than 40 meters deep. This is due to their vicinity to the lower stretches of River Mandovi to their west (Fig 4. 1) unlike the deepest borewell of 130 m in Joggers Park (in Altinho hillock), which is ~30 m above mean sea level and, at quite a distance of ~3 km from the northern or western banks of River Mandovi. Notably, in Ambedkar Park, the borewell located within 800 m south of Mandovi that was drilled back in mid -1980s yielded saline waters unsuitable for plant growth. For many years, some volume of corporation water was supplied once or twice a week until the use of treated wastewater became regular from 2007 onwards.

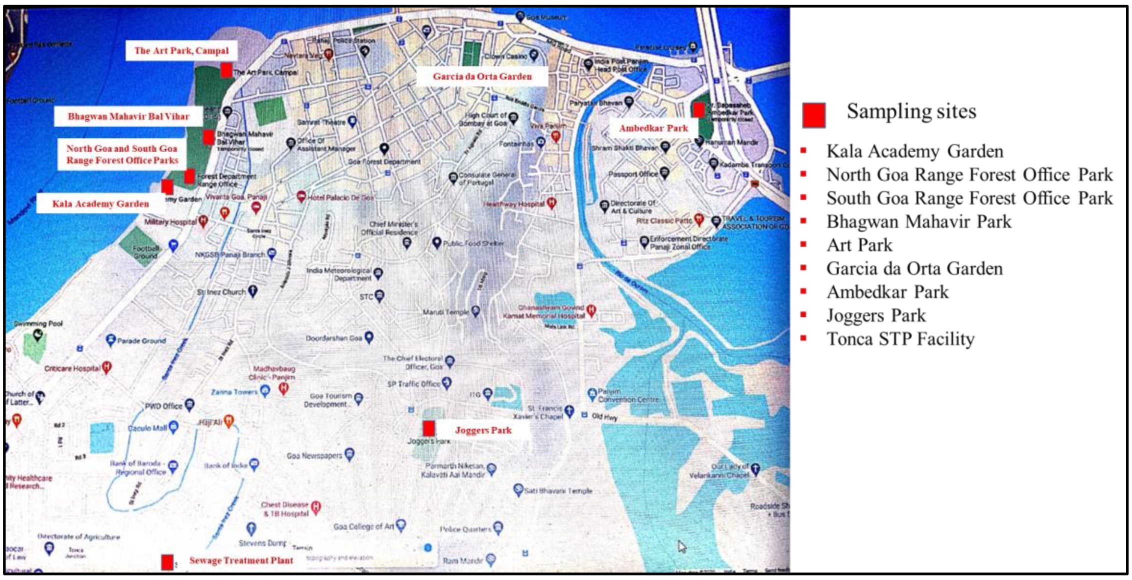


Figure 4.1: Parks and Gardens in Panaji city surveyed for this study for calculating water requirements of hedge-plants, groundcover (=lawn), and trees. Details from the sewage treatment plant (STP) located at Tonca were collected and are made use of in Chapter 6.

Striking differences in the maintenance practices between each of these parks are as follows: In Mahavir Park established (1963), the water is pumped out directly onto the ground cover and lane edge plants. In Kala Academy (established 1982), the water is pumped out into two overhead tanks from where it is distributed through sprinklers to groundcover and through hand-held pipes to the hedge plants. Within the precincts of Mahavir Park are North Goa Range Forest and South Goa Range Forest Office parks. In the former, the water is used only for ca 200 m long hedge of ornamental plants. There is a saplings nursery measuring 800m^2 in the South Goa Range Forest Office park. Year-round regular rearing of tree/forest plants and saplings of as many as 52 different species of ornamental/medicinal plants (Appendix Table A5) is done. Saplings are sold or distributed free of cost to the interested public. There are also ornamental and hedge plants reared in Mahavir Park (Table A6) and in Ambedkar Park (Table A7). In the Art Park, which is right on the banks of River Mandovi, there are big trees (most of them older than 20 years and some planted within the last 6 years) and shrubs not at all watered. Garcia da Orta garden, the oldest park in Panaji established in 1876 in the middle of the city, is home for rain-trees older than 80 years. The girth circumference of many of these 76 rain trees exceeds 3 m.

In most of these parks, watering is done for three hours in the morning and three hours in the afternoon for covering only the grass-cover (lawns) and ornamental plant-hedge along the walkways (Fig A4 to A7). About 20% of the total tall trees in Mahavir Park and those in the Range Forest offices of North and South Goa Districts are trimmed to a maximum height of 10 meters to allow unobstructed passage of light signal from the lighthouse nearby. It was learnt that in addition to litter (dry leaves, twigs, prunes, and mowed grass piles) over 30 tons of stem-wood is cut down annually from these trees. Mostly the Casuarina trees ca 200 in numbers stand in the path of the lighthouse signal beam. Joggers Park, created in 2002, is located on top of the Altinho Hill. Its hard laterite surface is levelled, suitably landscaped, and maintained to keep a largely plain surface for joggers, for a kindergarten playground and public amenity (toilet, parking space, and garden office) in an area of ca.700m^2.

4.2.3 Derivation of ETo for Panaji and Tumkur regions

The month-wise ET_o (mm d^{-1}) for the parks of in Panaji and Tumkur was derived using the formula provided in Snyder et al. (2015):

$$ET_0 = \left[0.408\Delta(R_n - G) + \gamma\left(\frac{37}{T} + 273\right)u_2(e_s - e)\right] \div [\Delta + \gamma(1 + 0.24u_2)] \quad (1)$$

for daytime and

$$ET_0 = \left[0.408\Delta(R_n - G) + \gamma\left(\frac{37}{T} + 273\right)u_2(e_s - e)\right] \div [\Delta + \gamma(1 + 0.96u_2)] \quad (2)$$

for night-time

Variables in these equations are, net radiation (Rn, MJ m^{-2}h^{-1}), ground heat flux density (G, MJ m^{-2}h^{-1}), psychrometric constant (Δ, kPa K^{-1}), mean air temperature (T, ◦C), wind speed (u2, m s^{-1}), saturation vapor pressure (es, kPa), vapor pressure (e, kPa), and slope of the saturation vapor pressure at temperature T (γ, kPa K^{-1}). Data on meteorological parameters viz., solar radiation, temperature, vapor pressure, and wind speed available in the literature were used (Tables 4.2 and 4.3). The psychometric constant, slope of the saturation vapor pressure at temperature T were either derived and, for reliability, compared with those of FAO Penman-Monteith datasets (Allen et al., 1998).

Table 4.2: Monthly mean climate and related data (from FAO) solar radiation (Rs), psychometric constant (PC) maximum (T_{max}) and minimum (T_{min}) dew point (T_d) temperature, wind speed (ws), slope of saturation vapour pressure (SVP slope), saturation vapour pressure (SVP), vapour pressure (VP), and ETo for Goa during day and night times.

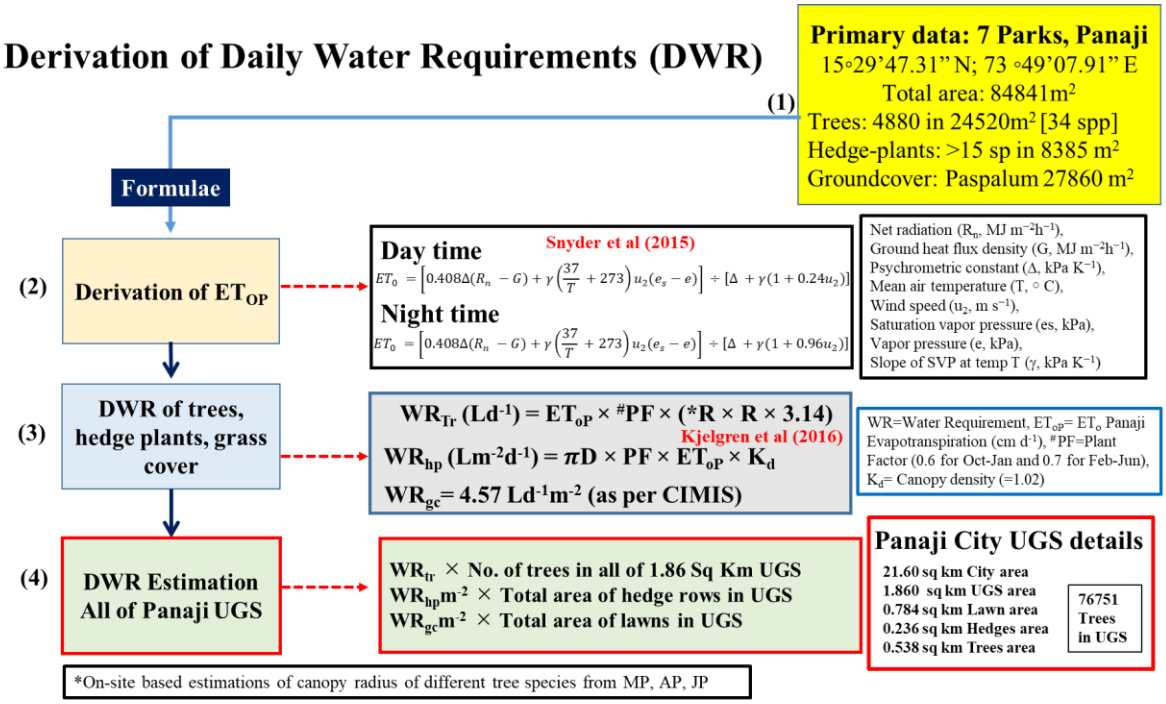
Month	R_n	PC	T_{min}	T_{max}	T_d	ws (m s^{-1})	SVP slope kPa K^{-1}	SVP	VP e, kPa	EToG daytime	EToG night-time
Jan	28.9	0.067	20.3	31.5	19	1.194	0.198	3.36	3.4	8.213	6.829
Feb	32.3	0.067	21.0	31.4	20	1.278	0.201	3.39	3.4	9.180	7.564
Mar	35.7	0.067	23.4	32.1	23	1.278	0.218	3.78	3.7	10.395	8.500
Apr	38.1	0.067	25.8	33	24	1.472	0.236	4.17	4.1	11.233	9.227
May	38.7	0.067	27.0	33.4	25	2.083	0.245	4.35	4.3	11.199	8.676
Jun	38.6	0.067	25.2	30.8	25	1.833	0.22	3.78	3.8	10.947	8.556
July	38.5	0.067	24.6	29.3	25	2.861	0.209	3.57	3.6	10.193	7.135
Aug	38.1	0.067	24.4	29	25	2.639	0.206	3.53	3.6	10.147	7.230
Sep	36.4	0.067	24.2	29.6	25	1.556	0.208	3.58	3.6	10.296	8.236
Oct	33.2	0.067	24.0	31.2	24	0.972	0.216	3.76	3.7	9.799	8.469
Nov	29.6	0.067	22.4	32.2	22	1.056	0.212	3.75	3.6	8.655	7.384
Dec	27.9	0.067	21.0	32	20	0.917	0.204	3.46	3.5	8.126	7.037

Table 4.3: Monthly mean climate and related data (from FAO) solar radiation (Rs), psychometric constant (PC), maximum (T_{max}) and minimum (T_{min}) dew point (T_d) temperature, wind speed (ws), slope of saturation vapour pressure (SVP slope), saturation vapour pressure (SVP), vapour pressure (VP), and ETo (mm d^{-1}) for Tumkur during day and night times

Month	R_S	PC	T_{min}	T_{max}	T_d	ws (m s^{-1})	SVP slope kPa K^{-1}	SVP	VP e, kPa	ET_{oT} daytime	ET_{oT} night-time
Jan	29.9	0.054	16	29	13	1.111	0.169	2.809	2.81	8.679	7.342
Feb	33.1	0.054	18	31	12	1.111	0.179	2.984	2.99	9.753	8.297
Mar	36.1	0.054	20	33	13	1.111	0.209	3.565	3.57	11.079	9.579
Apr	38.1	0.054	22	34	17	0.833	0.220	3.78	3.79	11.989	10.758
May	38.4	0.054	22	33	19	1.389	0.209	3.565	3.57	11.633	9.750
Jun	38.1	0.054	21	30	19	2.222	0.188	3.168	3.17	10.779	8.167
July	38.1	0.054	20	29	19	2.500	0.179	2.984	2.99	10.461	7.647
Aug	38.0	0.054	20	28	19	1.944	0.179	2.984	2.99	10.726	8.288
Sep	36.7	0.054	20	29	19	1.667	0.179	2.984	2.99	10.506	8.366
Oct	33.9	0.054	20	29	18	1.111	0.179	2.984	2.99	9.988	8.497
Nov	30.6	0.054	18	28	17	0.833	0.169	2.809	2.81	9.019	7.921
Dec	28.9	0.054	17	28	15	1.111	0.161	2.644	2.65	8.259	6.946

4.2.4 Calculation of water requirement of trees

Daily water requirement (DWR) of different tree species, major ornamental shrubs maintained by pruning along both sides of the walk paths and of the turf grass in the ground cover area was calculated based on the principles of SLIDE Rules (Kjelgren et al., 2016). Unlike the complicated WUCOLS and LIMP methods, the SLIDE rules are used widely to estimate landscape plant water demand as products of evapotranspiration (ET_o), canopy density, and plant factors (PF) which are discrete adjustment factors for broad plant types (Beeson, 2005) based on multiple observations. Since there are many different species of shrubs (<3m tall) and trees (>3m tall) in the parks covered for this study, ranges of height and canopy diameter for each species of trees were obtained from Mahavir Park, Ambedkar Park, and Joggers' Park during the field visits. Help and knowledge of park maintenance staff was sought to ascertain the height and canopy diameter estimates. The steps followed are shown in the flow chart below:



Flow chart 4.1: Steps followed in the methods for estimating daily water requirements of plants.

Water requirements of isolated trees in the parks was calculated by appropriately substituting the formula**:**

$$WR= ET_o \times PF \times (R\times R \times 3.14) \times 0.623 \text{ as follows}$$

$$WR_{Tr}\ (Ld^{-1}) = ET_{oP} \times PF\times (R \times R \times 3.14) \quad (3) \quad \text{and}$$

$$WR_{Tr}\ (Ld^{-1}) = ET_{oT} \times PF\times (R \times R \times 3.14) \quad (4)$$

WR is water requirement, ET_{oP} (Panjim), ET_{oT} (Tumkur) are evapotranspiration factors (cm d^{-1}); PF is Plant Factor for established landscape trees by following UCANR (2020). Two plant factors were used: (a) 0.6 for all trees during somewhat cooler, mildly humid October-January and (b) 0.7 for all trees during warmer February-June. R (tree canopy radius in meters), R×R×3.14 (area of tree's canopy-equivalent floor cover), and ET_o in mm d^{-1} were multiplied with this floor cover area to calculate daily water requirement (DWR) in liters. Irrespective of the canopy shape (triangular, irregular or tapering), its area for a given tree was estimated by projecting the two far endpoints of the canopy to the floor for a straight line distance that was noted as canopy diameter as per UCANR (2020).

4.2.5 Calculation of water requirements of hedge plants

With an average height of 0.8 m in all sampled parks where the pruning is done to achieve circular/globular shaped canopy, the perimeter is 3.4 m. Hence, the DWR was calculated using the following relationship:

$$WR_{hp} (L\ m^{-2}d^{-1}) = \pi D * PF * ET_{oP} * K_d \quad (5)$$

Where πD is the area of the perimeter, PF used is 0.65, ET_{oP} is the evapotranspiration rates (cm d^{-1}) and K_d of 1.02 for higher density mixed species (as per Snyder et al. (2015)), which works out to 6.77 L m^{-2} d^{-1} *vis a vis* the 7 L m^{-2} d^{-1} calculated following SLIDE Rules. Both these volumes closely corroborate with the experience-based input by the garden staff watering 6 to 8 L m^{-1} hedge length.

4.2.6 Calculation of water requirements of grass cover (=lawns)

For estimating DWR of grass cover, the "non-turf groundcover water demand calculator 2.0" (= NGWDC 2.0) was used (UCANR, 2020). The ET_{oP} (0.889 cm or equivalent to 0.36 inches as per American style) derived for this study was applied. Paspalum grass is mostly used as lawn grass in public gardens. The DWR works out to 42.53 for a grass cover area of 9.29 m^2 (= 100 sq. ft.) (or 4.577 $Ld^{-1}m^{-2}$). Using this rate, the DWR for grass cover was calculated for all parks.

Using the monthly day- and night- time averages of ET_{oP} (=0.889 cm d^{-1}) derived in this study, the DWR was worked out for trees, grass-cover, and area of hedge plants for all 17 parks of Panaji. Using the metadata collected during 2019, the DWR for over 400 parks in Tumkur city (Sharma, 2018) was estimated as per the weighted mean percentage of landscape spaces.

4.3 Results

4.3.1 Determination of evapotranspiration rates

All required values for different variables essential for the equations (1) and (2) were determined appropriately. Using these derivatives, the daily evapotranspiration rates (mmd^{-1}) for Panaji (ET_{oP}) and Tumkur (ET_{oT}) regions for each month were obtained. The net radiation (Rn, MJ $m^{-2}h^{-1}$) value was from the FAO site and the ground heat flux density (G, MJ $m^{-2}h^{-1}$) used was zero since the ground flux was < 2.5 to 3 MJ $m^{-2}h^{-1}$. The monthly day and night averages are ET_{oP} = 8.89 mm d^{-1} (= 0.889 cm d^{-1}) for Panaji and ET_{oT} = 9.35 mm d^{-1} (= 0.935 cm d^{-1}; Tables 4.2 and 4.3) for Tumkur.

4.3.2 Daily water requirements (DWR) of hedge and grass cover

Hedge area in Joggers Park, Mahavir Park and Ambedkar Park respectively, are 2340 m^2 (20.34% of total), 2700 m^2 (7.20%), and 1620 m^2 (16.20%); and grass cover area is ~ 6410 m^2 (35% of combined area of Mahavir Park and Art Park area of 37211 m^2), 6900 m^2 (60% of 11500 m^2) in Joggers Park, and 6500 m^2 (65% of 10000m^2) in Ambedkar Park. These details are listed in Table 4.4. Weighted mean DWR of all plant types in seven sampled/surveyed parks in Panaji were used to estimate the DWR for all parks in Panaji as well as Tumkur cities. The percent proportion of areas in all parks of Panaji and Tumkur cities are presented in Figure calculated using the weighted mean mentioned in Table 4.5

were used.

The daily volumes of water currently applied in these parks varied from 4,000 liters to 16,000 liters (Table 4.5). As mentioned earlier, borewells are the source of water for all parks except for the Ambedkar Park, which uses treated water (given out free of cost) it is ferrying daily from the STP. This supply either from borewells or from other sources is not enough for meeting the daily demand of hedge plants or grass cover (Table 4.5). For instance, the DWR for 27860 m^{-2} grass cover is 127320 L at 4.77 liters.m^{-2}, and for 8385 m^{-2} hedge area is 56767L at 6.77 liters m^{-2}. The current supply of 76200 L *vis-a-vis* the ET_{oP}-based DWR of 183342 L is at a shortage of over 2.88 times. Notwithstanding the presence of over 20 different ornamental plants randomly grown in these parks (Appendix Table A6), the DWR for the hedge-plants was calculated at the rate of 6.77 liters m^{-2} of hedge area.

Table 4.4: Details of different UGS parameters from sampled parks in Panaji, Goa

Park	**Area (m^2)**	**Trees (n^)**	**Hedge area (m^2)**	**lawn (m^2)**	**Present supply (LPD)**	**Daily Water Requirement (Liters per Day)**			
						Trees#	**Hedges**	**Grass cover**	**Demand**
Kala Academy	10630	250	360	2675	**10000**	5937.50	1692.50	12224.75	19854.75
NGRF Office Park	5000	290	160	2250	**4800**	6887.50	1083.20	10282.50	18253.20
SGRF Office Park	6500	180	800*	1625	**6000**	4275.00	5416.00	7426.25	17117.25
Mahavir Park+Art Park	37211	3130	2700	6410	**8400**	74337.50	18279.00	29293.70	121910.20
Garcia da Orta Garden	4000	150	405	1500	**15000**	3562.50	2741.85	6855.00	13159.35
Ambedkar Park	10000	480	1620	6500	**16000**	11400.00	10967.40	29705.00	52072.40
Joggers Park	11500	400	2340	6900	**16000**	9500.00	15841.80	31533.00	56874.80
Total	84841	4880	8385	27860	**76200**	115900.0	56021.75	127320.20	299242.00

Table 4.5$: Details of numbers of trees, hedge areas and groundcover in different parks/gardens in Panaji, and their daily water requirement derived using the evapotranspiration factor of 0.889 mm d^{-1}.

Park	Kala Academy	NGRF Office Park	SGRF Office Park	Mahavir Park+Art Park	Garcia da Orta Garden	Ambedkar Park	Joggers Park
Total Area (m^2)	10630	5000	6500	37211	4000	10000	11500
Trees (n^)	250	290	180	3130	150	480	400
Hedge area (m^2)	360	160	800	2700	405	1620	2340
lawn (m^2)	2675	2250	1625	6410	1500	6500	6900
Road/lanes/parking lot (m^2)	4300	1200	2800	6000	600	750	2500
Hedges area (%) [A]	3.39	3.20	12.31	7.26	10.13	16.2	20.35
Lawn area (%) [B]	25.17	45	25.00	17.23	37.50	65	42.61
Road/parking area (%) [C]	40.46	24	43.08	16.13	15.00	7.50	21.74
sum of [A]+ [B] +[C]	69.01	72.20	80.38	40.61	62.62	88.70	84.70
Area covered by trees (%)	31.99	27.80	19.62	59.39	37.38	11.30	15.30
Area covered by trees (m^2)	3295	1390	1275	22101	1495	1130	1760
No of trees	250	290	180	3130	150	480	400
Area available per tree (m^2)	13.18	4.79	7.08	7.09	9.97	2.36	4.40

$ Data collected through a personal visit. ^rounded off to lower 10s (for example 404 in Joggers park rounded to 400); #currently no direct watering of trees. Daily demand of water estimated at an average of 23.75 liters per tree (see later), *nursery plot including narrow access lanes for watering, nursing/caring or for picking out the saplings for sale or free distribution.

4.3.3 Canopy areas and water requirements of different species of trees

At the outset, it is to be noted that most trees in all parks are not watered, except that they may get some moisture/wetness from the nearby groundcover or hedge area. Keeping the objective of exploring the use of treated water for UGS management, daily water requirement by trees was estimated. This was done for trees in three different parks (Tables 4.6-4.8) from where the species composition of the trees and their numbers were available. Their taxonomic identification was confirmed in consultation with experts in tree taxonomy. The water requirement was calculated for October- January (low to moderate water stress) and February-June (higher water stress) periods using the plant factors (PF) of 0.6 and 0.7, respectively.

Mostly older than 35 years, over 48% (or 1525) of the 3130 individual trees had more than 7m canopy diameter. As stated above, canopy diameter is the important parameter for estimating DWR, the same is described for some trees with quite larger canopy area. The top 10 tree species in Mahavir Park in terms of canopy diameter are Rain tree (*Samanea saman* min ~25m and max 30 m), Gulmohar (*Delonix regia* max diameter 18m), Pithecellobium dulce (*Inga dulcis*), Chinch (*Tamarindus indica*; 15m), Badam (*Terminalia catappa*), Taman (*Lagerstroemia speciosa*; 14 m), Jambal (*Syzygium cumini*), Peltaphorum (*Peltophorum pterocarpum* 12m), Spatodea (*Spatodea companulata* 11m), Saton (*Alstonia scholaris*), Oval (*Mimusops elengi*), Ritha (*Sapindus mukorossi* 10m), Acacia (*Acacia auriculiformis*), Shankar (*Caesalpinia pulcherima*), Apto (*Bauhinia purpurea*), Tecoma (*Tecoma capensis* 9m), Karanj (Millettia pinnata), Palm (*Dypsis lutescens*), Palas (*Butea monosperma* 8m), and Musaenda (*Mussaenda erythrophylla* 7m). Accounting for another 48%, the canopy diameter of over 40 years old Casuarina (*Casuarina equisetifolia*) trees ranged narrowly between 5 and 6m. As per Park office information, Casuarinas were planted along the riverside earlier than other species that were introduced. This information serves useful to know the age of these trees in these parks.

Table 4.6: Details of different tree species from Mahavir Park, Panaji, Goa. It is to be noted that canopy area is the main parameter useful for DWR. Height and girth circumference details are also listed as they are used for estimation of carbon biomass sequestration (see Chapter 5).

Tree (scientific name)	Number	Height (m; range)	Canopy dia (m; Range)	Girth circumference (cm)		
				n	Mean	±SD
Casuarina (*Casuarina equisetifolia*)	1485	18-22	5-6	23	102.35	19.24
Acacia (*Acacia auriculiformis*)	510	7-10	8-9	18	129.56	13.81
Karanj (*Millettia pinnata*)	294	15-18	7-8	15	126.73	21.3
Shankar (*Caesalpinia pulcherima*)	147	8-11	8-9	12	101.67	10.47
Badam (*Terminalia catappa*)	129	6-8	12-14	12	102.92	8.908
Ashok (*Polyalthia longifolia*)	89	6-9	3-4	10	76.40	6.168
Apto (*Bauhinia purpurea*)	87	11-15	8-9	11	119.18	17.14
Jambal (*Syzygium cumini*)	74	9-11	10-12	11	124.09	21.61
Tecoma (*Tecoma capensis*)	53	7-9	7-9	11	112.36	14.42
Gulmohar (*Delonix regia*)	44	16-19	15-18	10	198.10	15.99
Saton (*Alstonia scholaris*)	27	8-10	8-10	10	112.90	17.77
Taman (*Lagerstroemia speciosa*)	26	10-12	12-14	9	138.78	9.935
Peltophorum (*Peltaphorum pterocarpum*)	25	17-19	10-12	16	80.50	8.422
Spatodea (*Spatodea companulata*)	24	13-15	9-11	13	121.08	10.28
Oval (*Mimusops elengi*)	23	7-9	8-10	11	132.09	8.608
Palm (*Dypsis lutescens*)	16	8-11	7-8	6	124.33	11.91
Musaenda (*Mussaenda erythrophylla*)	15	4-6	6-7	13	52.154	4.947
Bottle Palm (*Hyophorba lagenicaulis*)	13	8-12	4-5	8	41.25	2.55
Bayo (*Cassia fistula*)	13	9-12	5-6	7	110.86	7.625
Rain tree (*Samanea saman*)	11	19-23	25-30	6	259.83	23.56
Ritha (*Sapindus mukorossi*)	9	5-7	8-10	6	111.83	24.76
Pithecellobium dulce (*Inga dulcis*)	5	9-12	14-15	3	100.67	11.72
Palas (*Butea monosperma*)	4	7-10	7-8	3	92.50	4.95
Avalo (*Phyllantus emblica*)	3	7-9	5-6	2	64.00	0
Chinch (*Tamarindus indica*)	2	11-12	15	2	164.00	11.31
Java cassia (*Cassia javanica*)	1	7	8	NM	NM	
Surang (*Mammea suriga*)	1	9	9	NM	NM	

In Ambedkar Park, Peltophorum accounted for 38% of the 484 trees belonging to 13 species. Followed by Ashoka tree (11%), Bottle palm (10%), Coconut palm and Badam (5% each). The park was built in 1990s and the age of the trees is taken as 28 years. In Jogger‘s Park, individual trees of *Peltophorum* sp accounted for 53% of the 404 trees followed by Coconut palm (12%), Beetlenut palm (10%), Bottle palm and Ashoka tree (8% each) with the age of the trees being ~15 years in this park built during 2002. The age of two sandalwood trees is about 2 years. Overall, the tree species with larger canopy diameter are Gulmohar, *Delonix regia* (25-30 m); Rain tree, *Samanea saman* (20-24m); Acacia, *Acacia auriculiformis* (11-14m); Mango, *Mangifera indica* (8-13); Bamboo, *Phyllostachys pubescens* (bundles of 7-12m); Badam, *Terminalia catappa* (8-12m); Veni tree, *Acacia ferruginea* (7-10m); Coconut palm, *Cocos nucifera* (7-9m); Peltophorum, *P. pterocarpum*

(3-7m); and Casuarina, *Casuarina equisetifolia* (4-7m). Most of the trees with larger canopy are older and those with smaller ones being younger. It was learned that the two sandalwood trees with ca. 2m canopy diameter were planted about two years ago.

Table 4.7: Details of different tree species from Ambedkar Park, Panaji, Goa

Tree	Number	Height (m; range)	Canopy diameter (m; Range)	Girth circumference (cm)		
				n	Mean	±SD
Peltophorum, *P. pterocarpum*	184	10-15	3-7	22	81.67	6.64
Casuarina, *Casuarina equisetifolia*	92	8-11	4-7	13	95.25	14.69
Ashoka tree, *Polyalthia longifolia*	52	10-12	3-5	8	81.57	3.69
Bottle palm, *Hyophorba lagenicaulis*	48	5-8	3-4	10	42.40	2.99
Coconut palm, *Cocos nucifera*	26	7-10	7-9	12	98.17	5.97
Badam, *Terminalia catappa*	26	7-10	8-12	10	102.80	8.40
Veni tree, *Acacia ferruginea*	12	11-15	7-10	6	55.33	1.75
Rain tree, *Samanea saman*	9	20-22	20-24	4	271.00	35.35
Acacia, *Acacia auriculiformis*	8	10-12	11-14	5	118.60	0.89
Bamboo, *Phyllostachys pubescens*	7	8-10	7-12	18 shoots	38.22	3.04
Mango, *Mangifera indica*	6	13-16	8-13	6	72.67	3.56
Gulmohar, *Delonix regia*	6	17-19	25-30	4	138.00	18.20
Sandalwood, *Santalum album*	2	3	2	2	24.50	2.12

Table 4.8: Details of different tree species from Joggers Park, Panaji, Goa

Tree	Number	Height (m; range)	Canopy diameter (m; range)	Girth circumference (cm)		
				n	Mean	±SD
Peltophorum, *P. pterocarpum*	213	12-15	3-7	11	82.46	8.99
Coconut palm, *Cocos nucifera*	48	5-11	7-9	14	95.79	7.88
Beetlenut palm, *Areca catechu*	42	6-10	11-14	10	34.67	3.74
Bottle palm (*Hyophorba lagenicaulis*)	33	5-6	3-5	6	67.33	5.79
Ashoka tree, *Polyalthia longifolia*)	32	10-12	2-3	8	71.50	7.09
Palm, *Dypsis lutescens*	12	3-10	4-9	8	114.25	9.47
Casuarina, *Casuarina equisetifolia*	10	7-10	4-6	10	77.40	7.71
Badam, *Terminalia catappa*	8	6-8	8-10	5	40.60	2.07
Sandalwood *Santalum album*	6	4	3	6	29.00	2.83

In Joggers' Park, only four tree species had the maximum canopy diameter of 7 m or more and they accounted for 67.4% of the 402 total trees. The canopy diameter was in the range of 8-10 m for Badam, *Terminalia catappa*; 7-9m for Coconut palm, *Cocos nucifera*; 3-7 m for Peltaphorum, *P. pterocarpum*; and 4-7m for Palm, *Dypsis lutescens*. The water requirement was of higher volumes for trees with larger canopy. The DWR is the same for identical canopy diameter irrespective of the tree species.

By calculating the DWR, it was evidenced that it is different for different species solely based on the canopy area/diameter of a given species of tree. The DWR (Fig 4.2 a-

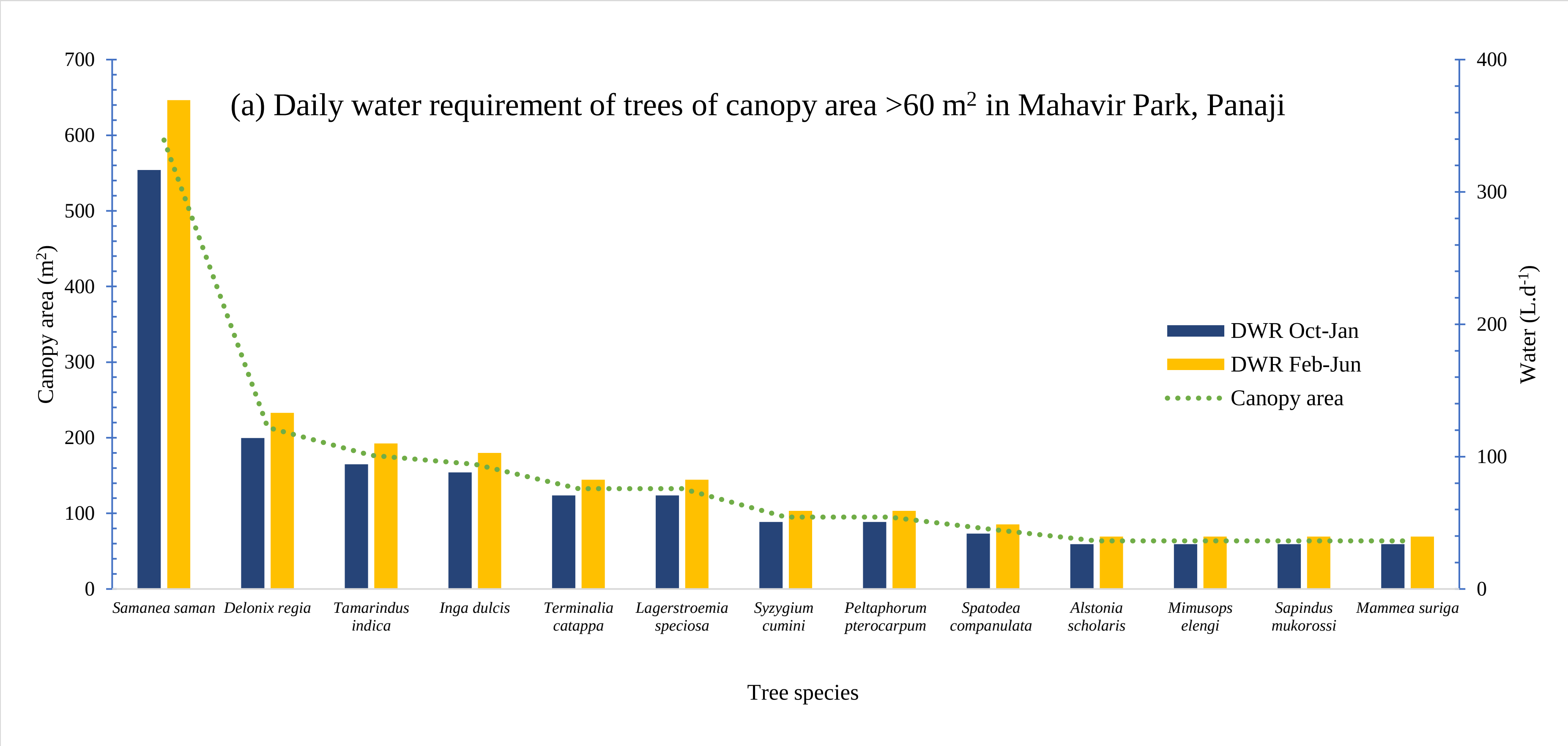
b) of 3130 trees in Mahavir Park during Oct-Jan period is 79346 liters (on an average of 25.35 liters/tree). During Feb-June, the total volume of water required is 92570 liters (average 30 liters/tree). Similarly, in Ambedkar Park (Fig 4.3), the DWR for 478 trees during Oct-Jan is 10823 liters (average 23 liters/tree). During Feb-June, it is 12626 liters (average 26.41 liters/tree). Further, the DWR of 402 trees with younger (<15 years) ones of lesser canopy area, in Joggers' Park (Fig 4.4) during Oct-Jan is 7180 liters (averaging 18 liters/tree) and during Feb-June, the DWR is 8376 liters (average of 21 liters/tree).

For a sum of 4012 trees from Mahavir Park, Ambedkar Park, and Joggers' Park together, the total volume of water required daily during Oct-Jan is ca. 0.096 MLD, and during Feb-June, 0.112 MLD. Thus, on an average for 4012 trees in three parks, the DWR for the eight non-rainy months of October 15-June 15 is 0.208 MLD averaging to 23.75 liters/tree.

Indeed, a linear relationship was invariably seen between canopy diameter and volume of water required (Table 4.9). Larger the canopy diameter, higher the volume required during both these periods using different PFs. During Oct-Jan, the minimum water required ranged from 13 liters for *Phyllanthus emblica* to a high of 317 liters for Rain tree, followed by Gulmohar, Dulce, Badam, Taman, Jambal, Peltophorum, and Chinch most of which possess larger canopies need higher volumes compared to narrow canopied Ashoka, Bottle palm, Avalo, Bayo, Casuarina, and Java cassia.

4.3.4 Regression Relationships

Regression relationship between independent variables (mean tree heights, canopy, and circumference) and dependent variables such as DWR for lower PF 0.6 and higher PF 0.7 periods within a given species in Mahavir Park, Ambedkar Park, and Joggers Park, as well as R^2 values for all these relationships were examined. Invariably, the level of significance between independent variable (canopy area) and dependent variable (DWR) was linear and highly significant in Mahavir (R^2=0.9417) and Ambedkar Park (R^2 =0.833) among the taller, broader canopied, and bigger circumference trees. R^2 values were low for trees in Joggers Park.



(a) Daily water requirement of trees of canopy area >60 m2 in Mahavir Park, Panaji
Canopy area (m2)
Water (L.d-1)
700
600
500
400
300
200
100
0
400
300
200
100
0
DWR Oct-Jan
DWR Feb-Jun
Canopy area
Samanea saman
Delonix regia
Tamarindus indica
Inga dulcis
Terminalia catappa
Lagerstroemia speciosa
Syzygium cumini
Peltaphorum pterocarpum
Spatodea companulata
Alstonia scholaris
Mimusops elengi
Sapindus mukorossi
Mammea suriga
Tree species

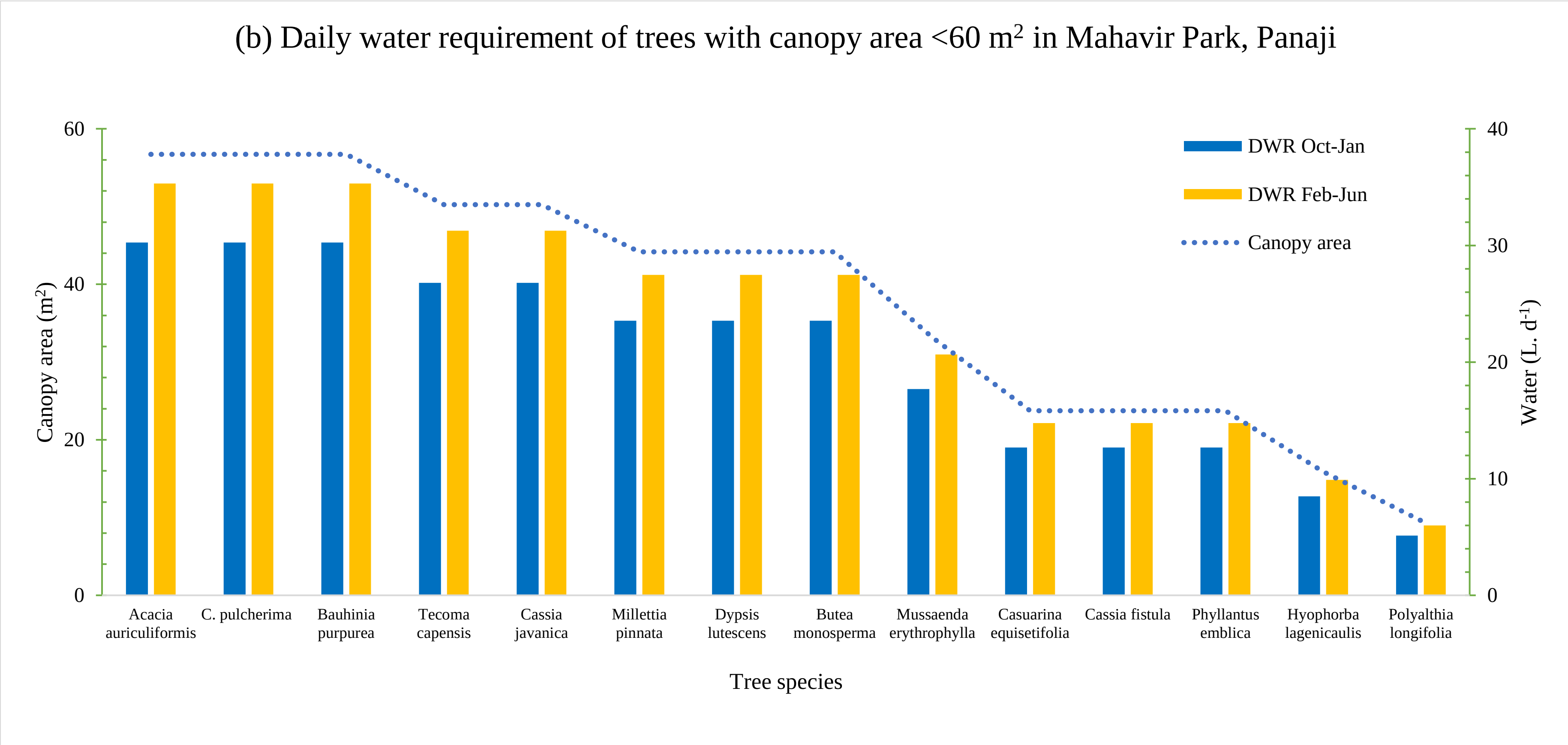


Figure 4.2: Canopy area (m^2) and water requirements ($L\ d^{-1}$) of larger (a), and medium to small (b) sized tree species in Mahavir Park, Panaji, Goa, during Oct-Jan and Feb-June periods. See Table 4.6 for tree species names sequentially and other details.

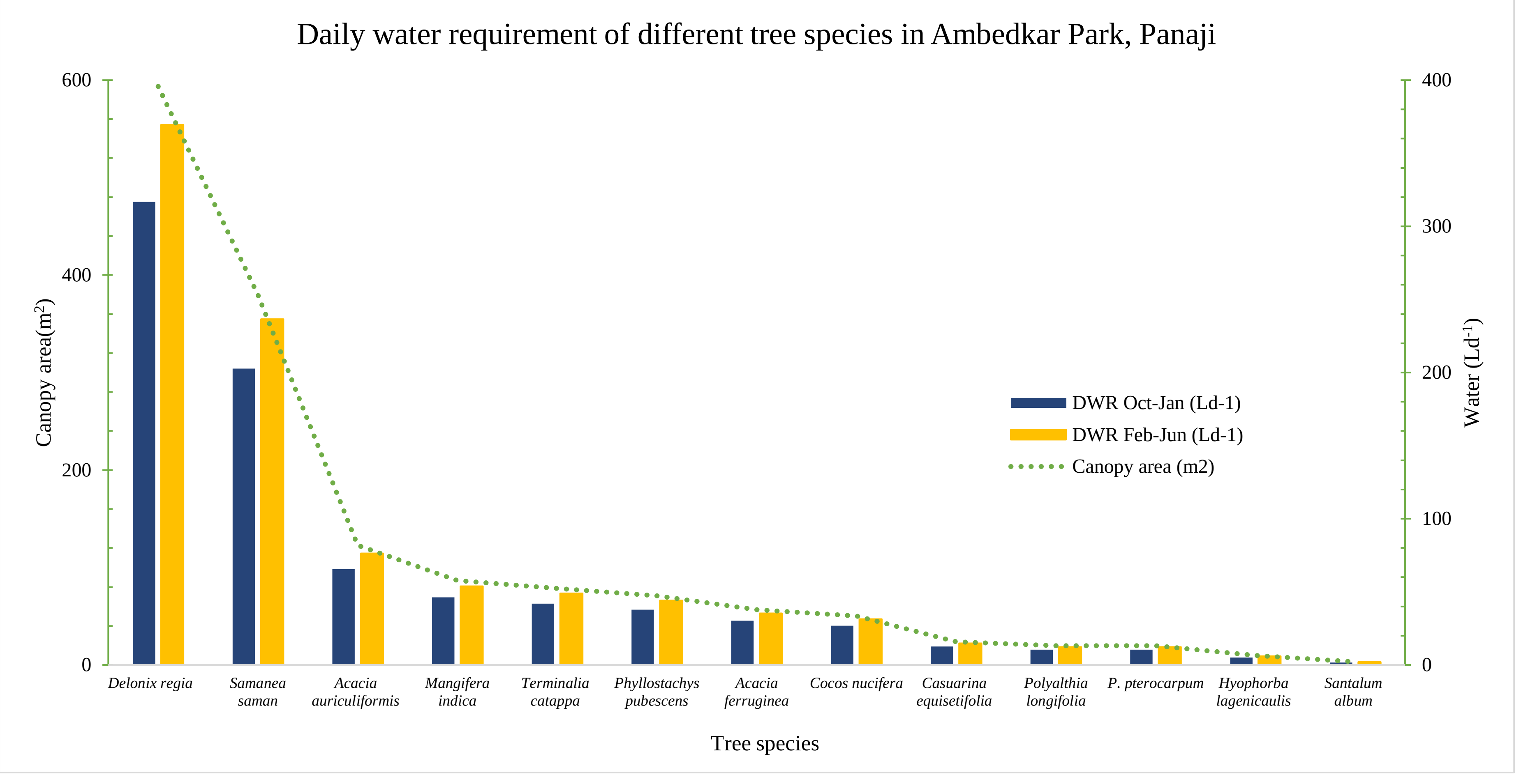


Figure 4.3: Canopy area (m^2) and water requirements ($L\ d^{-1}$) of different tree species in Ambedkar Park, Panaji, Goa, during Oct-Jan and Feb-June periods. See Table 4.7 for other details.

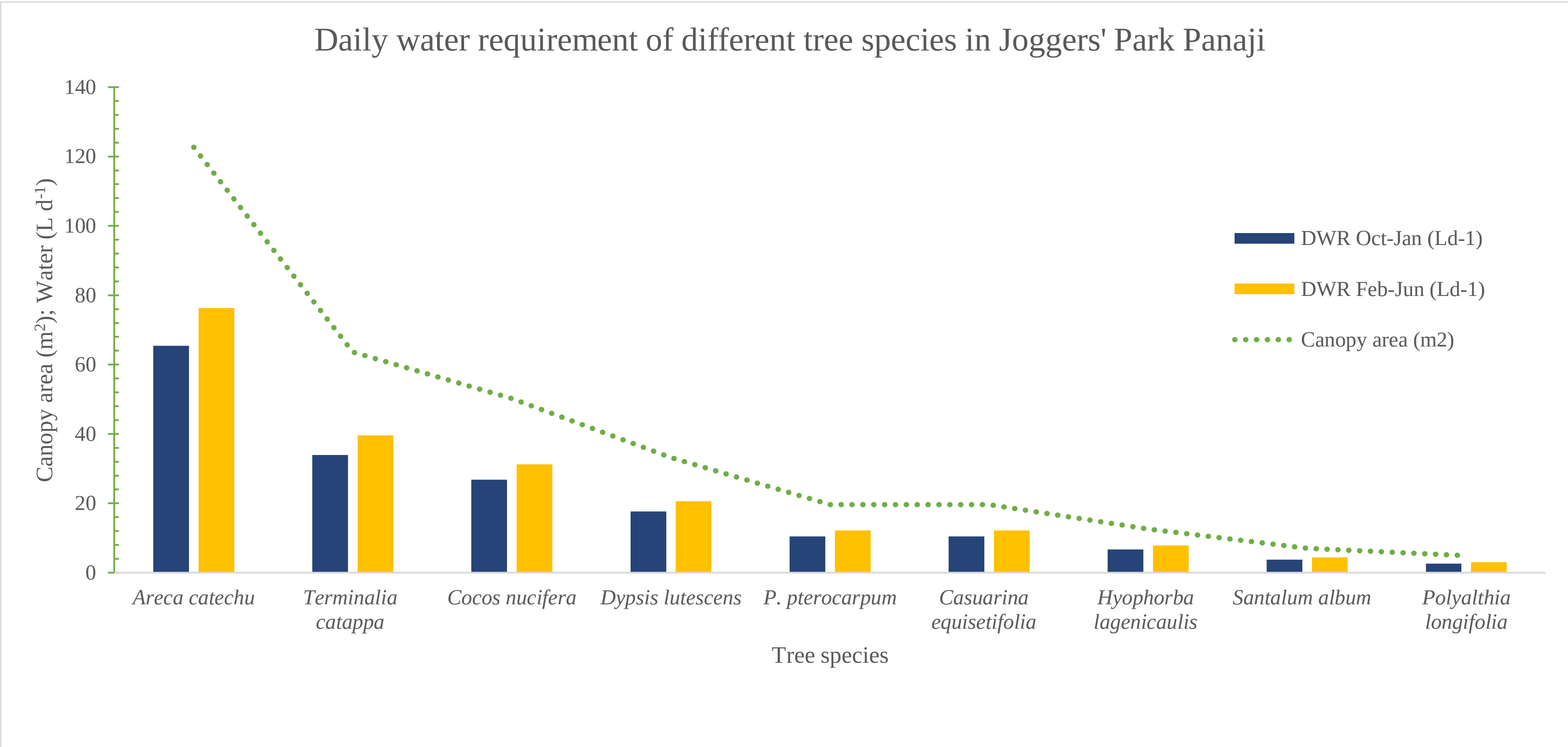


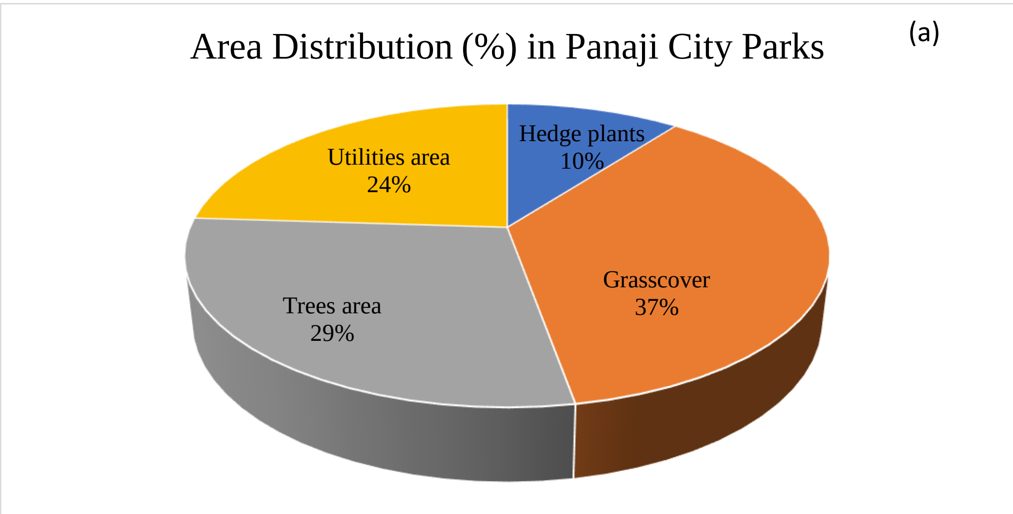
Figure 4.4: Canopy area (m^2) and water requirements ($L\ d^{-1}$) of different tree species in Joggers' Park, Panaji, Goa, during Oct-Jan and Feb-June periods. See Table 4.8 for other details.

Table 4.9: Regression equations for dependent (DWR) and independent variable (Canopy area) for calculating the daily water requirements

Independent variable	Dependent variable	Regression Equation	R^2
Mahavir Park			
Mean Canopy	DWR Oct-Jan	y = 236.42x - 622.42	0.8333
	DWR Feb-Jun	y = 275.82x - 726.15	0.8333
Ambedkar Park			
Mean Canopy	DWR Oct-Jan	y = 469.32x - 2230.6	0.9417
	DWR Feb-Jun	y = 547.55x - 2602.5	0.9417
Joggers Park			
Mean Canopy	DWR Oct-Jan	y = 20.306x + 3.5236	0.4358
	DWR Feb-Jun	y = 23.69x + 4.1144	0.4358

4.3.5 DWR in the parks of Panaji and Tumkur Cities

Using the information derived from the seven parks, water requirement was worked out for all the parks and gardens in Panaji and Tumkur cities from where certain relevant metadata were collected during 2019 survey visits. In addition to these two main parameters, literature-search based information on several parameters is also listed for a comprehension as to recognize the value of using treated water for UGS management, described in Chapter 6. The mean proportions/percentages of hedge rows, grass cover, tree, and utilities areas in Panaji and Tumkur cities are indicated in Fig 4.5. The volume of water applied currently for watering only the hedge area of 193252m^2 and the grass cover area of 683330 m^2 in all 17 parks is 2.66 MLD. Whereas the ET_{oP}-based DWR together for hedge plants and grass cover adds up to 4.43 MLD (Fig 4.6). Similarly, in Tumkur parks, the approximate volumes of water applied daily to the hedge area of 96064m^2 and the grass cover area of 339679 m^2 may be about 1.2 MLD (Fig 4.6). However, the DWR for hedge plants alone exceeds 1.30 MLD and for grass cover, 3.12 MLD. Thus, the daily supply for hedge plants and grass cover apparently falling short by 1.77 MLD (or 60.05%) of the requirement in Panaji and, analogously by over 1.00 MLD (or 54.54%) of the DWR of Tumkur parks (Table 4.10).



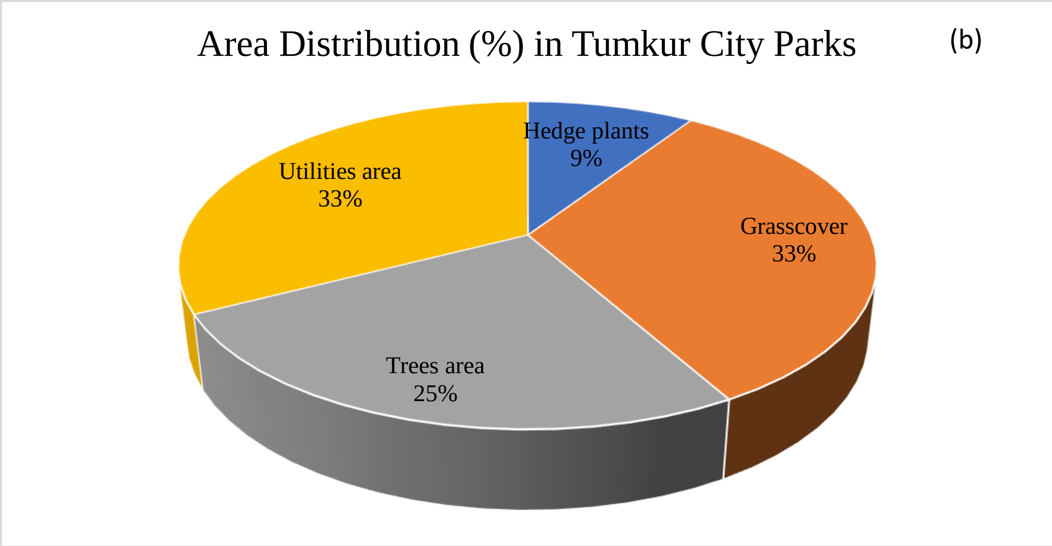


Figure 4.5: Estimated proportions of UGS in (a) Panaji (within 1.86 sq km spread in 17 parks) and (b) Tumkur (within 0.923 sq km covering 400 parks)

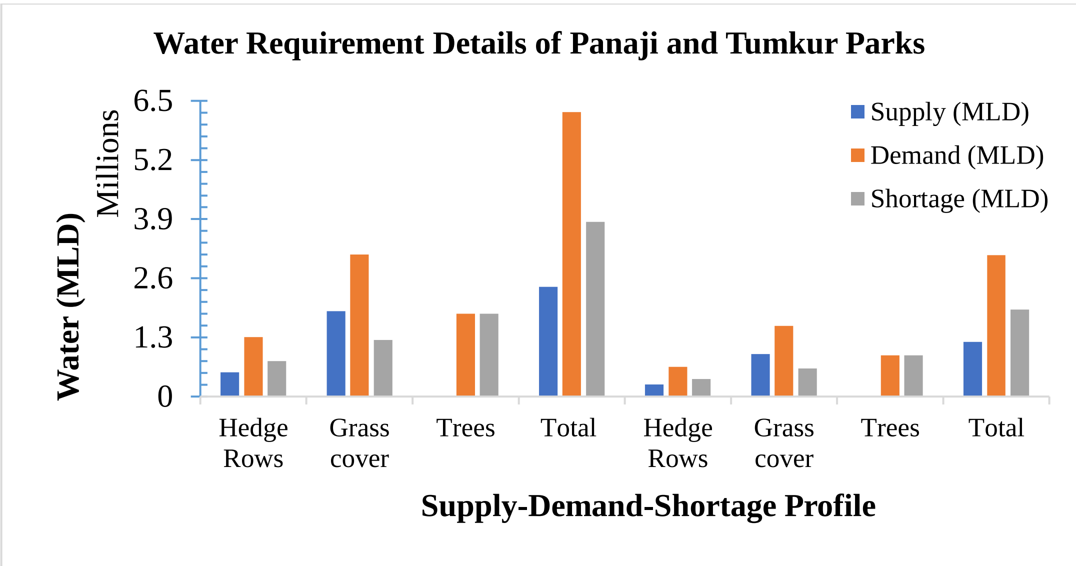


Figure 4.6: Current supply, demand of water (MLD) for hedge plants, lawn (=grass cover) and tress in the UGS of Panaji (Left) and Tumkur (right) cities. Currently, trees are not watered.

Table 4.10: Compilation of different parts of UGS in Panaji and Tumkur cities.

Parameters	Data/Estimates on DWR + other details	
	Panaji	**Tumkur**
City area km^2	21.60*	48.60*
Area of Parks (% of city area)	8.60*	1.90*
Parks area (km^2)	1.86*	0.92*
Parks area in Hectares	185.76	92.34
Hedge plants area (@10.40% of parks area (ha)	19.33	9.61
Grass cover area (@ 36.79% of parks area (ha)	68.33	33.97
Water used in parks for HP+GC (MLD)	**2.66***	**1.20**
Hedge DWR @ 6.77L m^{-2} (MLD)	1.31	0.65
Grasscover DWR @ 4.57Lm^{-2} (MLD)	3.12	1.55
Total DWR (MLD) for HP+GC	4.43	2.20
% DWR shortage hedge + groundcover	60.05	54.54
Trees area in ha	53.55	26.62
No of treesin the parks [@ 1 tree in 6.98 (±3.66) m^{-2}]	76751	38152
DWR/tree @ av 23.75L (MLD)	1.82	0.91
Trees' DWR % of available treated wastewater	13% of 14MLD	0 ##

#Details of seven parks surveyed for this study are in Tables 4.1, 4.4 and 4.5. * Data collected through informant questionnaire (officials). $$Trees not watered presently in any UGS. ##Untreated wastewater used in an industrial estate in Tumkur city

4.4 Discussion

4.4.1 Need for background details of microclimate factors

To improve the DWR estimates the ET_o were derived in this study for both the cities by following three basic steps. Firstly, based on tree/plant density and diverse species grown, the parks were categorized as mixed type. As per the WUCOLS plant density (K_d) coefficients, the parks in Panaji and Tumkur fall into the category of high or mixed (1.1–1.3) type. Thus, a K_d of 1.2 might seem appropriate for the purposes of inference. The next step was to recognize as to which of the landscape coefficient best describes these parks. In their study, Snyder et al. (2015) reviewed the WUCOLS and LIMP methods and identified the following coefficients as useful for deriving and practicing improved landscape management strategies. These are KL: landscape coefficient; Kmc: microclimate coefficient; Kp: plant species coefficient which includes plant type and managed water stress, and Kd: plant canopy density. They stated that the K_p coefficients are *subjectively separated*, depending on estimated water use of specific vegetation as, extremely low (<0.1), low (0.1–0.3), moderate (0.4–0.6), and high (0.7–0.9). Similarly, K_p values are also "determined subjectively based on experience of the authors of WUCOLS". In that, the K_p for any plant species with moderate water use during the post-monsoon months of October-January can be up to 0.6 and higher (at least 0.7) during the warm months, wherein the water use in the high humidity coastal location of Panaji can be higher at 0.7. With this consideration, these two plant factors were used (UCANR, 2020).

In Panaji and Tumkur parks with high plant diversity, the K_d would be 1.2. The K_{mc} of plants grown in a windy location such as Panaji city can be up to 1.2 as per Snyder et al. (2015).

Using these inputs suitably in to the equation $K_L = K_{mc} * K_d * K_p$ adapted from (Snyder et al., 2015), the landscape coefficient of Panaji parks could be $K_L = 1.2 * 1.2 * 0.6$ (i.e., $K_L = 0.864$) for October-January and $K_L = 1.2 * 1.2 * 0.7$ ($K_L = 1.008$) for February-June.

4.4.2 Importance of establishing regional ETo

ET_o rates ranging from 3.97 to 6.54 mm d^{-1} recorded for California Coachella Valley Water District with wide ranging annual temperature and weather are reported in the literature (Kjelgren et al., 2016; Snyder et al., 2015; Nouri et al., 2013; Rosa et al., 2013). Both the ET_{oP} and ET_{oT} derived for the first time within the Tropic of Cancer are higher by over 20% of these values. Derivations of regional ET_o are useful to meet regional needs. The importance of using appropriate factors of ET_o for landscape groundcovers and shrubs are useful to achieve acceptable landscape performance (Beeson, 2012; Pittenger & Shaw, 2013). A median ranged ET_o value of 0.889 (equivalent to 0.35 as per Kjelgren et al. (2016)) derived and used in this study is much more valuable than picking any ET_o rate in the range of 0.16 to 0.48 (= 0.406 to 1.22 cm d^{-1} as per the derivations of this study) supposedly holding good (Beeson, 2012) for most tropical tree species considered to experience. The ET_{oP} of 8.89 mm (column), multiplied by 1.86×10^6 (km^2 area converted to square meters) would equal a phenomenal volume of 16.54×10^6 liters (=16540 m^3 water) per day for Panaji UGS.

By meeting the total DWR of 6.252MLD (of the hedge area (0.193 km^2), grass cover area (0.683 km^2) and of ~76750 trees 0.536 km^2), all the daily transpiration losses of groundwater of over 16500 m^3 can be prevented. Similarly, in the highly water-scarce city of Tumkur, the groundwater loss to the tune of 3.45 MLD can be prevented by treating the wastewater and using it in the UGS. Derivation of regional ET_o is of significance for planning and meeting the water requirements in the urban green infrastructure. Apparently, the month-wise ET_o derivations of this study could be of regional significance in many Asian countries.

4.4.3 Considerations for Assessing Water Requirements in the UGS

Pittenger et al. (2001) noted that many factors are to be considered for working out the water requirement and frequency of watering. Among them, temperature, season of the year, soil moisture content, soil's water holding capacity, the extent of tree root development, depth of root zone, root system-health, and tree species' ability to resist drought are of great significance. Several authors (Beeson, 2012; Pittenger & Shaw, 2013; Shaw & Pittenger, 2004) have used the values of ($ET_o \times PF \times$ Canopy area) for estimating water requirement for a variety of groundcovers, shrubs, and trees.

The same approach can be successful in estimating the amount of water required for landscape tree species to provide acceptable performance in most landscape settings, but a species-specific tree PF can be a constraint (Pittenger & Shaw, 2010; Pannkuk et al., 2010). To overcome this, Kjelgren et al. (2016) provided simplified landscape irrigation demand estimation (SLIDE) Rules. However, focused research efforts across the spectrum of climatic conditions and plant species in UGS settings are essential for a realistic measurement of DWR that permits the acceptable performance of any given tree species.

For estimating DWR of landscape-trees, Beeson (2012) recommended a single plant factor (PF) of 0.5, or 50%, to adjust reference evapotranspiration (ET_o), as in $ET_o \times 0.5$. This

PF is reported as applicable to all established, climatically adaptable, traditionally grown, drought tolerant, low-water use, native, or social forestry compatible trees. As explained earlier, two different PFs of 0.6 (for less warm and less humid October- January period) and 0.7 (for warmer and more humid February-June period) were used in this study. The calculated DWR using the formula adapted in this study are largely in the ranges reported by Shaw & Pittenger (2004) for many trees growing in tropical regions. In the absence of previous studies on water requirement data for all the species grown in the urban areas of Panaji (or Tumkur), weighted average of 23.75 liters/tree can be adapted to project the DWR by trees in UGS in most Asian cities for the non-rainy periods during the year.

Due to water-stress induced reduction in evapotranspiration efficiency in plants and trees (Qaderi et al., 2019), several physiological processes get altered. For instance, rates of carbon fixation, growth, inflorescence output, as well as fruiting physiology can be adversely affected. Therefore, carbon sequestration potential during the warmer, non-rainy periods of over 6 months from January in the parks and gardens of Panaji ought to be low apart from reduced efficiency of constraining the UHI because of increased LST.

4.4.4 DWR for trees, hedge-plants, and grass cover

There are no previous reports on DWR by hedge plants or grass cover of UGS from all/most cities in India. The DWR assessment done after deriving the ET_{oP} (and ET_{oT}) in this study included sizable lengths of hedge plants, groundcover and of 4012 trees. Thus, it can be proposed that the DWR of 6.77 Lm^{-2} for hedge plants, 4.57 Lm^{-2} for grass cover and the weighted average of 23.75 L/tree using the ET_{oP} of 0.889 cm d^{-1} may be considered as of practical value. Although Kjelgren et al. (2016) suggest that for acceptable plant performances, these volumes as adequate for 1-4 days, the porous, low retention characteristics of sandy/loamy soils in most of the parks covered for this study would need watering at least once in two days in Panaji. The UGS in Tumkur city, which experiences 3-6 °C higher LST than that of Panaji may need to be watered daily for an acceptable UGS appeal.

In this study, for calculating the DWR for all 76,751 trees in Panaji parks, the weighted mean DWR for 4012 trees from three parks was applied. As noted, depending on canopy area the DWR varied. While over 250 different species are recorded from the state of Goa, the number of species planted in UGS might be less than 75 to 80. Hence in addition to canopy area, the DWR could be different among different tree species as was also evident from this study. This aspect needs to be recognized for deriving the water requirements for each tree species in each of the different parks.

Approximately, 2.66 MLD of water is currently being used in Panaji city for all 17 parks with an estimated sum of the hedge area of 19.33 ha and the grass cover area of 68.33 ha. Based on the DWR for the hedge-area and grass cover, watering the tree - currently not in practice - would fetch several advantageous ecosystem services (details in Chapter 6).

4.4.5 Treated wastewater use in UGS for reducing groundwater extraction

As much as 60% is the combined short supply of water for hedge-plants and lawns in the whole of Panaji parks. This implicitly suggests that the plants are experiencing water stress. This is despite continuous groundwater pumping out (or frequent resorting to diversion of significant volumes of processed water meant for domestic use (Corporation of the City of Panaji & CRISIL Risk and Infrastructure Solutions Limited, 2015). Therefore, not only this shortfall but also the DWR of all trees, hedge rows and grass cover together can be effectively met by ferrying in the treated wastewater available to the tune of over 14 MLD. Keeping aside the differences of species-wise requirement, the DWR per tree for 4012 trees in three parks during the eight month-period of October 15-June 15 averages to ~24 liters/tree daily. This average can be applied to all 76751 trees in Panaji UGS as well as to over 38152 trees in Tumkur city parks (Table 4.10) to meet DWR rather regularly.

From the ET_{oP} derived in this study for Panaji, it could be estimated that over 16500 m^3 is the volume evapotranspired (equivalent to 8.89 mm d^{-1} m^{-2}) daily from all of city's UGS area of 1.86 sq. km. For the non-rainy 240 days, it amounts 2,134 mm m^{-2}. In other words, close to 76% of the centennial mean rainfall of 2774 mm is lost through evapotranspiration in this region. Such a loss is an overly critical problem in Tumkur region with higher ET_o (of 9.36 mm d^{-1} m^{-2}) receiving far lesser rainfall annually. The ET_{oT} far exceeds the rainfall by 386%. Perhaps for such reasons are the rapid and huge depletion of groundwater in most low rainfall/snowfall areas across the globe.

While it is beyond the scope of the present study, it may be suggested that the greatly receding groundwater reserves are posing severe water crises in many parts of the globe (Ramaiah & Avtar, 2019). By using the treated wastewater meeting all the safe-limits criteria (Chapter 6), a complete stoppage of groundwater extraction can be possible. Currently, Panaji city is practicing groundwater extraction for watering UGS except for Ambedkar Park. This park resorted to transporting ca 16000 liters after its borewells pumped out saline water which was found unsuitable for garden uses. As ecological proactivity, adequate use of treated wastewater will ensure zero water-stress and would save both on recovering treatment costs and groundwater extraction. Thus, the use of treated wastewater would meet up SDG 3 (Good Health and Well-being), 6 (Clean Water and Sanitation), and 11 (Sustainable Cities and Communities). These aspects are highlighted in Chapter 6.

In cities like Tumkur, due to failing borewells (some drilled deeper than 250 meters: (Central Ground Water Authority (CGWA), 2020)), it is hard to avoid intense water stress, particularly during summer. It may be an issue to save the plants in the UGS even when a consideration-based option exists to divert some portion of water processed for potable purposes to UGS use. Cities like Tumkur can avoid LST rise by reusing the treated wastewater.

4.5 Conclusion

Landscape irrigation management is an extremely important factor for water conservation in cities where water losses are often unrecoverable. Efforts to reduce these losses help to distribute water more widely within cities, which is becoming increasingly important in a world with rapid population growth and decreased water supplies. Optimal irrigation application is typically achieved by applying the correct amount of water to maintain quality of the landscape plants without excessive losses to deep percolation or runoff onto hardscapes. As Snyder et al. (2015) pointed out, though the ET-based scheduling to improve on the efficient use of water for irrigation has seen considerable advancements in recent decades, there is still a need to improve the estimation of ET in regions with multiple microclimates and where the vegetation is mixed or fetch is inadequate for measurement of ET using traditional methods.

Chapter 5

Carbon Sequestration Potential of Urban Green Spaces

5.1. Introduction

The quality of urban living is enhanced by the landscaped UGS. Through their basic, natural process of photosynthesis, all species of plants offer many benefits (Hodel & Pittenger, 2015) and make many densely populated urban areas live-able. In expanding cities (Nouri, Chavoshi, et al., 2019), where air pollution levels can be tremendous, the UGS help purifying air, serve as microclimate regulating, UHI controlling (Jennings et al., 2016) units. They reduce noise pollution, soil erosion, and energy consumption, and through evapotranspiration, regulate the surface temperature (Qian et al., 2015; Wei, 2013). Mcpherson et al. (2011) highlighted that researchers, planners, and the public are concerned about how rapid urbanization could affect sustainability and quality of life in the future. There are continued efforts on developing models that can quantify the role of urban vegetation in removing pollutants from the atmosphere (Brack, 2002). Around the world, much data is essential to have useful models by considering the recent expansion of urban areas.

Major lack of quantitative information from urban settings in different climatic regions seriously constrain the recognition of the formidable role UGSs play in carbon storage and sequestration. While there is burgeoning literature from around the world portraying how agroforestry offers to increase carbon stocks/sequestration in the terrestrial biosphere, the role of UGSs with analogous plant-growing practices is hardly recognized. A key and substantial role in reducing atmospheric concentration of CO_2 can be ascribed to UGSs as they do store carbon in above- and below-ground biomass identical to trees in a forest or in any agroforest.

By attaching similar importance as it is for agroforestry practices, the great potential of UGS to add to carbon stocks must be recognized and their potential fully realized. For instance, green cover in New York City is reported to annually sequester 22.8 million tons and store a staggering 700 million tons of carbon (Nowak & Crane, 2002). However, estimates of carbon sequestration potential (CSP) even for the widely investigated agroforestry vary substantially. Although many factors affect its reliable estimation, any reasonable derivation of CSP in urban settings would prove handy for urban planners and developers, among other needs to (a) make allowances for controlling pollution, (b) to reduce UHIs, (c) to look after and sustain existing UGSs, and (d) to create new ones as can be expected in rapidly expanding urban developments including to gear up to meet smart city guidelines.

5.2 Data and Methods

The study area details are provided in Chapters 3 and 4. A brief detail of data collection and measurements made are as follows.

Data: As mentioned previously, many different species of shrubs (<3 m tall) and trees (>3m tall) in the parks were covered for this study. In addition to the approximate ranges of height and canopy diameter for each species of trees, the measured mean girth circumferences of randomly fetched individual trees of 25 of 27 tree species in Mahavir Park, all 13 species in Ambedkar Park and all 9 species in Joggers' Park were noted. The girth circumference (Fig A8) was measured from as many as 494 random number of accessible trees (without creepers or other fetch/accessibility issues). Ages of all three parks (Mahavir 57 years, Ambedkar

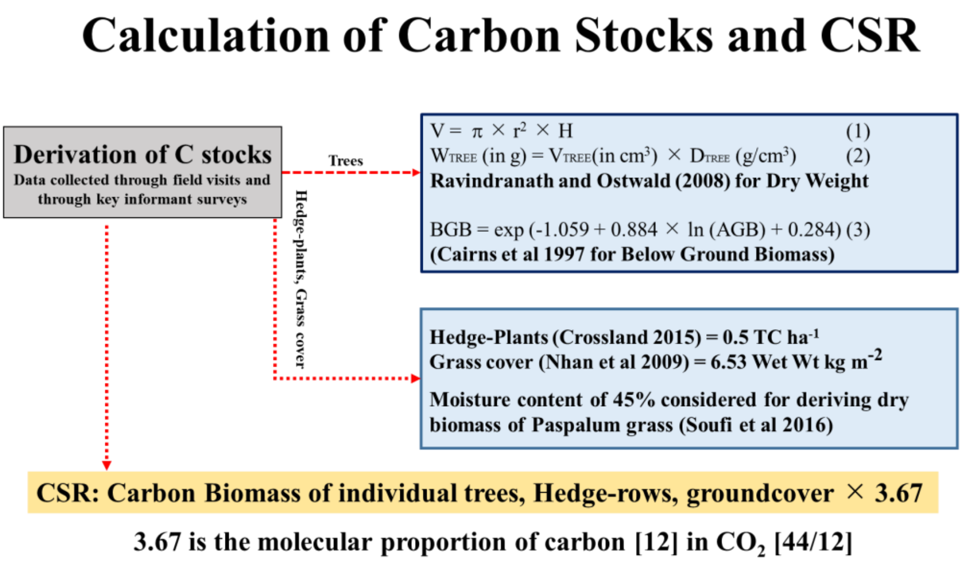
28 years, and Joggers 15 years) were used to derive the annual amounts of CO_2 sequestered per tree and in each park. Also, the species total CSR was also noted.

Calculations of CSP for this study were based on (a) the number of trees of individual species in the parks and (b) on per hectare area of groundcover and hedge plants. Most number of the trees in Ambedkar Park, Joggers Park, Municipal Garden (Garcia da Orta), and in the premises of Kala Academy are in the edges of the park/on both sides of the road. Carbon stocks of trees in these seven parks derived in this analysis were used for calculating the same from all other 10 parks in Panaji city as well as all those from four other cities (See Chapter 6) using the minimum of 108 tons biomass ha^{-1} reported in Lahoti et al. (2020).

5.2.1 Estimation of carbon sequestration potential based on wood density data

Unequivocally, the carbon sequestration rate is regulated by several factors, including trees' growth characteristics, wood density, and local conditions affecting trees' growth and age (Toochi, 2018). The carbon sequestration potential was estimated by following Ravindranath & Ostwald (2008) for all tree species recorded from Mahavir Park, Ambedkar Park, and Joggers' Park.

Main steps involved calculating the carbon stock and sequestration are shown in this flow chart below.



Ravindranath & Ostwald (2008) described a method for estimating dry weight of the tree as the product of volume (derived using tree DBH and height) and wood density. These experts recommend that the estimates of volume of the tress converted into weight-terms by using wood density yield the dry weight biomass of the tree species examined. One prerequisite is collection of wood density value for each of the tree species, or of dominant species, or of the species most closely related species from literature. Using this method, both above ground dry biomass (AGDB) and below ground dry biomass (BGDB) were calculated. The procedure involved the following steps.

A: Measuring and tabulating the height and DBH of trees species-wise in the study site as explained above

B: Estimating the volume of each tree in the sample plot using the formula of (Ravindranath & Ostwald, 2008) for cylindrical shape.

$$V = \pi \times r^2 \times H \quad (1)$$

where, V is volume of the tree in cubic centimeters (or cubic meters), r, the radius of the tree ~130 cm above the ground = DBH/2 and H, tree the height (in cm or m).

C: Multiplying the volume of the tree with the respective wood density to deduce the dry weight of that tree and then converting the weight from grams to kilograms or tonnes as follows:

$$\text{Weight of tree (in g)} = \text{volume of the tree (in cm}^3\text{)} \times \text{density (g/cm}^3\text{)} \quad (2)$$

D: Adding up of weight of all individual trees in each species in the study site (in kilograms for each species).

E: Then the BGB (dry) was calculated following Cairns et al. (1997) and using the dry biomass as:

$$BGDB = \exp(-1.059 + 0.884 \times \ln(AGDB) + 0.284) \quad (3)$$

F: Extrapolating the total dry weight of each species from the three parks in tonnes of biomass per hectare. Wood density data collected from literature, including those from Lahoti et al. (2020) were used (Tables 5.2-5.4).

G: Derivation of Cstocks tonnes per tree or tonnes ha^{-1} based on $W_c = 0.475 \times W_{dw}$ and sequestration potential in tonnes per tree per year based on $W_{CO2} = W_c \times 3.67$

Further, the dry carbon biomass/stocks of a total of 4012 trees in three parks (3128 in Mahavir, 484 in Ambedkar and 402 in Joggers' parks) derived by following Ravindranath & Ostwald (2008) and Lahoti et al. (2020) were used for calculating the Cstocks from all the 17 parks in Panaji city. Based on the estimated of tree numbers (described in chapter 4), the C stocks and possible sequestration potential were calculated for the estimated 33438 trees from 400 parks in Tumkur city UGS. For calculation of carbon sequestered the biomass value of 108 tons ha^{-1} estimated by Waran and Patwardhan (2001), as reported in Lahoti et al. (2020) was adapted. These were used for deriving an estimate of CO_2 sequestration rates of trees in the UGS areas of both Panaji and Tumkur cities. Additionally, for a comprehension on ecosystem services of UGS, these relationships are applied for the UGS existing in three other cities (Chapter 6).

The carbon biomass production ((t $ha^{-1}.y^{-1}$) was also calculated following Kumar et al. (1998) using the relationship:

$$P_{cb} = W_c/T \quad (4)$$

where, P_{cb} is carbon biomass production (t $ha^{-1}y^{-1}$); W_c, Total tree carbon weight in tons; T, age of trees in years.

5.2.2 Estimation of carbon sequestration potential of hedge rows and grass cover

There have been no studies which definitively provide for an assessment of CSP of hedge plants growing in tropical cities. A weighted mean of 0.5 t C ha^{-1} hedgerows involving at least 12 species of hedge plants was provided by Crossland (2015). This relationship was used to arrive at the dry weight, total green weight (i.e., above, and below ground biomass) by applying the universally accepted formula of Toochi (2018). This totals to a wet biomass of ~3.6 kg m^{-2}, which was used for calculating the total wet/green weight, dry weight, carbon weight, and CO_2 sequestration rates from the surveyed parks and extrapolated to all parks in Panaji and Tumkur.

As noted earlier, *Paspalum vaginatum* is the predominant grass in all 7 parks in Panaji surveyed for this study. For the groundcover wet biomass calculations, the estimates of 3.56 tons ha^{-1} provided by Nhan et al. (2009) were considered. The moisture content of this turf grass is 50 to 55% of wet weight (Soufi et al., 2016). Using this information, the total wet biomass at 6.53 kg wet/green biomass m^{-2} was used for calculating its dry weight (=2.94 kg) and carbon content (1.47 kg). The CSP of the grass covers/lawns in all parks was calculated following Toochi (2018) using the factor 3.67 as done for trees, to get an approximate estimate of CO_2 sequestered in the parks/UGS of Panaji and Tumkur cities.

5.3. Results

5.3.1 Carbon stocks and sequestration rates

5.3.1.1 Mahavir Park

The total dry biomass of 3128 trees from Mahavir parked calculated using the formula of (Ravindranath & Ostwald, 2008) equaled 4379676 Kgs (= 4379.68 tons). The corresponding carbon weight is 2080346 Kgs (or 2080.35 tons). In Mahavir Park, the total CO_2 sequestered in the last 57 years is 7634870 Kgs (= 7634.87 tons). This amounts to annual CO_2 sequestration of 133945 Kg (=133.95 tons) by 3128 trees. This plantation of mixed tree-species is spread in an area of 22101 m^2 of the total 37199 m^2. Thus, their number ha^{-1} is 1,416 and their CO_2 sequestration works out to 60608 kg (or 60.61 tons) $ha^{-1}y^{-1}$.

The CO_2 sequestration $tree^{-1}$ y^{-1} (Table 5.1) by nine large tree species in Mahavir Park (Fig 5.1 a) are: *Samanea saman* (385.60 kg), *Delonix regia* (161.61 kg), *Tamarindus indica* (76.79 kg), *Spatodea companulata* (58.88 kg), *Millettia pinnata* (56.31 kg), Casuarina equisetifolia (53.89 kg), *Bauhinia purpurea* (49.25 kg), *Acacia auriculiformis* (45.39 kg), *Lagerstroemia speciosa* (44.40 kg), *Cassia fistula* (39.51 kg). The eight medium trees with moderate CO_2 fixation rates (<40 kg per tree per year) were *Mimusops elengi* (37.95 kg), *Dypsis lutescence* (37.60kg), *Ceasalpenia pulcherima* (27.94 kg), *Peltophorum pterrocarpum* (27.83 kg), *Inga dulcis* (25.47), *Tecoma capensis* (21.15), *Butea monosperma* (20.46) *Syzygium cumini* (19.66 kg). In other seven species with lower CO_2 fixation rates (carbon sequestration) per year ranged from ca 2.9 kg $tree^{-1}y^{-1}$ (*Mussaenda erythrophila*) to 19.14 kg $tree^{-1}y^{-1}$ by *Alstonia scholaris*. The larger the girth circumference, higher was the sequestration rate regardless of the tree age (~50 years) or species.

Table 5.1 Details of total dry weight, carbon content and sequestration rates of different species of trees (50-year-old) in Mahavir Park.

Tree (scientific name)	**Number**	**Mean ht (m)**	**Specific gravity (g)***	**Girth circumference (cm)**			**Dry weight, C-stock and CO_2 sequestration/tree (weight in kgs)**			**CO_2 Sequestered/ species/kg/yr**
				Sample size	**Mean**	**±SD**	**dry wt**	**Carbon**	**CO_2 seq/yr**	
Casuarina (*Casuarina equisetifolia*)	1485	24.5	0.63	23	102.35	19.24	1545.80	734.25	53.89	80032.87
Acacia (*Acacia auriculiformis*)	510	10.5	**0.77**	18	129.56	13.81	1301.91	618.41	45.39	23149.38
Karanj (*Millettia pinnata*)	294	19.5	**0.54**	15	126.73	21.3	1615.40	767.32	56.32	16558.34
Shankar (*Caesalpinia pulcherima*)	147	12.5	0.64	12	101.67	10.47	801.27	380.60	27.94	4106.64
Badam (*Terminalia catappa*)	129	8.5	**0.52**	12	102.92	8.908	459.17	218.11	16.01	2065.17
Ashok (*Polyalthia longifolia*)	89	7.5	**0.54**	10	76.40	6.168	235.44	111.84	8.21	730.58
Apto (*Bauhinia purpurea*)	87	15.5	**0.67**	11	119.18	17.14	1412.73	671.05	49.25	4285.18
Jambal (*Syzygium cumini*)	74	12.5	0.30	11	124.09	21.61	563.76	267.78	19.66	1454.50
Tecoma (*Tecoma capensis*)	53	8.5	**0.58**	11	112.36	14.42	606.68	288.17	21.15	1121.06
Gulmohar (*Delonix regia*)	44	19.0	**0.80**	10	198.1	15.99	5568.74	2645.15	194.15	8542.78
Saton (*Alstonia scholaris*)	27	9.0	**0.49**	10	112.9	17.77	549.11	260.83	19.15	516.91
Taman (*Lagerstroemia speciosa*)	26	13.0	**0.53**	9	138.78	9.935	1273.57	604.95	44.41	1154.48
Peltophorum (*Peltaphorum pterocarpum*)	25	20.5	**0.62**	16	80.5	8.422	798.14	379.12	27.85	695.68
Spatodea (*Spatodea companulata*)	24	17.0	0.71	13	121.08	10.28	1688.75	802.16	58.88	1413.08
Oval (*Mimusops elengi*)	23	9.0	**0.72**	11	132.09	8.608	1088.56	517.06	37.95	872.91
Palm (*Dypsis lutescens*)	16	11.5	0.63	6	124.33	11.91	1078.47	512.27	37.60	601.62
Musaenda (*Mussaenda erythrophylla*)	15	5.0	0.60	13	52.154	4.947	83.41	39.62	2.91	43.63
Bottle Palm (*Hyophorba lagenicaulis*)	13	11.0	0.55	8	41.25	2.55	104.61	49.69	3.65	47.42
Bayo (*Cassia fistula*)	13	13.5	**0.71**	7	110.86	7.625	1133.24	538.29	39.51	513.63
Rain tree (*Samanea saman*)	11	25.0	0.71	6	259.83	23.56	11059.22	5253.13	385.58	4241.38
Ritha (*Sapindus mukorossi*)	9	7.0	**0.58**	6	111.83	24.76	497.09	236.12	17.33	155.98
Pithecellobium dulce (*Inga dulcis*)	5	13.5	**0.55**	3	100.67	11.72	730.55	347.01	25.47	127.35
Palas (*Butea monosperma*)	4	9.5	**0.74**	3	92.5	4.95	586.74	278.70	20.46	81.83
Avalo (*Phyllantus emblica*)	3	9.5	0.78	2	64	0	300.50	142.77	10.48	31.44
Chinch (*Tamarindus indica*)	2	11.5	**0.75**	2	164	11.31	2202.57	1046.22	76.79	153.58
Total number of species	*25*	**12.96**		**Average**	**116.00**		**1491.20**	**708.42**	**52.00**	**6107.90**
Total number of individual trees in 22101 m^2 area (=1416 trees ha^{-1})	*3128*	**5.31**		**Std deviation**	**44.53**		**2264.97**	**1075.86**	**78.97**	**16358.72**

*Specific gravity data from Lahoti et 2020 (in bold) and from Brown, 1997; Carsan et al., 2012; Harja et al.,2016

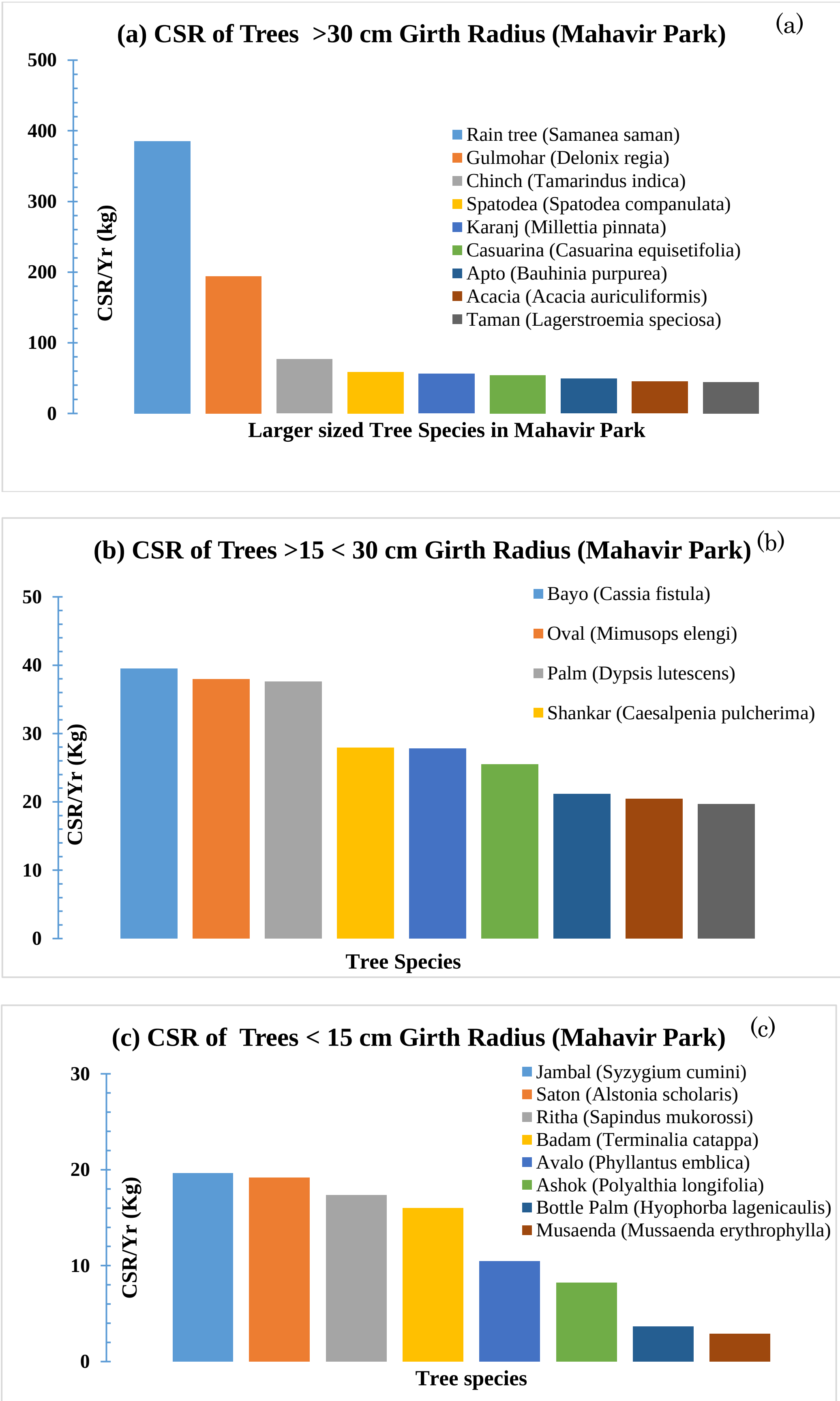


Figure 5.1: Carbon sequestration rates (CSR; kg $tree^{-1}$ yr^{-1}) of different trees with (a) larger (a: >30 cm), (b) medium (b: <30 to >15 cm) and (c) small (c: <15 cm) girth radius

5.3.1.2 Ambedkar Park

In Ambedkar Park total dry biomass of highly close-spaced 478 trees (all along the roadside border) belonging to 13 species in an area of 1130 m^2 was 312.97 tons, and carbon biomass of 148.65 tons. Their numbers per ha correspond to a very dense 4230 trees with a dry biomass of 2770 and probable carbon biomass of 1316 tons. The individual species of trees with the highest rate of CO_2 sequestration per year were Rain tree (630 kg $tree^{-1}y^{-1}$), Gulmohar (162 kg $tree^{-1}y^{-1}$), and Acacia (71.34 kg $tree^{-1}y^{-1}$), The CSR of other species is: Mango (34.50 kg $tree^{-1}y^{-1}$); Casuarina (33.00 kg $tree^{-1}y^{-1}$), Peltophorum (31.50 kg $tree^{-1}y^{-1}$), Coconut tree (29 kg $tree^{-1}y^{-1}$), Badam (28.50 kg $tree^{-1}y^{-1}$) followed by Ashoka 24 kg $tree^{-1}y^{-1}$ and Veni tree (21.00 kg $tree^{-1}$ y^{-1}). The annual CO_2 sequestration rates by all 478 trees aged 28 years amounts to 19.48 tons at an average of 82.54 (± 169.71) kg $tree^{-1}$. Apparently, the probable ha^{-1} annual of 349 tons from an estimate of 4230 trees must be highly skewed. This is because, just 23 large trees (9 Rain trees, 6 Gulmohar and 8 Acacia; Table 5.2) in a total of 478 trees account for over 37% of the annual sequestration amounts. By excluding the higher CSR of rain tree, gulmohar and the least CSR of two-years-old sandalwood trees, the mean CSR for the remaining 453 trees belonging to 10 different species works out to 28.65 kg $tree^{-1}$ y^{-1}.

Table 5.2 Details of total dry weight, carbon content and sequestration rates of different species of trees (28-year-old) in Ambedkar Park.

Tree (scientific name)	**Number (n)**	**Mean height (m)**	**Tree specific gravity**	**Girth circumference (cm) (n)**	**Mean**	**± SD**	**Dry wt kg/tree**	**Carbon wt kg/tree**	**CO_2 seq kg/ tree/yr**	**CO_2 Sequestered/ species kg/yr**
Peltophorum, *P. pterocarpum*	184	12.5	**0.62**	22	81.67	6.64	505.88	240.29	31.50	5795.20
Casuarina, *Casuarina equisetifolia*	92	9.5	0.63	13	95.25	14.69	530.83	252.14	33.05	3040.5
Ashoka tree, *Polyalthia longifolia*	52	11	**0.54**	8	81.57	3.69	389.06	184.81	24.22	1259.6
Bottle palm, *Hyophorba lagenicaulis*	48	6.5	0.55	10	42.4	2.99	66.105	31.4	4.12	197.55
Coconut palm, *Cocos nucifera*	26	8.5	0.58	12	98.17	5.97	465.82	221.27	29.00	754.04
Badam, *Terminalia catappa*	26	8.5	**0.52**	10	102.8	8.4	458.13	217.61	28.52	741.58
Veni tree, *Acacia ferruginium*	12	13	0.86	6	55.33	1.75	338.01	160.56	21.04	252.53
Rain tree, *Samanea saman*	9	21	0.71	4	271	35.35	10120	4807.1	630.07	5670.7
Acacia, *Acacia auriculiformis*	8	11	**0.77**	5	118.6	0.89	1145.9	544.29	71.34	570.72
Bamboo, *Phyllostachys pubescens*	7	9	0.40	18	38.22	3.04	54.38	25.83	3.39	23.698
Mango, *Mangifera indica*	6	14.5	**0.74**	6	72.67	3.56	553.44	262.88	34.46	206.74
Gulmohar, *Delonix regia*	6	18	**0.80**	4	138	18.2	2595.7	1233	161.6	969.63
Sandalwood, *Santalum album* (2yr old)	2	3	0.54	2	24.5	2.12	10.56	5.01	0.66	1.31
Number of species	*9*	**11.23**	**Average**		**93.86**		**1325.69**	**629.70**	**82.54**	**1498.75**
No of individual treesin 1130 m2 area (=4230 trees ha^{-1})	*478*	**4.74**	**Std deviation**		**62.47**		**2725.90**	**1294.80**	**169.71**	**2039.22**

Specific gravity data from Lahoti et 2020 (in bold) and from many wood-data bases mentioned at Table 5.1

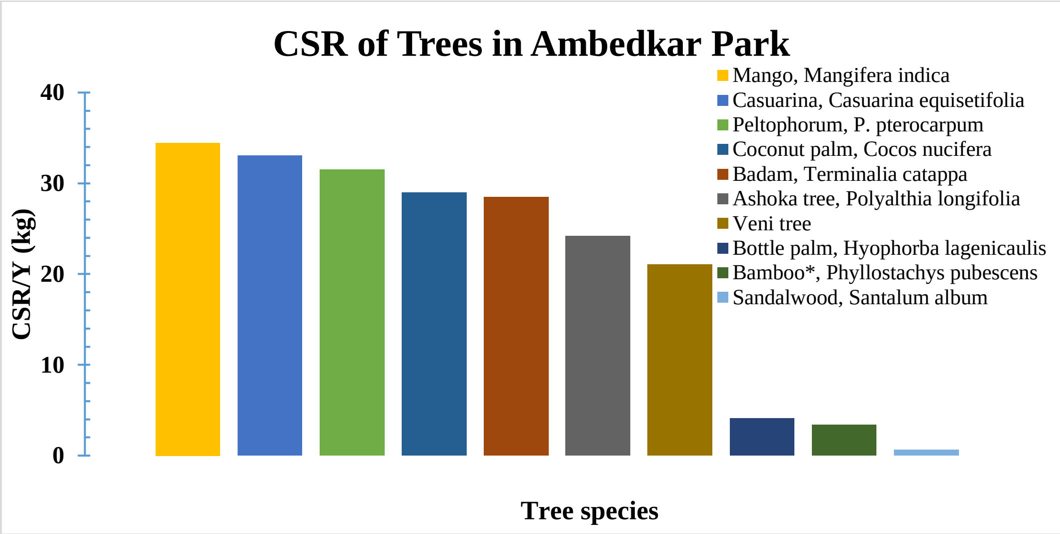


Figure 5.2: Carbon sequestration rates of 10 medium to small-sized trees in Ambedkar Park. In addition, the CSR of Rain tree, Gulmohar and Acacia respectively was 630, 160 and 71 kg CO_2 sequestered y^{-1}. These higher values not fitted into the figure

5.3.1.3 Joggers' Park

In Joggers' Park dry biomass of 404 trees was 164.11 tons, and carbon weight of 77.95 tons. In the last 15 years, the total CO_2 sequestered worked out to 286.1 tons (equivalent to 19.1-ton y^{-1}). The top five CO_2 sequestration trees (Table 5.3) were Peltophorum (64.60 kg $tree^{-1}y^{-1}$), Palm (53.2 kg $tree^{-1}y^{-1}$), Coconut (48.6 kg), Casuarina (36.9 kg $tree^{-1}y^{-1}$) and Ashoka (35 kg $tree^{-1}y^{-1}$). The per ha^{-1} conversion of 404 trees in 1760 m^2 works out to 2296 trees and at a mean of 29.97 kgs (table 5.3) per individual tree, the annual carbon sequestration would be a moderate 68.81 tons ha^{-1}.

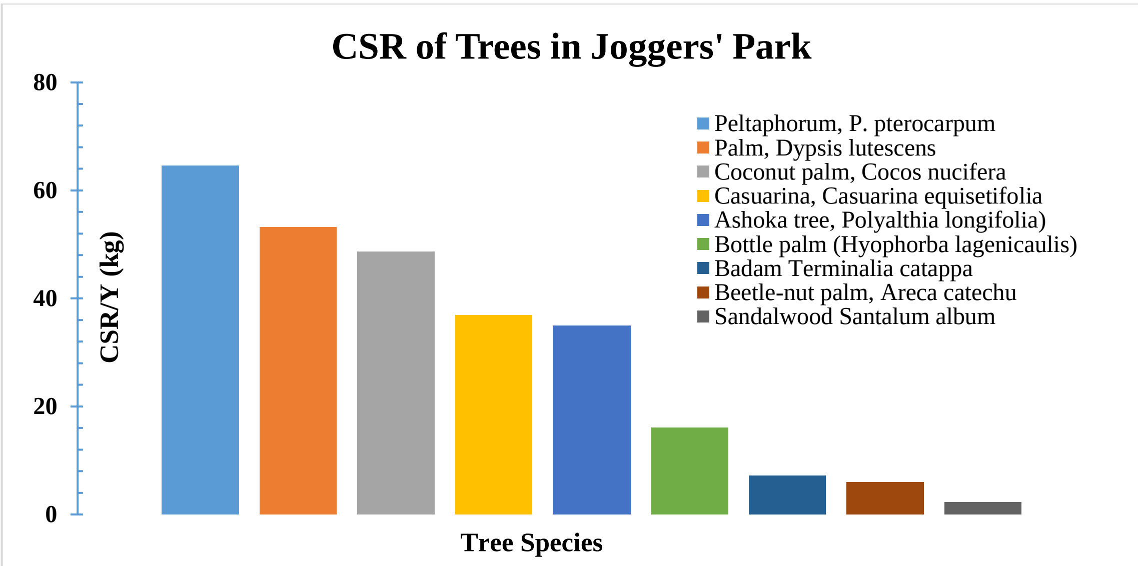


Figure 5.3: Carbon sequestration rates of 9 medium to small sized trees in Joggers Park

Table 5.3 Details of total dry weight, carbon weight and sequestration rates of different species of trees (~15-year-old) in Joggers' Park.

Tree (scientific name)	**Number**	**Mean height (m)**	**Tree spec gravity**	**Girth circumference (cm)**			**Dry weight kg/tree**	**Carbon Wt Kg/tree**	**CO_2 seq/ tree/yr**	**CO_2Seq/species(kg/y)**
				n	**Mean**	**±SD**				
Peltophorum, *P. pterocarpum*	213	13.5	**0.62**	11	82.46	8.99	555.82	264.02	64.60	13,758.81
Coconut palm, *Cocos nucifera*	48	8.00	0.58	14	95.79	7.88	418.43	198.75	48.63	2,334.14
Beetlenut palm, *Areca catechu*	42	8.00	0.52	10	34.67	3.74	51.77	24.59	6.02	252.72
Bottle palm (*Hyophorba lagenicaulis*)	33	5.50	0.55	6	67.33	5.79	138.37	65.73	16.08	530.66
Ashoka tree, *Polyalthia longifolia*)	32	11.00	**0.54**	8	71.5	7.09	300.71	142.84	34.95	1,118.31
Palm, *Dypsis lutescens*	12	6.50	0.55	8	114.25	9.47	457.69	217.40	53.19	638.30
Casuarina, *Casuarina equisetifolia*	10	8.50	0.63	10	77.4	7.71	317.28	150.71	36.87	368.73
Badam *Terminalia catappa*	8	7.00	**0.52**	5	40.6	2.07	61.83	29.37	7.19	57.48
Sandalwood *Santalum album* (2y old)	6	4.00	0.54	6	29	2.83	19.35	9.19	2.25	13.49
Total number of species	*9*	**8.00**	**Average**		**68.11**		**257.92**	**122.51**	**29.97**	**577.43**
Total number of trees in 1760 m^2(=2295 trees ha^{-1})	*404*	**2.85**	**Std deviation**		**28.73**		**197.46**	**93.79**	**22.95**	**1205.08**

Specific gravity data from Lahoti et 2020 (in bold) and from many wood-data bases mentioned at Table 5.1

An overall comparison on the mean values of height (m), diameter at breast height (DBH (cm); Fig 5.4a) and of dry and carbon weights (Fig 5.4b) along with the per tree and per species carbon sequestration rates (Fig 5.4c) is presented. It is useful to note from this comparison that irrespective of tree species composition both mean height and DBH are larges in the older trees, which are taller and bulkier than in the ones ~ 15 years old in Joggers park. As mentioned earlier the mean sequestration rate per tree is the highest in Ambedkar Park.

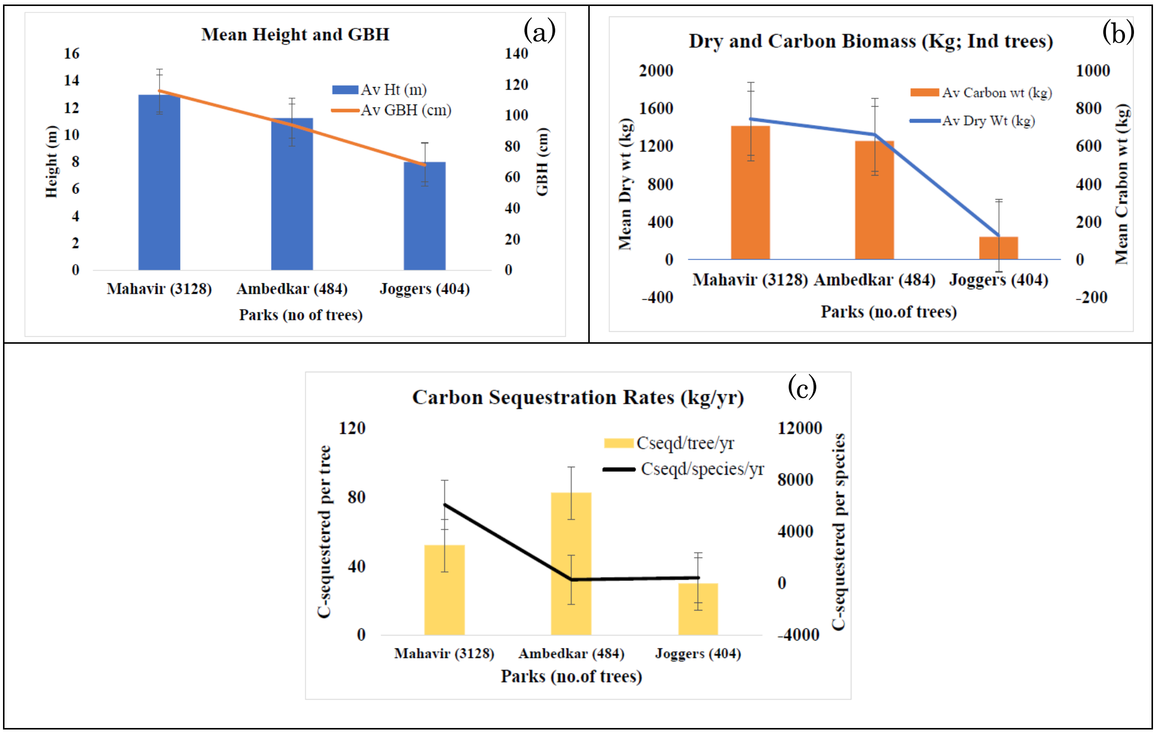


Figure 5.4: (a) Mean values of height (m), GBH, (b) dry and carbon weights and (c) carbon sequestration rates per tree and per species. Mean values are for total number of trees in Mahavir, Ambedkar and Joggers' parks in Panaji city.

5.3.2 Average carbon sequestration rates of trees in surveyed parks

The mean CSR tree^{-1} is summarized at the end of each table above (Tables 5.1-5.3). Although the total number of trees and other details were noted from the seven parks surveyed, the list of trees with names were made available officially from only three parks. There are 4012 trees in 24991 m^2 area exclusively for trees (i.e., in Mahavir Park 3130 trees are in 22101 m^2, in Ambedkar Park 478 in 1130 m^2 and in Joggers', 404 in 1760 m^2). The number of trees in other four parks in the summed-up area of 7855 sq m is 868. These 4880 (i.e., 4012+868) trees in 32446 sq m average to 1433 trees ha^{-1}. Despite the wide differences between the tree species in each of the three parks, the weighted mean of CO_2 sequestered per tree from the averages to 55 kg y^{-1} (i.e., 52 +82.54+29.97 kg tree^{-1}y^{-1} respectively from Mahavir, Ambedkar and Joggers' parks). With this average of 55 kg tree^{-1}y^{-1}, the CSR ha^{-1} is 78.82 tons. This rate is used for estimating the per ha and per tree carbon sequestration potential of trees in the UGS of Panaji and Tumkur cities.

5.3.3 Carbon biomass and sequestration rates of hedge-plants and grass cover

From the data pertaining to hedge rows (Table 5.4) and ground cover (=lawn, Table 5.5) collected from each of the seven parks were analyzed further. The total area of hedge plants and their wet and dry biomass values (Table 5.4) as well as carbon sequestration rates (Fig 5) were estimated. In the 7 surveyed parks, total hedge area is 8,385 m^2, carbon biomass is 10,943 kg, and carbon sequestered amounts to 40,159.7 kg. With hedge row carbon biomass of 13.18 tons ha^{-1}, the fixation/sequestration of CO_2 is equivalent to 48.38 tons ha^{-1} y^{-1}. Similarly, the grass cover area totaling 25,860 m^2 from these parks hold carbon biomass of 37,995 kg and sequester 13,9940 kg y^{-1} (equaling 53.92 tons ha^{-1} y^{-1}).

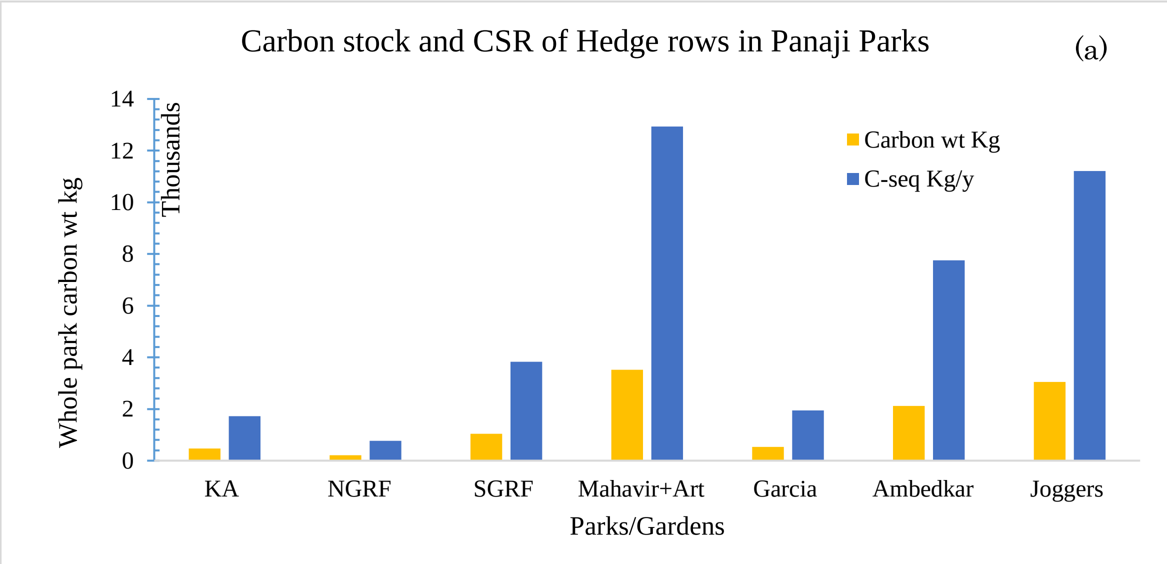
Another approach of using the mean leaf mass area of 12.1 mg cm^{-2} derived by Gratani et al. (2016) for four hedge plants was also applied to arrive at a reasonable estimate of above ground and below ground wet biomass which worked out to 13.07 kg m^{-2}. The CSP of hedge plants was calculated using both these derivations to give a feel of possible CSP in the UGS considered in this study. The CO_2 sequestration was over 3-4 times higher than that of the one derived using Crossland (2015).

Table 5.4 Details of biomass (wet, dry and carbon) in hedgerows and their carbon stocks and sequestration rates in different sampled parks in Panaji City (plus per ha conversions).

Park	Hedge-area (m^2)	Wet biomass (W_{tgw}); kg	Dry biomass (W_{dw}) kg	Carbon biomass (W_c); kg	Carbon sequestered in hedge area kg
Kala Academy	360	1296	939.6	469.8	1,724.17
NGRF Office Park	160	576	417.6	208.8	766.30
SGRF Office Park	800	2,880	2088	1044	3,831.48
Mahavir Park+Art Park	2,700	9,720	7047	3,523.5	12,931.25
Garcia da Orta Garden	405	1,458	1057.05	528.53	1,939.71
Ambedkar Park	1,620	5,832	4228.2	2,114.1	7,758.75
Joggers Park	2,340	8,424	6107.4	3,053.7	11,207.08
Total	8,385	30,186	21884.85	10,942.43	40,158.72
Biomass (Tons ha^{-1})		**36.37**	**26.37**	**13.18**	**48.38 tons/ha**

Table 5.5 Details of biomass (wet, dry and carbon) in grass cover (lawns) and their carbon stocks and sequestration rates in different sampled parks in Panaji City (plus per ha conversions).

Park	Lawn area (m^2)	Wet biomass (W_{tgw}) kg	Dry biomass (W_{dw}); kg	Carbon bio-mass (W_c); kg	Carbon sequestered in lawn area (kg)
Kala Academy	2,675	17,467.75	7,860.49	3,930.24	14,423.00
NGRF Office Park	2,250	14,692.5	6,611.63	3,305.81	12,132.33
SGRF Office Park	1,625	10,611.25	4,775.06	2,387.53	8,762.24
Mahavir Park+Art Park	6,410	41,857.30	18,835.79	9,417.89	34,563.67
Garcia da Orta Garden	1,500	9,795	4,407.75	2,203.88	8,088.22
Ambedkar Park	6,500	42,445	19,100.25	9,550.13	35,048.96
Joggers Park	4,900	31,997	14,398.65	7,199.33	26,421.52
Total **area (m)**; weight (kg)	**25,860**	168,865.80	75,989.61	37,994.81	139,440.93
Biomass Tons ha^{-1}		**65.30**	**29.39**	**14.69**	**53.92tons ha^{-1}**



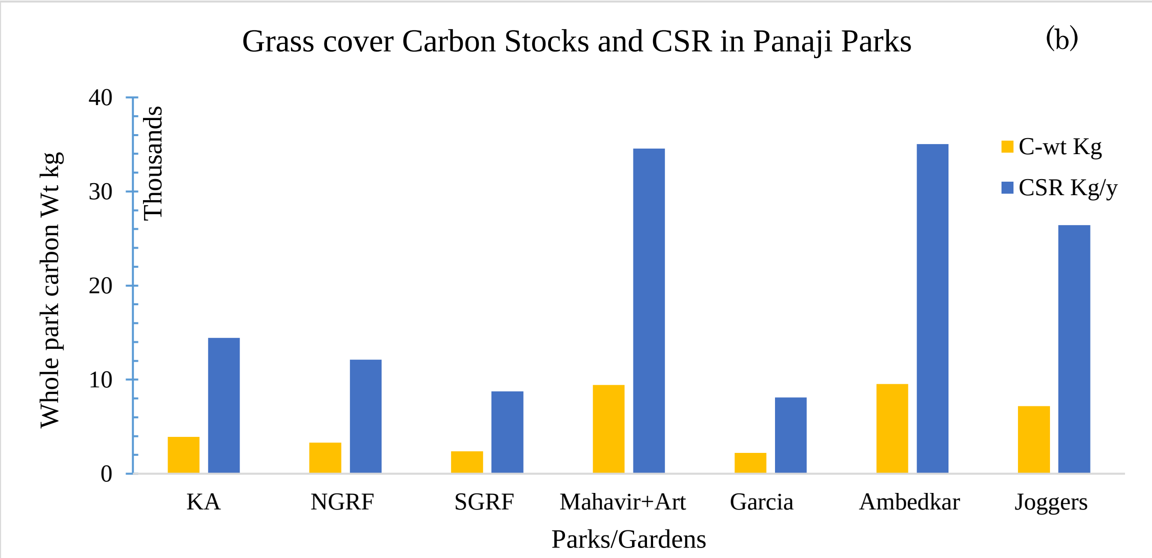


Figure 5.5: Carbon stocks (kg) and CO_2 sequestered (kg. y^{-1}) by pruned plants in hedge rows (a) and grass cover (b) in different parks in Panaji city. Area and other details included in Tables 5.4 and 5.5

5.3.4 Carbon stocks, production and CSP in the UGS of Panaji and Tumkur cities

The per hectare carbon stocks of trees, grass cover and hedge rows respectively are 697.69, 53.92, and 48.38 tons. Trees account for up to 12-14 times the stocks of grasscover or hedge rows in Panaji city parks. The average carbon biomass production in Mahavir Park, Ambedkar Park, and Joggers Park is 18.82-, 46.97-, and 29.52-tons $ha^{-1}yr^{-1}$ respectively.

CSP rates for all of Panaji and Tumkur cities UGS was worked out using the information derived from the seven parks by making use of the derivates of carbon stock (Fig 5.6a) and CSR of trees (55 kg $tree^{-1}y^{-1}$- or 78.82-tons $ha^{-1}y$-1; calculated from the averages data in Tables 5.1-5.3), hedge plants (48.38 tons $ha^{-1}y^{-1}$; Table 5.4) and grass cover (53.92 tons ha^{-1} y^{-1}; Table 5.5). Trees hold large amounts of carbon and sequester far higher (Fig 5.6a). Though larger plot areas are allocated to grass cover (from easy maintenance and water saving angles), the CO_2 sequestration contributions are meagre (6c). The volumes sequestered by trees per hectare are over six times of either groundcover or hedge plants.

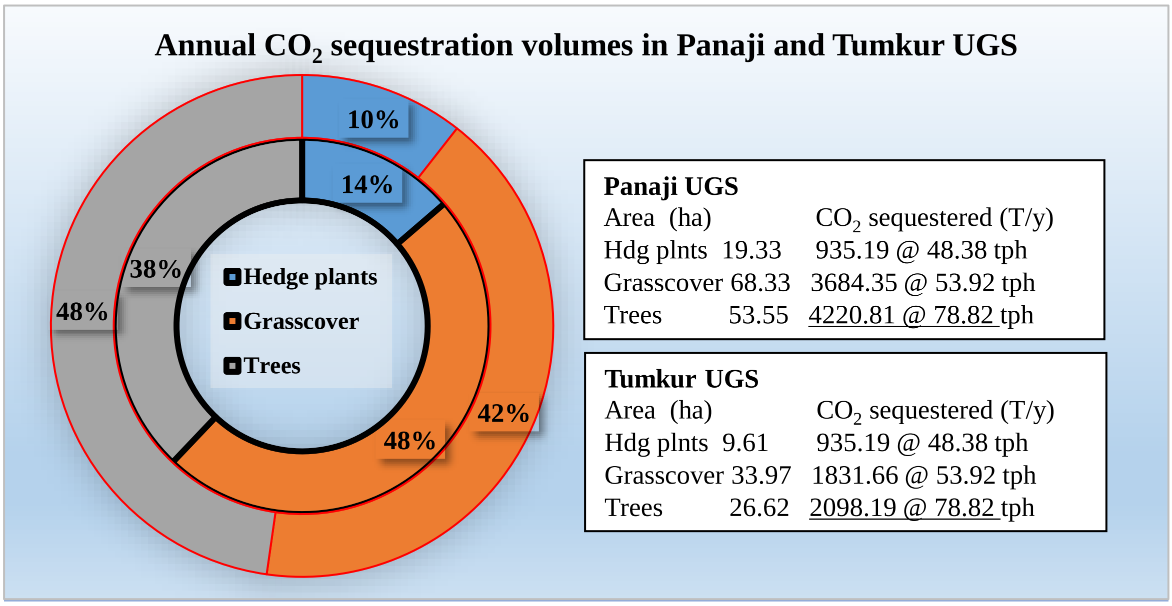


Figure 5.6: Area proportions (in percentage; inner circle) of hedge plants, grass cover and trees (ha) and annual CO_2 sequestration volumes (tons ha^{-1}) derived in this study for UGS of Panaji and Tumkur cities

The carbon sequestration potential of trees in UGS of Panaji and Tumkur cities was calculated using the average annual production of 78.82 tons ha^{-1} y^{-1} obtained in this study than the rates of 108 tons ha^{-1} CSR reported in Lahoti et al. (2020). This to avoid over estimations and to use these carbon stocks and CSR for Panaji and Tumkur city UGS from where many details of LULC (chapter 3) and water needs (chapter 4) were analyzed.

Trees numbering 76751 in Panaji UGS would sequester 4221.31 tons y^{-1} at 55 kg tree^{-1} y^{-1} and those 38152 trees in Tumkur would sequester 2098.36 tons y^{-1}. The rates on per ha basis too are remarkably similar. In that, the CO_2 sequestered would be 4220.81 tons y^{-1} in Panaji and 2098.19 tons y^{-1} in Tumkur parks (Table 5.6). Further, as stated earlier, the weighted averages of sequestration potential of grass cover and hedges derived from all seven surveyed parks in Panaji were used to get an estimate of their carbon stock and sequestration rates in the UGS of these two cities (Table 5.6). With over 36% of the UGS, the CO_2 sequestered by the lawn/grass cover/groundcover is quite substantial. From a summing up. it can be inferred that, in these cities, the existing UGS neutralizes 4556 (Panaji) and 2265 (Tumkur) peoples' carbon footprint/emissions.

Table 5.6. Carbon stock (CST) sequestration rates (CSR) ha^{-1} y^{-1} of hedge-plants, grass cover and trees, in the parks and gardens of Panaji and Tumkur cities

Parameters	**Panaji**	**Tumkur**
City area Km^2	21.6	48.6
UGS area Km^2	1.858	0.924
UGS% in city area	8.6	1.9
UGS; m^2	1857600	923400
Details of Hedge Plants		
Hedge plants area (@10.40(±6.42)% of UGS, ha	19.33	9.62
Hedge plants CS (@ 13.18 tons ha^{-1*} (Tons)	254.71	126.61
Hedges CSP y^{-1}@ 48.39 tons ha^{-1*} (Tons)	**935.15**	**464.85**
Details of Grass cover		
Grass cover area (@ 36.79 (±16.09)% of UGS; ha	68.33	33.97
Grass cover C-stock (@ 14.69 tons ha^{-1*} (Tons)	1003.81	4989.88
Grass cover CSP y^{-1}@ 53.90 tons ha^{-1*} (Tons)	**3683.15**	**1830.87**
Details of trees		
Trees' area 28.83(±16.27)% of UGS; ha	53.55	26.62
No of trees ha^{-1} (@ 1433 trees ha^{-1}	76751	38152
C-sequestered in the UGS (@78.82* tons y^{-1}	**4220.67**	**2098.06**
Total seq (Trees+Hedge-rows+Grass cover; Tons)	**8838.96**	**4393.78**
C-sequestered by trees @ 55 kg $tree^{-1}$ y^{-1}, Tons	4221.31	2098.36
CFPR** @1.94 T per capita (no. of persons)	4556	2265

* Values derived from this study **CFPR- Carbon footprint reduction

5.4. Discussion

This first-time study on calculation of tree carbon biomass and species-wise yearly carbon sequestration in the three of the seven different parks sampled from Panaji city is useful to recognize the importance of urban vegetation biomass for improving living conditions. This is also apparent from the far higher carbon production rates (see below) than previous estimates of 3.23 (Swamy & Puri, 2005) to 6.55 (Kumar et al., 1998) tons ha^{-1} y^{-1}.

5.4.1. Carbon production and sequestration rates

A broad spectrum of vegetation carbon production $ha^{-1}y^{-1}$ are available from agroforestry practices in India (Jose & Bardhan, 2012). Depending on the region where rainfall exceeds 2000mm, the rate of biomass production is stated to be higher (Kumar et al., 1998). The high carbon biomass production averaging 31.77 tons ha^{-1} y^{-1} in comparison to reports by (Suryawanshi et al., 2014) and sequestration rates of 78.82 tons ha^{-1} y^{-1} in all three parks might be due to consistently higher growth rates of all tree species in these parks. Panaji city located in the monsoon fed region, receives annually on an average of over 2770 mm rainfall. Also, all three parks with higher numbers of fast-growing tree species, Casuarina and Peltophorum might be contributing substantially. A few large trees in Ambedkar Park also skew the production rates to high values. Indeed, based on this production rate, the carbon sequestration rate would be 116.60 tons $ha^{-1}y^{-1}$. This data, together with the CSR of hedgerows (48.38 tons ha^{-1} y^{-1}) and grass cover (53.92 tons ha^{-1} y^{-1}) are depicted in Figure 5.7.

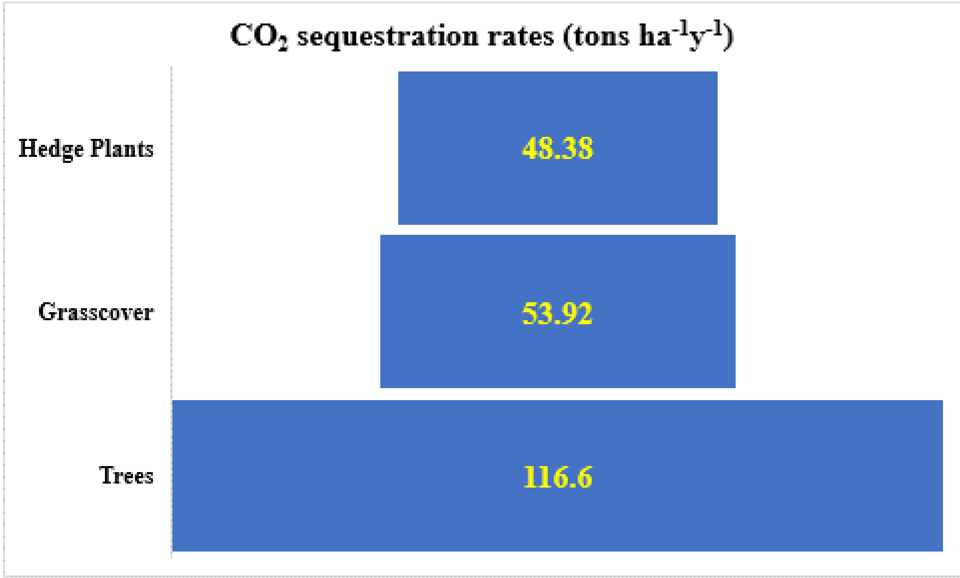


Figure 5.7: Carbon sequestration rates (CSR) of hedge plants, grass cover and trees in Panaji city parks. The CSR of trees based on their average carbon production rates ha^{-1} derived from Mahavir, Ambedkar, and Joggers' parks.

Vegetation carbon production of mere 1.37 tons yr^{-1} ha^{-1} from arid regions receiving less than 1000 mm rainfall annually was reported by Kaur et al. (2002). The rates of overall growth, carbon biomass production and sequestration may vary widely in trees growing in the UGS of different cities. Although Goa is receiving higher than 2000 mm rainfall unlike Tumkur, the CSR ha^{-1} in the UGS areas calculated on per tree and per hectare basis in this study are useful to note a wide difference within the three parks itself. This result is implicit enough to suggest that the CSR is higher in taller, broader, and relatively younger trees.

5.4.2 Carbon storage and sequestration potential of trees

Two decades back, the Intergovernmental Panel on Climate Change (NJ et al., 2000) had recognized agroforestry as a vital opportunity for both adaptation and mitigation actions. Together with the management of cropland, grazing, forest, the agroforestry is projected to sequester over 1.2 billion tons of carbon annually (NJ et al., 2000); (Jose & Bardhan, 2012). The greatest sequestration stage is the younger ages, depending on rates and peaks of individual species. While exact CO_2 sequestration rates may require more accurate measurements under controlled experimental conditions, the impact trees bear on CO_2 sequestration is undeniable in the global fight against climate change as they annually sequester 22.8 million tons and store 700 million tons in US cities alone (Nowak & Crane 2002).

There are no previous studies on the possible CSP of the tree species in the parks of Panaji or Tumkur. Carbon sequestration rates calculated using standard methods are useful to note wide ranging rates from under 2 kg yr^{-1} by ~2yr old sandalwood tree to over 630 kg y^{-1} by 28-year-old rain tree. These results are suggestive of the possible wide ranges of sequestration rates within a given UGS. Nair (2012) remarked that non-linear growth of each tree, widely differing CO_2 sequestration potential even within a given tree species. Numerous ecological factors, including plant growth conditioning ones affect CO_2 sequestration. Ultimately, as Nair et al. (2010) had earlier summed up, the growth of each tree is non-linear, and the greatest sequestration stage is in the younger stages of tree growth, depending on rates and peaks of individual species.

In this regard, choice of trees in urban forestry is crucial. As noted earlier, out of the 478 trees in Ambedkar Park, the superior rates of sequestration by only 23 number of trees in three species (Rain tree, Gulmohar and Acacia) might substantiate such a need. Higher production rates in Ambedkar Park may also be due to these few individual species. In Mahavir Park with trees older than 50 years, the carbon stock was remarkably high but sequestration rates moderate. The per ha carbon stock worked out by following Ravindranath & Ostwald (2008), equals 697.69 tons from an estimated 1433 trees ha-1 in the parks of Panaji city. With a CSR of 78.82 tons ha-1 y-1, the rate of tree carbon stock building in these parks with an average age of 31 (Mahavir: 50, Ambedkar: 28, Joggers: 15 [=93/3=31]) years is 22.51 tons ha-1 y-1 which equals a CSR of 82.60 tons ha-1 y-1. This CSR value closely corroborates with the CSR of 78.82 tons ha-1 y-1, derived in this study based on the average CSR of 55 kg $tree^{-1}$ y^{-1}.

While the exact CO2 sequestration rates may require more accurate measurements to pinpoint the impact trees can create, it is undeniable that in our global fight against climate change, addition of inputs and data from studies like these can aid in the mitigation measure as well as in fulfilling the local/regional plans and needs.

5.4.3 Carbon storage and sequestration potential of hedge-plants and grass cover

Besides providing multiple benefits as border-fences, aesthesis-keepers, many diverse species of hedge plants, including innumerable medicinal herbs also sequester carbon (Hedgelink, 2019) in their above ground biomass and in roots, leaf litter, pruned discards, and other soil organic matter at and below ground level. Although the management of mixed hedgerow systems certainly improves overall carbon sequestration (Falloon et al., 2004), they are often overlooked in favor of larger carbon-capturing trees. The annual carbon sequestration rate of 48.38 tons ha^{-1} hedge plants in the UGS of Panaji city calculated by following Crossland (2015) is apparently substantial. As per IPCC (2007) report, an increase in hedges "results in benefits to biodiversity through habitat creation" and regulate air and water quality through intercepting pollutants, maintain essential diversity, besides being landscape features (Hedgelink, 2019). With over 53.9 tons ha^{-1} y^{-1} of sequestration rate, similar is the prospect with grass cover. These substantial rates both by hedge-plants and by grass cover, majorly of Paspalum grass, are possible through regular watering in the parks surveyed.

5.4.4 Treated wastewater for stress-free plant growth and increased carbon storage

Indeed, together with trees the hedge plants and grass cover, the combined UGS areas have substantial carbon sequestration potential that needs to be harnessed. In this regard, by opting to utilize the assured availability of treated wastewater to supply all the hedge lengths and groundcover in the UGS, the pressure on groundwater and/or processed water meant for domestic uses can be eliminated (Chapter 6).

From the estimations of UGS water requirement (Chapter 4) and carbon stocks and sequestration potential derived in this study, it is to be noted that trees are not a priority for watering. Assuming a 10% better growth when freed from water stress, the amounts of carbon storage and sequestration might also be about 10% or more than the current levels. The increased growth via watering, especially the trees, could amount carbon footprint neutralization of considerable significance. As such, treated wastewater is abundantly available in more volumes than the requirement of trees, groundcover, and hedge plants in all the Panaji city's parks.

Though trees can adequately tolerate the water stress, they can perform physiologically optimally so that the growth is free of water stress and carbon fixation potential is increased. With this reasoning, it is suggested from this study that diverting treated wastewater for use in the UGS in Panaji city enhances the UGS performance. Tumkur city receiving far lower rainfall, with low humidity but warmer temperatures and LSTs, would benefit by using treated wastewater in the UGS. Treating all its wastewater is not only ecologically valuable but also of great economic value in terms of avoiding groundwater extraction that seems to have depleted beyond reasonable limits. Further, the use of treated wastewater available in enormous quantities would aid in building up the tree biomass (higher C-stock) via enhanced CSR. This ecosystem functioning would meet the SDG 13 meant for climate action (Chapter 6).

5.5 Conclusion

In deciphering the complex processes of climate change, carbon is the currency in use to unravel and adapt to the adverse impacts this phenomenon is understood to cause (NJ et al., 2000). From the burgeoning literature on plant biology, Jansson et al. (2010) observed that it is a great challenge to generalize on innumerable ecological and biological aspects of plants. The climate factors (rain and drought), geographic regions and associated spatio-temporal variabilities of numerous ecological characteristics, availability of water, suitable land factors, age differences, inter- and intra-specific differences govern the biomass production, carbon storage or sequestration potential.

It can be suggested from this study that there is a definite scope for increasing the UGS area and for efficient upkeep of existing UGS by utilizing this currently wasted treated water resource (see Chapter 6). Notably, even as a minor contributor, the combined CSP of existing trees, grass cover, and hedge rows in the UGS of Panaji is neutralizing the carbon footprint of over 4500 persons annually at a 1.94-ton per capita emission. Even with its insufficient green cover, Tumkur city's UGSs neutralize the carbon footprint of over 2200 inhabitants. This aspect seems to have not received the attention it deserved, although Nowak & Crane (2002) had provided an estimate that the UGS in New York City alone can sequester 22.8 million tons of CO_2 thus neutralizing the carbon footprint of nearly one million Americans.

Chapter 6

Treated Wastewater for Enhancing UGS Regulatory Ecosystem Services

"…we would benefit from the creation of a stronger emotional and spiritual connection to water" –Prof. Herbert Dreiseitl (Margolis et al., 2014)

6.1 Introduction

Even prior to Plato (c. 400 BC), there already was an acknowledgement of ecosystems services supporting humankind (Daily et al., 1997). The earlier civilization was in the knowing that deforestation -in complex ways- could lead to soil erosion and drying of springs. During the last 200 years, many modern ideas of ecosystem services have emerged. These developments have continued to expand our knowledge of the intricate functional mechanisms that are at play (Ehrlich and Ehrlich 1970), which have changed the perception of human dependence on the inhabited ecosystems.

The concept of ecosystem services introduced in 1970 (Study of Critical Environmental Problems et al., 1970) has become the standard in the current scientific literature. It has continued to expand and currently includes socio-economic, cultural, and conservation objectives as well. The Millennium Ecosystem Assessment (MA, 2006) consolidated all these together as ecosystem services, which are "the benefits people obtain from ecosystems". The MA also delineated them as supporting, provisioning, regulating, and cultural services. Syrbe & Walz (2012), by making a strong reference to spatial characteristics and more integrative approaches in recent years, suggested replacing the term "ecosystem services" with "landscape services" to appraise the services on the landscape which scale to include many more "neighboring processes".

In addition to the above-mentioned ecosystem services, Livesley et al. (2016) recognized the role of urban trees in managing urban catchment hydrology. Among other ecosystem services (Fig 6.1) they offer, urban tree and soil systems play a significant role in reducing nutrient pollution concentrations in urban catchment run-off. Additionally, being stationary sources, the trees can trap and metabolize surge of inorganic nutrients received during the storm surges or monsoonal run-off.

Through a variety of species of plants and trees, well-kept ground cover, and hedge rows, the urban greenery would be fulfilling both regulatory and cultural services. They hold enormous quantities of carbon in their biomass and sequester carbon through the photosynthetic processes. Land surface temperature reduction and regulation of many parameters of microclimate (urban climate regulation) are among the widely regarded services (Chichilnisky & Heal, 1998; Jennings et al., 2016). Although it is outside the scope of this study, their services in bioremediation through assimilation of excess nutrients, detoxification processes, purification of water, and oxygenating the air are vital. As for cultural services, the urban green spaces serve inspirational, therapeutic, recreational and tourism, biodiversity conservation motifs, as well as science and educational interests.

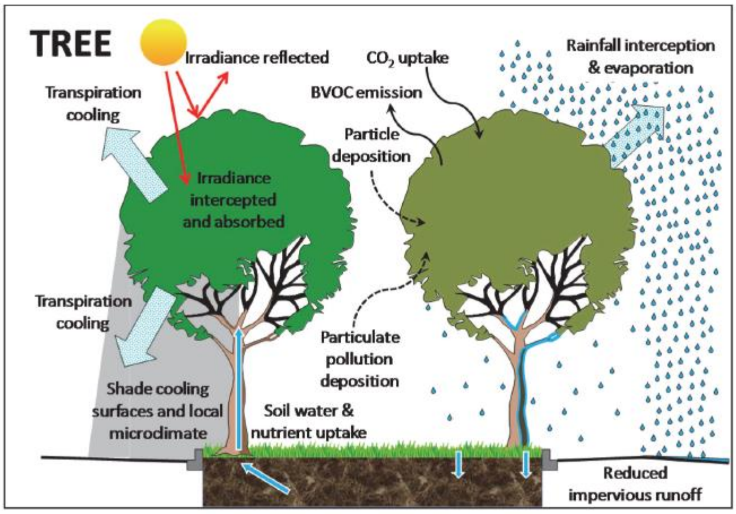


Figure 6.1: Urban Green Space ecosystem service and function (Figure adapted from Livesley et al., (2016))

In an increasingly urban and urbanizing world, pollution arising from industrial areas and agricultural activities in the peri-urban locations can be a serious concern. Human sewage effluents, transport-induced emissions, and city storm waters can create acute health issues. In many developing countries, over 80 or even 90% of wastewater is discharged directly into open streams or coastal water, thus severely harming the environment and causing water-borne diseases, along with hindering tourism and economic development (Anderson et al., 2009).

The way in which water resources in urban settlements are utilized does play a significant role in the preservation, development, and maintenance of urban green spaces. While some studies have focused on how the water resource management practices in urban settlements affect the urban green space cover, due attention has not been paid to the treatment and reuse of wastewater for urban green space management (Ávila et al., 2016; Nicolics et al., 2016). The collection of information, and insights thereof, on change in green spaces and wastewater treatment and reuse can benefit policymakers and urban planners for long-term sustainable urban development through an environmentally friendly approach (Livesley et al., 2016). The major focus, therefore, is to analyze the effect of management of water resources, particularly wastewater treatment and its non-potable reuse for maintenance of urban green spaces and key challenges (Ramaiah & Avtar, 2019).

The nexus between a gradually warming global climate, UHIs, and summer heat waves is a serious one for the environment and humans alike. This is indeed a bigger challenge faced in urban settings. It is highly pertinent thus, that urban planners consider green spaces in city development to realize sustainable urbanization. In many rapidly expanding urban locations, reduction of adverse impacts can be effective and possible speedily by increasing green spaces such as parks, gardens, terrace agriculture, and vertical vegetation (Gill et al., 2007; Bonan, 2015). Livesley et al. (2016) recommend that by creating UGS, carbon can be sequestered for decades or centuries in urban trees, durable social forestry and into their products.

Some parts of India receive excess rains. At the same time, many regions face high water-stress and droughts or seasonal scarcities. Rainwater harvesting for domestic use in urban areas receiving good (sufficient) rains during the monsoon months is of some practical value. However, to harvest and store rainwater for parks/UGS use requires large, suitable open space which may be far from the city and vulnerable to pollution due to possible dumping, evaporation losses as well as diversion for other uses. In such situations, perennial supply of treated wastewater is an assured resource. Unfortunately, the insignificant volumes of wastewater being treated on the one hand, and grossly inefficient use of whatever volumes treated wastewater on the other are hindering the economic benefits. From the estimation of water requirements (Chapter 4), it can be highlighted that the DWR is inadequately met even for the hedge plants and grass cover. As also made clear earlier, the trees are not watered in any of the seven parks in Panaji city from where field visit-based data was collected on various parameters. Easing of water stress is advantageous severally in the UGS with the acceptable performance with all types of vegetation in the UGS, the regulatory ecosystem services (RES) are enhanced in terms of improved thermal comfort, reduced UHI, shading (particularly during the hot/summer months) in addition to aesthetic appeal and other services. Adequate water supply in the UGS, including trees, is among the greatest desirable requirement of the plants which can help in increased carbon sequestration.

Considering these aspects, it was aimed to examine whether the use of treated wastewater as a reliable option for facilitating the RES of the UGS. The challenges of ferrying over 6.25 MLD of treated wastewater to the parks and gardens of Panaji city, safety concerns regarding water quality, and cost factors are highlighted in this chapter. Possible solutions and various UNSDGs met by opting for treated wastewater use in UGS in Panaji city are included. Since Tumkur city does not currently process its sewage effluent, the focus in this chapter is on Panaji city, which treats over 14 MLD of its sewage effluent every day. These analyses being realistic approximations for showcasing the importance of using treated wastewater for sustainable maintenance of UGS, several costs involved for transporting treated wastewater either through water tankers/trucks or through the pipeline options are included. Major results described in chapters 3, 4, and 5 are used in this chapter to provide an overview of the RES the use of treated wastewater could offer for reducing/regulating LST and water-stress of UGS vegetation, for saving on groundwater extraction, and for overall improvement in the aesthetic appeal.

6.2 Data and Methods

6.2.1 Sampling method and data collection

A key-informant survey questionnaire (data collection sheet) was prepared (Appendix-Table A6) and the required details were sought from the offices of the STP located at Tonca in Panaji city. Data on the quality of raw sewage received and the water quality achieved post-treatment were also obtained. Many details were obtained during the four visits made back in 2019 (January) and 2020 (September).

6.2.2 Panaji city sewage treatment plant and sewage handling

Panaji city is among the Indian cities to begin treating sewage effluent early back in 1967. The sewage treatment facility located at Tonca is at an elevation of 3m above sea level. The STP began with a handling capacity of 6 MLD sewage which was doubled to 12.5 MLD in 2005 with an improved continuous-operation technique (C-Tech; Sequential Batch Reactor) based practices. Sewage is collected through the underground sewage network of 45 km, serving 71,000 people residing in an area of ca 6 km^2. In late 2018, another plant of 15 MLD treatment capacity was added within the same premises to treat sewage from over 100,000 people, including those from newly included/developed suburban areas. With this, total sewage treatment capacity of 27.5 MLD from Panaji and suburban areas, this C-Tech Technology-based Tonca Plant can handle an inflow of 65 MLD and employs 26 regular staff members.

The STP in Tonca receives the effluent from the Corporation of the City of Panaji (CCP) and Taleigao panchayat units. In addition, over 100000 liters of sewage is received from the offshore anchored casinos. In all, the amount of sewage treated is more than 14 MLD. It was noted that, during the October-June period, on an average 14-16 MLD water is received for treatment. This volume often goes up to 19 MLD due to rainwater runoff during June-September.

Both the 12.5 MLD and 15 MLD capacity plants within the same premises operate on cyclic activated sludge process. The 12.5 MLD STP was built at the cost of INR 140 million. For every Million liter of raw sewage processed, up to 200 Kwh power is consumed. The annual operation and maintenance costs are INR 19.6 million as per the data shared by the officer. This data is useful get an overview of major costs involved in construction of STPs, electricity requirement and other operational costs involved in treating the urban wastewater. As much as 14 MLD treated water is produced from this facility. As mentioned earlier, over 99% of the treated wastewater -produced at quite a cost and power input- is let away into an already polluted creek.

6.2.3 Characteristics of the raw sewage and treated water

The authorities receive periodic guidance on operation and maintenance, and necessary consultancy from the Indian Institute of Technology Chennai. Analyses of various physico-chemical parameters and coliform counts from both sewage effluent received and treated wastewater at decantation point are measured daily. From the records maintained by the STP office, characteristics of the pooled raw sewage and at various stages of its treatment are provided in Table 6.1. From the documents maintained, it was evident that the plant invariably achieves safe discharge limits for all the various parameters (Table 6.1 and Fig A9) routinely measured.

6.2.4 Estimation of costs for transporting treated wastewater to different parks

As detailed in Chapter 4, about 2.66 MLD groundwater is drawn from borewells using submersible pumps for irrigating the hedge plants and grass cover in the parks of Panaji city. A cost estimate for drawing this water is worked out and major details are included in results section (Table 6.2). Similarly, costing is worked out for transporting over 6.24 MLD water to different parks by deploying water tankers (Table 6.3) and by laying pipeline to reach the treated wastewater to all 17 parks (Table 6.4). The procedures of Clark et al. (2002), Akintola & Solomon (2009), and Dahasahasra Waternet Solutions (2016) were referred to for major details of equipment/installation costs, power requirement with its costing based on current tariff in Goa State. Major equipment/resources (water tankers and manpower as well as fuel) were factored in for working out the costs.

There have been a variety of approaches to develop theoretical models for cost estimations of water supply distribution systems (Clark et al., 2002 ; Akintola & Solomon, 2009). The basic principles of cost estimation in laying water supply pipeline involves the type of pipe (for ex., ductile iron pipe, PVC pressure pipe, asbestos cement pipe etc.), soil conditions, installation conditions, and the following associated activities (Excavation, dewatering, sheeting, etc.) and costs.

A. Construction costs include pipeline cost and pump station costs. Major pipeline costs are for land excavation for pipelines running under pressure including trimming and dressing sides, levelling of beds of trenches to correct grade, cutting joint holes, cutting trees and bushes etc., refilling consolidation and watering of refill, restoration of unmetalled or unpaved surface to its original condition, including the cost of rainwater drainage, fixing caution boards etc., and disposal of surplus soil.

B. Supply and transportation plus laying of 36 cm diameter (PN8 grade [for water application; 8.0 $kgcm^{-2}$] HDPE pipes), joining, field testing and complete at-site commissioning including all cost of material, labor required costs.

C. Cost of intermediate storage tanks in the parks is included, as is the cost of control and telemetering equipment for automatic, unattended operation of pump stations. Since the main pipeline would be all along the side of the public road (Fig 6.2), the right of way, engineering allowance, contingencies and subsequent costs are not included in the estimate done for this study.

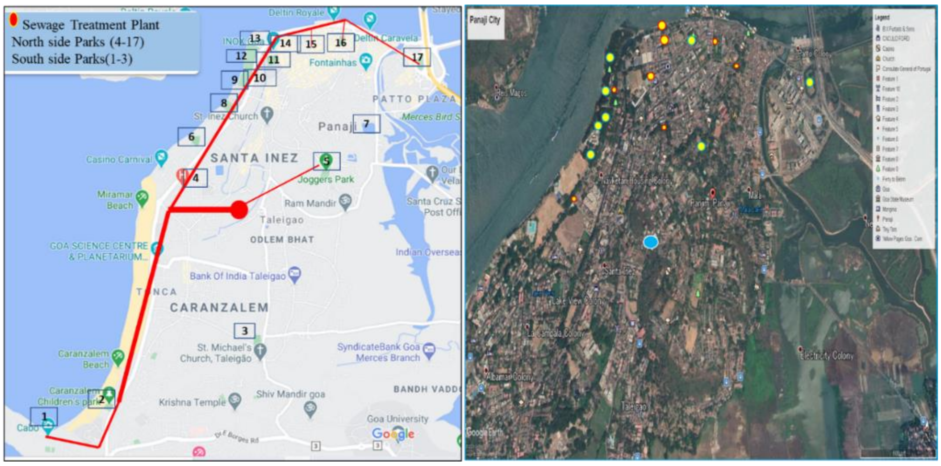


Figure 6.2: Map showing the pipeline to carry treated wastewater from Tonca STP shown in red dot.

The indicative pipeline of a length of ~14 km from the Garden point of Cabo Raj Niwas to Ambedkar Park can be laid all along the side of coastal road which can reach the treated wastewater to 14 of the 17 parks. Treated wastewater from the STP to Joggers Park (5) ~ 2.6 km away might need two booster pumps to reach the water to an elevation of 30 meters above sea level. Much smaller sized public gardens nearer to St. Michael's Church (marked 3 on the map) and on the slopes of Altinho Hill (marked 7) can also be suitably connected by an additional 2 km long pipeline of much smaller diameter (< 25 cm). The numbers marked on the map are 1: Cabo Raj Niwas Garden (The largest of the parks needs a pipeline distance of ~ 4.5 km from STP along the roadside); 2: Caranzalem Children's Park; 3: St Michael's Church Park; 4: Bal Bhavan; 5: Joggers Park; 6: Campal Garden; 7: Military Garden; 8: Kala Academy; 9: South Goa Range Forest Office Park; 10: North Goa Range Forest Office Park; 11: Francisco Luis Gomes Park; 12: Mahavir Park; 13: Art Park; 14: Menezes Braganza Garden; 15: Azad Maidan Park; 16: Garcia da Orta; and 17: Ambedkar Park. Google Map on the right side shows all seven parks surveyed (yellow dots with blue outline) and some other parks (yellow dots with red outline) and Tonca STP (blue dot with white outline)

Based on these aspects, the general estimated costs range anywhere from 50 to 250 US$ per meter length of pipeline laying (Centre for Science and Environment (CSE), n.d.). The cost for Pimpri-Chinchwad continuous pressurized water supply was also referred to get an idea of the costing. In that project, laying of 81 km long heavy density polyethylene (HDPE) pipeline of different diameters ranging from 300 to 500 mm during 2013 costed 112,649,031 INR (= ca 19 USD per m^3) (Dahasahasra Waternet Solutions, 2016). In this study, a cost of US\$100/m^3 is used to calculate the costs for 15 km (actual length may be shorter by 15%). In the entire city of Panaji, the top layer being sandy/lateritic nature, the excavation costs may be minimal, but cement concreting the pipeline laid with the excavated ground may be essential. In view of that, higher cost estimate of US\$100/m^3 is adapted.

6.3. Results/Inferences

Many basic data of relevance to UGS management from Panaji city covered for this study are provided for an overview and general comprehension in Table 6.1.

6.3.1 Characteristics of the raw sewage and treated wastewater

The authorities receive periodic guidance on operation and maintenance, and necessary consultancy from the Indian Institute of Technology Chennai. Also, as per the authorities at the STP, the characteristics of the pooled sewage and at various stages of treatment are provided in Table 6.2. From the routine and officer-in-charge verified documents maintained in the Plant's office, it was evident that the plant invariably achieves safe discharge limits for all the various parameters routinely measured.

From these data, it is evident that the wastewater handling and operations are of high stringency. It is thus inferred that as the water quality of out-falling treated wastewater achieved meets the safe dischargeable limits in all the parameters routinely monitored by the facility. In fact, close to 99% of the treated water is let out daily into the ca. 4-km long tide-influenced creek running in to lower stretches of River Mandovi north of Art Park. This practice thought as a desired measure has been unsuccessful in improving the creek's water quality, aesthetic appeal, reducing foul smell/easing the stress to resident/migrant aquatic and avian fauna, and in quenching the thirst of stray land animals as well. Apparently, the creek continues to receive domestic, plastic, and other wastes from three or four clusters of non-legal dwellings on both banks in the immediate vicinity of this creek.

Table 6.1 Summary of geographic and physical features of Panaji city.

Parameters	**Panaji (Goa)**
Elevation (above MSL; m)	11#
Annual average temp (Min-Max)	25.9-30.2#
Annual average rainfall (mm)	2774^
City area km^2	21.60
Recorded LST (◦C) ranges	38-42 ◦C
Population (millions, 2019)	0.268
Population density/km^2	12444
No. of vehicles (millions, 2019)	0.19
Carbon emission (Mln Tons, 2018)$	0.52
Urban water supply (mld)^	26
Wastewater generated (MLD)^	20
Wastewater treated (MLD)^	15
No. of sewage treatment plants	2
~No of gardens/parks	17 (3 large)
Roadside plantation length (km)	16
Ca. Green cover (% of total area)	8.6

#, Climatedata.org; @, distancesto.com; *, Timeanddate; ^, Ramaiah 2020; $, at 1.94 tons per capita; ^ reported by staff

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From these data, it is evident that the wastewater handling and operations are of high stringency. It is thus inferred that as the water quality of out-falling treated wastewater achieved meets the safe dischargeable limits in all the parameters routinely monitored by the facility. Regularly, more than 99% of the treated water is let out daily into the ca. 4-km long tide-influenced creek running in to lower stretches of River Mandovi north of Art Park. This practice thought as a desired measure has been unsuccessful in improving the creek's water quality, aesthetic appeal, reducing foul smell/easing the stress to resident/migrant aquatic and avian fauna, and in quenching the thirst of stray land animals as well. Apparently, the creek continues to receive domestic, plastic, and other wastes from three or four clusters of non-legal dwellings on both banks in immediate vicinity of this creek.

Table 6.2 Typical values of major parameters of raw sewage effluent received for treatment and treated water quality at Tonca wastewater treatment plant Panaji, Goa, India. Permissible/tolerance limits of each parameter for safe discharge (and, suitable also for plant/tree irrigation of almost all tropical species) are listed.

Parameters	**Tolerance limit**	**Raw sewage**	**Outlet values**
Colour/odour	-	--	Clear, odorless
Suspended solids ($mg.l^{-1}$)	100	400	10
Particle size suspended solids units	<850 u.	140	5
Dissolved inorganic solids max. ($mg.l^{-1}$)	2100	480	246
pH	5.5 – 9.0	6.88	7.56
Oil and grease. Max. ($mg.l^{-1}$)	10	86	NA
Ammoniacal nitrogen as N. Max. ($mg.l^{-1}$)	50	74	NA
Total Kjeldahi nitrogen as N. Max. ($mg.l^{-1}$)	100	28	NA
BOD_5 at 20° Max. ($mg.l^{-1}$)	30	540	33
COD. Max. ($mg.l^{-1}$)	250	960	64
Mercury as Hg. Max. (mg/l)	0.01	0.097	BDL
Lead as Pb. Max. ($mg.l^{-1}$)	0.1	0.035	0.002
Hexavalent chromium as Cr^{0+} Max. ($mg.l^{-1}$)	0.1	0.147	NA
Zinc as Z. Max. ($mg.l^{-1}$)	5	0.369	0.008
Nickel as Ni Max. ($mg.l^{-1}$)	3	0.214	0.08
Chloride as Cl. Max. ($mg.l^{-1}$)	1000	2400	20
Dissolved phosphate as P. Max. ($mg.l^{-1}$)	5	14	0.01
Sulphate as SO_4 Max. ($mg.l^{-1}$)	1000	550	11
Sulphide as S. Max. ($mg.l^{-1}$)	2	5	0.8
Coliform count number/100ml	25 to <60/100ml	$240x10^6$	Nil to 40

6.3.3 Estimation of costs for transporting treated wastewater to different parks

In the following tables, costing for drawing of borewell water (Table 6.3), transporting of 6.24 MLD treated wastewater to 17 parks (Table 6.4) and for laying pipeline (Table 6.5) and necessary explanatory notes are provided. From the regulatory ecosystem service (RES) point of view the supplying of 6.25 MLD treated wastewater will save groundwater extraction cover watering of estimated 76750 trees in the parks. Moreover, if all of 6.24 MLD groundwater were to be drawn, the annual cost would be US$182654.64 (=INR 13500040.52) requiring more borewells and/or drawing for longer duration daily than the 6-7 hours during the working days. Notably, the groundwater extracted in 240 days would be to the tune of 1497.60 MLD (or 1497600 m^3), an avoidable situation by using treated wastewater.

From the many details provided in Tables 6.3 and 6.4, between transporting treated wastewater through water tankers and through the pipeline, it is apparent that pipeline would be serving for a greater number of years than the water tankers can last. The maintenance cost would also be far lower with much less manpower requirement and much smaller carbon footprint.

Table 6.3. Costing of 2.66 MLD groundwater pumping using borewells for Panaji parks

A. Equipment/resources	**Cost (US$)**	**Explanatory note**
20 borewells (av150 ft deep in Goa) with bore pipes	**810. 80** (@40.54/unit)	Cost details not shared; current rates for drilling @ INR 200 ft^{-1} used for calculations
15 numbers of 2 HP submersible motors (+ 3 nos. of 5 HP in Joggers park)	**8,107.95** (@540.53/unit) **4,053.51** (@1351.17/unit)	Assuming all parks except Ambedkar Park have at least one borewell. A 2HP motor costs INR 40,000 and a 5 HP motor, INR 100,000.
16 pump operator staff on monthly wage basis	203.63/unit	Water is drawn out for at least 6 hours daily.
Total	**12,972.26**	Pumps work only for 1-2 years
B. Routine annual requirements		
Wages	**39,096.96**	@ 12,000 INR $month^{-1}$ (semi-skilled category employees) to maintain/run the pumps
Electricity charges for pumps water filling	**3,449.05**	To draw 2.66 MLD for watering in 16 parks 15 nos of 2 HP submersible motors and 3 nos of 5 HP submersible motors are run for 7 hrs. Power consumption is 1.50 Kwh for 2 HP motors and 3.75 Kw for 5 HP motors. 236.25 Kw power needed daily to draw 2.66 MLD groundwater. For 240 days watering, 56,700 Kw power is required. Current tariff for industry use is INR 4.50/Kwh.
Total	**42,546.01**	Wages already added to A
C. Recurring annual requirements (Total at 40% of A+B above)		
Operations/ maintenance	**22,207.31**	Regular servicing, repairs, replacement of motors, new bore wells, incidentals, Insurance cover, medical allowance etc.
Total of A+B+C [15%]	**77,725.58** (INR 5744776.77)	If 6.24 MLD were to be drawn the annual cost would be **US$182,654.64** (=INR 13500040.52); Groundwater extraction in 240 days 1,497.60 MLD or 149,7600 m^3

Table 6.4. Transport of 6.25 MLD treated wastewater using water tankers

A. Equipment/resources	Cost (US$)	Explanatory note
110 water tankers of 10000 L capacity	**1866719.80** (16970.18/unit)	Each costing INR 125000. Daily 104 tankers need to be used. Each to make six trips.
220 drivers (monthly wage)	203.63/unit	50% of the drivers to work in day/night shift
220 assistants (monthly wage)	162.90/unit	Spared tankers/personnel to meet any exigency
200 numbers of 5000 L capacity high quality (syntex) water storage tanks	**101820.00** (509.10/unit)	Each park would need to store treated wastewater received through tankers for watering as per their daily schedule. The storage capacity would vary in lieu of parks size and vegetation DWR. Up to 8-12 numbers may be needed in each of the 17 parks
8 nos. 10 HP motors	**2868.80** (@358.60)	For filling the water tankers. Two standby motors included for costing.
Total	**1971408.60**	Can work for 10-12 years with proper upkeep
B. Routine annual requirements		
Fuel costs for 240 days	**56309.10**	Calculated @21 km L^{-1} diesel at 1.05 US$ (=INR 77.55) present day rate of in Panaji. Each tanker runs on an average 45 Km d^{-1} for 240 days
Wages	**967639.20**	@ INR 15000 (=203.63 US$) $month^{-1}$ for drivers (skilled category employees) and @ 12000 INR $month^{-1}$ for assistants (semiskilled category employees) to maintain/clean the tankers
Electricity charges for pumps water filling	**9482.66**	To fill 10000 L, 6 mins needed for a 10 HP pump. Six such pumps must run for 14 hrs. Power consumption is 7.7 Kwh for 10 HP motor. 646.8 Kw power needed daily to fill 104 tankers. For 240 days watering, 155232 Kw power is required. Current tariff for industry use is INR 4.50/Kwh.
Total	**1033430.96**	
C. Recurring requirements (Total at 15% of A+B [3004839.56] above)		
Operations/ maintenance	**450725.93**	Regular servicing, repairs, replacement of tires, incidentals, Insurance cover, medical allowance etc.
Total of A+B+C [15%]	**3455565.89**	In INR 255,406,909.42

Table 6.5. Cost estimates for transporting 6.25 MLD treated wastewater by pipeline system

A. Equipment/resources	Cost (US$)	Explanatory note
15 km long pipeline	**1500,000** (@100$.m^{-3})	The farthest distance between two parks at extreme/ distal points is 12 Km along roadsides (see Fig 6.2 for additional points). Laying of pipeline involves many steps mentioned under section 6.3.3
4 electricians and motormen	203.63/ person	Two each per shift for smooth operation of pumps
200 numbers of 5000 L capacity water storage tanks	**101,820** (509.10/unit)	Details as in Table 6.2 above
2 units of 75 HP electric motors	**3,975.06**	To fill 6.24 MLD in 15 hrs each day. Two motors can work alternatively pumping 450000 L per hour. Each motor costs INR 147,130
Total of A	**1,605,795.06**	Can work for 35-40 years with proper upkeep
B. Routine Annual Requirements		
Electricity charges for pumps water filling	**12,799.68**	Power consumption is 58.5 kwh for 75 HP motor. power needed daily to pump out 6.25 MLD is 877.5 Kw. For 240 days watering, 210600 Kw power is required. Current tariff for industry use is INR 4.50/Kwh.
Wages	**9,774.24**	@ INR 15,000 (=203.63 US$) month^{-1} per electrician (skilled category employees)
Total of B	**22573.92**	
C. Recurring Annual Requirements (Total at 15 % of B above)		
Operation and Maintenance	**3,386.08**	Regular servicing, repairs, incidentals, Insurance cover, medical allowance, etc.
Total of A+B+C	**1631,755.06**	In INR 120,599,259.19

6.4 Discussion

It is a widely acknowledged fact that management of wastewater and pollution prevention in urban settings require a cost-effective approach. In view of this, the information obtained on the LULC changes (Chapter 3), daily water requirement in the UGS (chapter 4), and carbon stocks and sequestration potential (Chapter 5) during this study are of considerable significance. As such the major purpose of estimating water requirement in urban green spaces and their carbon sequestration potential was to (a) evaluate whether treated water from the sewage treatment facility could adequately meet the requirements of the trees and other greenery in the present 1.6 sq km UGS area in Panaji city during the non-rainy season from October to May, (b) offer data (and literature-based information) on the possible reduction in LST by supplying water to an estimated 76751 trees in 17 public parks/gardens and to (c) expand on the societal benefits mainly through additional job/infrastructure creation.

Utilizing treated wastewater (=recycled water) for maintaining UGS is a reliable and pragmatic strategy (Ramaiah & Avtar, 2019). This can help mitigate the UHI effect, a consequence of LST and, help address the larger issues of depleting groundwater resources and mitigation of climate change impacts. The direct benefit of reusing treated water is making adequate supply of processed water possible for potable purposes even if the cities grow rather rapidly. As such, it is technologically feasible to economically recycle wastewater which is produced daily in enormous quantities in all the highly urbanized settlements worldwide. Large quantities of wastewater generated daily from households and workplaces are often disposed without any consideration of the deleterious impacts the polluted waters cause upon reaching the natural ecosystems (Nagappa, 2019). For instance, Tumkur city is letting its wastewater to an industrial park (Ramaiah et al., 2020). In some cities (Hunshal et al., 1997), huge volumes of domestic wastewater without treating are diverted to grow vegetable plants and fruit trees in large areas.

6.4.1 Regulatory ecosystem services achievable using treated wastewater in UGS

6.4.1.1 Recycled water for UGS trees for urban heat (LST) balancing

The urban heat island is indeed an acknowledged real phenomenon. Increased exposure to it discomforts urban life and causes health problems. The UHI in towns and cities can be hazardous due to heat stress with a potential of heat stroke (United States Environmental Protection Agency, 2020). Invariably, the UHIs lead to increased energy use for building space cooling. Several investigations and sophisticated climatic and physiological models (e.g., Ballinas & Barradas (2016)) have helped recognize the potential of urban forests in mitigating heat island effects by reducing the LST (Bolund & Hunhammar, 1999). These studies are useful to note substantial cooling and shading benefits from the daily rates of evapotranspiration both by individual trees and other plants in a social urban forest. Thus, the regional evapotranspiration rates derived in this study for Panaji and Tumkur cities (the latter could be analogous and applicable for Pune) can help to credit the importance of UGS in achieving urban heat balance.

It was learnt during the survey that there are many parks in these cities which are hardly watered during April-June, the intense summer months in India, due mainly to dried up borewells and to shortage of drinking water supply to many/some city-areas. Absence of watering leads to wilting of some -and drying up of many- plants. During these times of raised LST, there is discomfort for urban pedestrians, toiling peoples, and commuters, among others.

The coastal Panaji city experiences annual LST variations in 38-42◦C ranges with fewer UHIs (Fig 3.1). The city is built on quite heterogeneous landscape, receives higher rainfall, has large water spreads, and maintains a near-optimal percent of green cover. Unlike this, Tumkur city in the interior region experiences far higher LST varying between 42 and 48 ◦C with higher numbers of UHIs (Fig 3.1). Plain landscape, arid zone, suboptimal green cover area, sparse water spread, sizable industrial activity, and continuously intense traffic on the 15 km-length of national highways passing through the city render the city vulnerable to higher LST (Chapter 3).

Making a quantitative projection on the possible reduction in LST would require further studies. From the analyses presented in this work it suffices to qualitatively note that the LSTs in these tropical cities may be brought down by at least by 3-4 °C. This supposition is based on the regular and assured availability of treated water aiding (a) the water-stress eliminated trees and other greenery with enhanced plant growth through elevated rates of photosynthesis and (b) expanded carbon fixation, storage, and sequestration potential (discussed later), year-round.

The daily use of recycled water regularly available in excess in Panaji city would advantageously help in this regard. Its use would enhance evapotranspiration from the UGS and help in easing UHI impacts (Ballinas & Barradas, 2016). Since the trees are not watered in any of the parks, probably to avoid excessive extraction of groundwater, the LSTs are let to raise rather unabatedly. By using the information derived in this study (Chapters 3, 4 and 5), it can be suggested that uninterrupted supplies of treated wastewater would be aiding the UGS and containing the LST, as Norton et al. (2015) note, in these times of global warming.

6.4.1.2 Importance of treated wastewater use in UGS

As discussed in chapter 4, the concept and practice of using treated water for irrigating crops and urban green spaces is not unique or novel (Dillon et al., 2013; Nicolics et al., 2016). However, the ecological and economic perspectives of its use for managing the UGS are yet to receive the attention deserved (Ramaiah & Avtar, 2019). A whole lot of ecological benefits are feasible. For example: (a) avoiding groundwater extraction, (b) conserving urban hydrological reserves, and (c) significant compensation of evapotranspiration-losses. In terms of living comforts, the trees when supplied with applicable water would perform at acceptable limits. This will enable shading, pedestrian thermal comfort and increased out-door workhours.

The “Green Infrastructure” is the vegetation system in place to promote environmental quality. As noted previously and as has been widely accepted, it can reduce the intensity of heat islands by providing shade and evapotranspiration-induced cooling (Livesley et al., 2016). As Norton et al. (2015) summarized: “urban trees are perhaps the most effective and least costly approach to urban heat island mitigation and adaptation”. While it is beyond the scope of the present study, it may be suggested that the greatly receding groundwater reserves year on year are posing severe water crises in many parts of the globe (Ramaiah & Avtar, 2019). By using the treated water from Tonca STP which is meeting all the safe-limits criteria, a complete stoppage of groundwater extraction practiced currently in Panaji for watering UGS can be possible.

As an unreported demonstration, the greenery inside the Tonca STP premises is watered daily during Oct-June with up to 30000 liters of treated water for keeping the premises evergreen and growing some vegetables and fruits. A staff member serving in the Plant from the start of this expanded facility back in 2005 stated that they use their treated water “to grow enough vegetables and to get many types of fruits enough for all 10 households residing on the premises for plant-keeping”. With over 200 coconut trees, 150 banana plants, 10 each of sapota and areca, nine guava trees, six each of mango, jackfruit, moringa, and guava trees, it is apparent that their garden produce exceeds the need for over 40 regular residents. Specifically, this staff member mentioned: “there have been no complaints of any sort either with health or appeal of the produce from within our premises”. There are four large rain trees and three each of banyan, neem, and peepal trees apart from ~ 600 m long hedge and a variety of shrubs all over the place.

To encourage the interested public, construction industry, and any institution intending to take away treated water for uses at their end, the STP office had installed back in 2015 itself two 10 horsepower motors (one each at the outlet points of both CCT units) and pumps with overhead pipelines to facilitate quick filling of treated water such that the trucks do not queue up for filling and are vacating the premises swiftly. As a public service, the STP has spent over 1200 US$ for setting up this facility.

6.4.1.3 Treated wastewater use in UGS for reducing groundwater extraction

The concept and practice of using treated wastewater for irrigating crops and urban green spaces is not unique or novel (Ávila et al., 2016). However, the ecological and economic perspectives of its use for managing the UGS are yet to receive the attention deserved (Ramaiah & Avtar, 2019). For instance, some 2.66 million liters of groundwater are drawn daily through borewells for watering all 17 parks of the UGS in Panaji city. This amounts to a whopping 638000 m^3 for 240 days a year for watering only the lawns (=grass cover) and hedgerows in these parks. Perceivably, all this extraction can be avoided plus over 76750 estimated number of trees also can be watered by diverting 6.25 MLD (or 44.64%) of ca.14 MLD of treated wastewater produced every day. As all safe-limit indicator parameters of water quality are met up in the treated wastewater produced by the STP units in Tonca facility. However, currently, most of this 14 MLD is let out into an already polluted creek adjacent to the STP.

The inference above is of greater relevance and applicable for the UGS in Tumkur city too which receives far less rainfall. With 1.9% of the total city area -a far lower than the optimum 9% of the total city area – the UGS in Tumkur city of more than twice the size of Panaji city, the daily water need in its parks and gardens is 3.77 MLD. Since the official records report that all the 26 MLD raw sewage is diverted for use in an industrial area, it would be desirable -in the immediate future- that all this volume is treated to safe levels and, used for existing UGS in the city as to comply with the smart city norms.

6.4.1.4 Treated wastewater use for compensation of evapotranspiration losses

The EToP and EToT derived in this study (Chapter 4), are useful to note that annually, 76% of the rainwater (2774 mm) recharging groundwater in the UGS region is evapotranspired in the 8 months needing water application. The EToT (of 9.36 mm d-1 m-2) far exceeds the rainfall produced water by 386% in Tumkur region. These losses can be greatly compensated by applying treated water to the UGS.

6.4.1.5 Treated wastewater for stress-free plant growth and more carbon storage

From the estimations of UGS water requirement (chapter 4) and carbon stocks and sequestration potential (chapter 5), it is to be noted that (a) most tress are not a priority for watering and (b) the volumes of groundwater extracted (or the treated ones ferried from Tonca STP to Ambedkar Park) for watering the hedge rows and ground cover are insufficient. Assuming a 10% better growth when freed from water stress, the amounts of carbon storage and sequestration might also be about 10% more than those calculated and presented in Chapter 5. Increased growth via watering especially the trees could amount carbon footprint neutralization of an additional 7000 to 9000 Indians contributing 1.94 tons per capita together from Panaji and Tumkur cities.

6.4.2 Challenges and solution steps based on cost benefit analysis

The first thought -and perhaps a stumbling one- is how is it practical or workable to ferry out treated wastewater daily 6.24 million liters? Many other quizzing challenges are: (i) How can 624 trucks of 10 m^3 be handled and filled daily? (ii) What is the cost/investment for infrastructure to achieve meeting of daily water demand? (iii) How much investment for manpower, energy needs, space for water carriages (trucks) and related utilities? These and more aspects for sustainable management of UGS keeping in mind of the need for enhanced growth, aesthesis, and carbon storage were considered in attempting to provide a cost estimation detailed in Results section 6.3.2. A comparative account of costing under different heads are listed below (Table 6.5). On the long run, the earliest laying of the pipeline and supplying treated wastewater to all the parks would help improving many of the RES of the UGS. It is more economic vis a vis water tanker-based transport both on capital and other costs.

In Panaji, the farthest public garden (Governor Residence arena with over 100000 m^2 green spread) is six-road km away from the STP. The next farthest is Dr. Ambedkar Park, five-road km away from the STP location. All other 15 parks are within 3.5 km reach. A suitably planned pipeline route shown in Fig 6.2 not exceeding a total length of 15 km can reach the treated water of safe quality for all the UGS of the city. The city getting drinking water from over 55 km distance could afford to use its highly safe treated wastewater for enhancing environmental services mentioned previously to benefit variously.

Table 6.6: Capital, routine, and operation-maintenance costs of three different processes applicable for meeting daily water requirements (DWR) in the parks of Panaji city

Costing (US$) Details	Water Transport-Process		
	Borewell based	Water tanker based	Pipeline based
Capital	12,972.26	1,971,408.60	1,605,795.06
Annual Routine	42,546.00	1,033,430.96	22,573.92
Annaual OM	22,207.31	450,725.93	3,386.08
Total cost	**77,725.38**	**3,455,565.89**	**1,631,755.06**
Source of water for parks	Groundwater within the parks	Treated wastewater from STP	Treated wastewater from STP
% DWR met (for only hedge plants + grass-cover)	**60.18**	**100**	**100**

In many Indian cities and elsewhere in the world, the authorities ought to plan and install pipelines to draw treated water on a continuous/need basis to achieve reduction in carbon footprint, howsoever small it might seem.

6.4.3 Employment opportunities in the UGS

Although it is out of the scope of this study, for reasons substantiated above the treated wastewater use in the UGS is a worthy option for sustainable maintenance of UGS in many parts of the globe. From the primary data collected and furnished in chapter 4 (Table 4.1) as many as 75 persons are employed on a regular basis in seven parks. There are employed women staff (Fig 6.3) for many lighter works as watering lawns and hedgerows using hand-held pipes, litter collection and disposal, tending to nursey plots, sapling care and planting as may be desired, tidying the garden area etc. Although these jobs are essentially required for maintaining the parks even if treated water is not used, the job opportunity aspect is highlighted here from the perspectives of the UGS meeting seven of the 17 United Nations Sustainable Developmental Goals (SDGs).

Figure 6.3: A picture from Ambedkar Park. Women folk make up a good proportion of the regular staff

6.5 UN Sustainable Development Goals met

Among the above 17 SDGs, Goal #6 on clean water and sanitation is one of the "outcome-oriented targets". It emphasizes, among other aspects, “on Safe and affordable drinking water; end open defecation and provide access to sanitation and hygiene, improve water quality, wastewater treatment and safe reuse, increase water-use efficiency and ensure freshwater supplies, implement IWRM, protect and restore water-related ecosystems” (United Nations). The two “means of achieving” targets are to “expand water and sanitation support to developing countries, and to support local engagement in water and sanitation management”(United Nations, 2018b). Thus, pragmatic rethinking on wastewater management is mandatory. Besides other newer knowledge add-ons from this work, it can be pointed out briefly that the following SDGs are met in some magnitude.

The SDGs 3, 6, 8, and 11 can be supposed to have been addressed in this study. This is because a primary information-input based highlighting of the employment opportunities and employability of physically (and more relevantly, economically) weaker folks covering gender equality (SDG 6) and inclusive growth (SDG 8). In some measure, the UGS functioning also meets up “ending all forms of discrimination against all women and girls everywhere” and of “making cities and human settlements inclusive, safe, resilient, and sustainable”.

Of the six "outcome-oriented targets", the SDG 5 includes wastewater treatment and safe reuse. This study has examined on the availability of treated water for use in sustainable UGS management. Possibilities of saving potable water for human consumption are included. Particularly the objectives set for this study are complying with the SDG 13: "Take urgent action to combat climate change and its impacts by regulating emissions and promoting developments in renewable energy". The outcomes can be useful for implementing activities to formulate and practice national adaptation plans.

Results of this study relate quite closely to The Paris Agreement (United Nations

Framework Convention on Climate Change, 2021). Briefly, The Paris Agreement was adopted by 196 Parties at COP 21 in Paris, on 12 December 2015 and entered into force on 4 November 2016. This Agreement is a legally binding international treaty on climate change. The enhanced regulatory ecosystems services of the urban green spaces can help achieve Paris Agreement's long-term temperature goal of limiting global warming to well below 2, preferably to 1.5 degrees Celsius, compared to pre-industrial levels. Thus, countries like India which is sincerely aiming to stop global peaking of greenhouse gas emissions as soon as possible to achieve a climate neutral world by 2050.

In the multilateral global climate change process, The Paris Agreement is indeed a landmark. For the first time, all nations agree to a common cause to remain bound to undertake ambitious efforts to combat climate change and adapt to its effects. In this context, the potential of sequestering ~ 116 tons of CO_2 ha^{-1} yr^{-1} by trees in the UGS need to be harnessed across the country and in many Asian cities in order move towards net zero carbon emissions by 2050 as aimed by Japan and Korea (IISD, 2020).

Further, creation of expanded UGS to meet the global per capita standards, suitable policy research applicable and resiliently adaptable regionally would synergize the efforts of achieving the highly desirable carbon-neutral urban settlements. For this to happen, required attention in terms of basic research on the carbon sequestration potential of UGS need to be pursued in all cities as a forerunner.

6.6 Conclusion

Treating and reusing city generated wastewater when utilized for upkeeping the existing UGS would reduce groundwater extraction, bring down LSTs, increase carbon sequestration potential through improved plant growth plus health, reduce pollution, beautify cities, employ many skilled, semi-skilled and physically weaker persons as well as result in gender equality. Above all, the UGS enhance the live-ability aspect. By proficient management systems, including the installation of pipeline transport systems for economic transportation of the treated wastewater, they can provide -albeit only a limited- locally produced food items leading, as mentioned in chapter 2, to reduction of food miles and some quantity of wood biomass, thereby helping to reduce deforestation. While a substantial CSP increase in the UGS may not result, the other regulatory services specifically of better thermal comfort, groundwater saving and remarkably reduced LST are certain to happen by meeting the DWR using the otherwise unused treated wastewater as the cost of processing the same is phenomenal.

Chapter 7

Summary

During the past 4-5 decades, environmentally friendly and sustainable urbanization are much sought after. This is because urbanization offers several opportunities for growth in the economic, educational, societal, and technology sectors. It offers benefits to society in terms of better living standards, healthcare facilities, and employment opportunities. Such seemingly desirable characteristics are dampened by the downsides of often unplanned and haphazard urbanization. The streaming migration into the urban areas and the consequent overcrowding reduces the green cover and leads to environmental degradation.

In any research endeavor aiming to recognize the importance/relevance of urban green spaces' existence, a deeper understanding of the impact of land surface temperature (LST) on human thermal comfort is an important requirement. While the impact of urbanization on LST has been widely studied to monitor the urban heat island (UHI) phenomenon, the sensitivity of various urban factors such as urban green spaces (UGS), built-up area, and water bodies to LST is not sufficiently resolved for many urban settlements.

In this regard, as an outcome of intense considerations and consultations, this work was planned for analyzing the landscape and microclimate features of two traditional cities in India currently being developed as smart cities. It was also the aim of this endeavor to collect data on UGS maintenance practices in these cities and their possible ecosystem services. Remote sensing techniques for satellite image analyses, key-informant questionnaire-based data collection, field visits, and measurements comprised the study methodology. Since little to null information on water requirement or carbon sequestration potential of UGS was available from these two Indian cities proposed to be developed as smart cities, the following major aspects were covered for this study.

Key-informant questionnaire-based and personal field surveys for the collection of information on current practices of UGS maintenance were carried out with the aim of estimating the water requirement of the trees, groundcover (=lawn), and hedge-row plants. During the 2019 visits to various government agencies and public parks in Panaji, it became evident that the borewell water extracted from mostly within the garden premises was supplied only to the lawn and hedge-row plants. It is to be noted that the trees were not watered in any of the parks. It was recognized that the amount of water supplied was sub-optimal. Therefore, the option of exploring whether a part of the current 14 million liters daily (MLD) treated water available for free from the city's sewage treatment plant (STP) could be opted for watering the current UGS area, including trees which are vital for balancing the UHI impacts.

The repertoire of literature has not paid enough attention to the need of water for UGS plants for their acceptable performance. This is especially true for almost all UGS of most Asian countries. An estimate of water requirements of trees in the green infrastructures is variously helpful. More than pruned/trimmed hedge rows of ornamental or medicinal plants or neatly made grass-lawns, it is the fast-growing tall trees which drawdown the atmospheric CO_2 copiously, produce oxygen, and thicket particulates on their foliage. They cool the land surface better, shade the buildings below their crown/canopy, and help pedestrian thermal comfort when in sufficient numbers. For these key urban services trees play, keeping them water stress-free is vital. In this regard, to ensure a realistic and reliable estimation of the daily water requirement, several available methods were considered before finally adopting the formula of Kjelgren et al (2016), widely applicable for all types of plant species across the globe. Evapotranspiration rates suitable for the region were derived in this study for calculating the daily water requirements (DWR) of trees, hedge rows, and groundcover.

The carbon stock and sequestration potential were worked out for 32 different tree species, hedge plants, and groundcover grasses. These plants/trees are grown in the seven different parks/gardens from where detailed data was collected. All trees were identified to their species level with the help of plant taxonomists and by referring to the literature. Standard methods of Ravindranath and Ostwald (2008) and Lahoti et al., (2020) were used for deriving the carbon stock and sequestration rates.

Regulatory (and some cultural) services are fulfilled by the UGS. For any UGS management system, the aim of achieving acceptable ecosystem performance and deriving many of its invaluable services continuously must be the top priority. Such priorities help wholesome, long terms benefits and returns from the UGS. Ideally, there would be a better and balanced diversity of plant, grass, and tree species in the well-kept parks with groundcover, hedge rows, and trees. All these varieties drawdowns hold and sequester enormous quantities of carbon.

The role of UGS in LST reduction and regulation of microclimate parameters are well known. This study explored as to why the use of treated wastewater/recycled water can indirectly add up to ecosystem services such as the elimination of groundwater extraction and significant compensation of evapotranspiration losses and, at the same time protect water stress-free status as well as reduce LST impacts.

Highlights of Main Results

A. LULC Changes and Spectral Indices

1 The multivariate regression model developed in this study was useful to note a strong negative correlation between MNDWI and LST with a value of 0.83 for Panaji. This relationship is useful to infer that because of large areas of water bodies in the region have been helpful in keeping a check on the LST. With 35% coverage in the grid, the maximum percentage share of cooling surfaces are water bodies in Panaji occupying 21.60 km^2 area and much smaller city than Tumkur with 48.60 km^2. Together with substantial green cover in around the city, Panaji city currently has this highly advantageous feature of expansive watershed.

2 On the contrary, the much larger Tumkur city with highly scarce areas of water bodies experiences persisting highs of LST. Therefore, many discomforts in the urban dwellings are experienced. It is thus possible to point out that the UGS and water bodies can help in bringing down the LST, as well as facilitating healthy living conditions and aesthetic appeal. Therefore, the significance of ecosystem services (green spaces and water bodies) should be given priority in the decision-making process of sustainable and vibrant (smart) city development.

B. Water Requirements in the UGS

1 Knowledge of regional evapotranspiration (ET_o) is vital for deciding on water management for irrigating the UGS. In this study, the ET_o for Panaji (ET_{oP}) and Tumkur (ET_{oT}) were calculated for every month of the year by assembling a variety of atmospheric data. Using the annual average evapotranspiration rate of 0.889 cm d^{-1} in Panaji region, the water requirement for different plant types was calculated.

2 Daily requirement of water was found to be higher by 3-4 liters/tree (than the annual average of ~ 25 liters/tree) in different parks during the warmer months beginning mid-February to mid-June. During the somewhat cooler months in Goa, the water requirement was lower than the annual average. Water requirement for every m^2 area of groundcover is 4.57 liters and for every m^2 row of hedge-plants, it is 6.77 liters d^{-1}.

3 The water currently applied for hedge area of 236,287 m^2 and the ground cover area of 784,465 m^2 in all 17 parks totals 2.66 MLD. At 6.77 LPD m^{-2} for hedge plants and 4.57 LPD m^{-2}, the daily demand is 5.34 MLD. A total of over 80000 trees needs 1.77 MLD. From this information, the total daily volume of water required for the entire UGS of 1.86 km^2 in Panaji city is 7.10 million liters. This volume is much lower (about 50%) than the total treated water of 14 MLD produced and drained into a polluted creek.

4 Tumkur city has much smaller UGS area (1.9 km^2 in a total of 48.60 km^2) and the water applied daily to the estimated hedge area of 117497 m^2 and the ground cover area of 389,952 m^2 is 1.2 MLD. However, the requirement for hedge plants is about 0.8 MLD and for groundcover, 1.78 MLD. Apparently, the daily supply for hedge plants and groundcover falls short by 1.53 MLD (or 46.57%) of the requirement. The city is diverting its untreated sewage effluent to an industrial zone. When the city considers processing its wastewater, the plant demand at under 3.5 MLD, including that of ~ 40000 trees can easily be met.

C. Carbon Sequestration Potential

1 Dry weight and carbon biomass of 34 different tree species was derived by following Ravindranath and Ostwald (2008). Carbon sequestration rates from these trees were also calculated. These results were obtained from a total of 4012 trees in 24,991 m^2 area in three parks of Panaji city.

2 Notwithstanding the wide differences between the tree species in each of the three parks, the weighted mean of CO_2 sequestered per tree averages 55 kg y^{-1}. With this rate, the CSR ha^{-1} is 78.82 tons. This rate was used for estimating the per ha carbon

sequestration potential of trees in the UGS of Panaji and Tumkur cities. The volume of CO_2 sequestered by 76751 trees in Panaji UGS is as much as 4221.31 tons y^{-1} ha^{-1} at 55 kg $tree^{-1}$ y^{-1}. In Tumkur city UGS, 38152 trees sequester 2098 tons $ha^{-1}y^{-1}$.

3 Further, weighted averages of carbon biomass and sequestration potential of groundcover and hedges were also derived from all seven surveyed parks in Panaji. These were used to get an estimate of their carbon stock and sequestration rates in the UGS of Panaji and Tumkur cities. The hedge row carbon biomass averages 13.18 tons ha^{-1} and the fixation/sequestration of CO_2 is equivalent to 48.38 tons ha^{-1} y^{-1}. Similarly, the groundcover, occupying over 42% of the UGS, with carbon biomass averaging 14.69 tons ha^{-1} sequesters 53.92 tons of CO_2 ha^{-1} y^{-1}.

4 Even as a minor contributor, the combined CSP of existing trees, groundcover, and hedge rows in the UGS of Panaji and Tumkur apparently neutralize the carbon footprint respectively of over 6900 and 3200 Indians at a per capita emission of 1.94-ton. Even with its insufficient green cover, Tumkur city's UGS contribute to carbon footprint reduction. This aspect ought to receive the attention it deserves.

5 While the exact CO_2 sequestration rates may require more accurate measurements to pinpoint the impact trees can create, it is undeniable that in our global fight against climate change, addition of inputs and data from studies like these can aid in the mitigation measure as well as in fulfilling the local/regional plans and needs.

D. Regulatory Ecosystem Services Using Treated Water

1 In this chapter, an overview of the regulatory ecosystem services offered by UGS is presented. This is done with a view of evaluating how the use of treated water is more pragmatic for sustainable management of UGS.

2 Using the data collected from the STP in Panaji and by noting the quality of treated water achieved for safe discharge, it is possible to safely use the treated water for UGS purposes.

3 The ecological and economic advantages of using the treated water are listed and discussed. For instance, complete stoppage of groundwater extraction -currently practiced in most parks in Panaji (and some parks of Tumkur)- is possible by using just about half of the volume of treated water currently drained out into an already polluted creek (as mentioned earlier). In fact, quite an amount of money invested on processing can be justified when this safe resource can be put back to advantageous uses.

4 Other advantages such as compensation of daily evapotranspiration losses, enhanced thermal comforts, and additional employment opportunities are discussed in brief. Further, some of the challenges or bottlenecks associated with the UGS in general and the delivery of treated water at the parks/destination are touched upon.

5 In the end, the UN SDGs met through the sustainable management of UGS and eco-friendly application of treated water are included.

Important outcomes of this research work:

- Spectral indices of relevance in recognizing the factors influencing the microclimate and LST. These were derived for Panaji and Tumkur, the two cities proposed to be developed as smart cities under India's National Smart Cities Mission, 2015.
- Identification of the need for UGS expansion in Tumkur city experiencing high and persistent LST (one paper published).
- Monthly evapotranspiration rates for Panaji and Tumkur and application of these regional ETo for calculating the daily requirement of water by the trees, hedge-plants, and groundcover in the UGS of Panaji and of Tumkur.
- Daily water requirements and carbon stocks of 34 tree species.
- Evaluation of the feasibility and challenges of using the treated water (A review Paper published).

Future Scope:

1. **Establishment of technology network for collecting quality data from UGS**
   Without the field data sets, any large-scale global models based on empirical formulae or algorithm-based derivations and estimations are more likely to result in serious under- or over-estimations of carbon. In fact, many flawed assumptions, working inadequacies, and inaccuracies can be found in the current literature. These need to be rectified by *in situ* measurements/studies as much as possible. In this regard, many of the technologically advanced sensors such as moisture, humidity, and temperature sensors at the sample-sites could also be opted for.

2. **UGS infrastructure framework for quantification of ecological processes**
   Several environmental and anthropogenic factors impact the UGS processes. The quality and quantity of material input (pollutants, pesticides, fossil fuel emissions, aerosols, etc.) and export (e.g. salts, minerals, and gases), including the removal rates (plant products from grass to fruits) affect the UGS soil, flora, and several other biological and chemical processes. Investigations quantifying and identifying various factors influencing these processes in the UGS would help in comparing their performance with natural forests and agroforestry in the context of climate change mitigation measures.

3. **Education on wastewater treatment and use for enhanced ecosystem services**
   As an adaptation measure linked to climate change mitigation strategies, newer establishment, and efficient management of all urban green spaces (UGS) must be encouraged. To help them perform at acceptable levels, the easily feasible and promising prospect is in using treated wastewater. Ramaiah and Avtar (2019) have provided detailed accounts of how the use of treated wastewater can be effective in the urban setting for substantial lowering of the UHI effect, local LST, and in sequestering sizable volumes of carbon within the hub-hubs of the urban area itself. Most tier I and II Asian cities generating sewage effluent must educate the public to create and sustain considerable areas of UGS for beneficially mitigating the imminent adversities from climate change impacts.

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APPENDIX

Table A1. Confusion matrix of the 2019 LULC map of Panaji

	Built-up area	Bare land	Water body	Vegetation/agriculture	Classification overall	Producer's accuracy
Built-up area	20	3	0	0	23	86.95%
Bare land	2	18	0	0	20	90.00%
Water body	0	0	24	3	27	88.89%
Vegetation/agriculture	0	0	2	23	25	92.00%
Overall Truth	22	21	26	26	95	
User's accuracy	90.90%	86.72 %	90.30 %	88.46%		
Overall Accuracy	90.32%					
Kappa coefficient	0.83					

Table A2. Confusion matrix of the 2019 LULC map of Tumkur

	Built-up area	Bare land	Water body	Vegetation/agriculture	Classification overall	Producer's accuracy
Built-up area	25	5	0	0	30	83.33%
Bare land	4	23	0	0	27	85.18%
Water body	0	0	27	5	32	84.37%
Vegetation/ agriculture	0	0	6	25	31	80.64%
Overall Truth	29	28	33	30	120	
User's accuracy	86.21%	82.14 %	81.81 %	83.33%		
Overall Accuracy	83.33%					
Kappa coefficient	0.778					

Table A3. List of medicinal plants grown in South Goa Range Forest Office garden

1	*Abrus precatorius*	27	*Jatropha curcas*
2	*Acacia catechu*	28	*Justicia adhatoda*
3	*Acorus calamus*	29	*Justicia gendarussa*
4	*Aegle marmelos*	30	*Lawsonia inermis*
5	*Aloe barbadensis*	31	*Mimusops elengi*
6	*Alstonia scholaris*	32	*Mesua ferrea*
7	*Andrographis paniculata*	33	*Moringa oleifera*
8	*Annona muricata*	34	*Murraya koenigii*
9	*Annona squamosa*	35	*Ocimum tenuiflorum*
10	*Artemisia vulgaris*	36	*Phyllanthus emblica*
11	*Asparagus racemosus*	37	*Phyllanthus fraternus*
12	*Azadirachta indica*	38	*Pogostemon cablin*
13	*Bacopa monnieri*	39	*Piper longum*
14	*Boerhavia diffusa*	40	*Piper nigrum*
15	*Bryophyllum pinnatum*	41	*Rauvolfia serpentina*
16	*Butea monosperma*	42	*Saraca asoca*
17	*Cassia fistula*	43	*Stevia rebaudiana*
18	*Catharanthus roseus*	44	*Strychnos nux-vomica*
19	*Centella asiatica*	45	*Syzygium cumini*
20	*Cinnamomum zeylanicum*	46	*Terminalia arjuna*
21	*Cissus quadrangularis*	47	*Terminalia bellirica*
22	*Ficus racemosa*	48	*Terminalia chebula*
23	*Garcinia indica*	49	*Tinospora cordifolia*
24	*Gloriosa superba*	50	*Vitex negundo*
25	*Gymnema sylvestre*	51	*Withania somnifera*
26	*Hemidesmus indicus*	52	*Zanthoxylum rhetsa*

All these plants are reared in the nursery and sold or distributed occasionally free of cost to interested public. Only a few of these are grown in the hedgerows

Table A4. Ornamental and hedge plants in Mahavir Park

Common name	Botanical Name
Golden duranta	*Duranta erecta*
Acalypha	*Acalypha wilkesiana*
Eranthemum	*Eranthemum pulchellum*
Allamanda	*Allamanda cathartica*
Panama Rose	*Arachnothryx leucophylla*
Gardenia	*Gardenia jasminoides*
Tutia	*Solanum sisymbriifolium*
Dracena	*Dracaena marginata*
Bouganvilla	*Bougainvillea spp*
Croton	*Codiaeum variegatum*
Areca Palm	*Dypsis lutescens*
Pentas	*Pentas lanceolata*
Balsam	*Impatiens balsamina*
Agave	*Agave americana*
Hibiscus	*Hibiscus rosa-sinensis*
Spider plants	*Chlorophytum comosum*

Table A5. Ornamental plants in Ambedkar Park grown in nursery and used* in hedge lines Ornamental plants. Many in the nursery area; grown for sales. Medicinal plants Mostly in nursey and sold

Local name	**Botanical name**	**Family**
Gardenia	*Gardenia jasminoides*	Rubiaceae
Tutia	*Solanum sisymbriifolium*	Solanaceae
Panama Rose	*Arachnothryx leucophylla*	Rubiaceae
Almonda	*Allamanda cathartica*	Apocynaceae
Croton	*Codiaeum variegatum*	Euphorbiaceae
Golden duranta	*Duranta erecta*	Verbenaceae
Eranthemum	*Eranthemum pulchellum*	Acanthaceae
Nerium	*Nerium oleander*	Apocynaceae
Ixora	*Ixora coccinea*	Rubiaceae
Hibiscus	*Hibiscus rosa-sinensis*	Malvaceae
Red and green dressina	*Dracaena marginata*	Asparagaceae
Althernatum	*Althernatum* sp	
Balsam	*Impatiens balsamina*	Balsaminaceae
Jocupus Rendulus		

Table A6 Questionnaire for seeking information from Forest Department

Area Under Forest Cover:

Total green spaces area (in ha) in city

1. Parks
2. Holy/sacred groves
3. Avenue plantations
4. Plant nurseries
5. Forest reserves, if any
6. Garden/park lawns in public places
7. Government offices areas

Maintenance practices

1. Types of plants/trees planted
2. Plant health care details
3. Frequency of pruning
4. Frequency of replacements
5. Frequency of manuring
6. Frequency of watering
7. Source of water
8. Types of distribution methods
9. Number of people employed

Table A7. Questionnaire for Urban Planning Department

1. What are your ideas of "smart" city?
2. Who is the deciding authority to implement smart city idea ?
3. When was the idea of smart city implemented by the city corporation?
4. What are the roles of your Department in implementation of smart city concept?
5. What are challenges faced in smart city planning and design?
6. How can the challenges be overcome?
7. What are the policy steps or implantation plans in place for resolving public
8. According to you, what are the environmental problems faced in the cities?
9. How are the issues addressed and dealt with?
10. What are the challenges faced in addressing and dealing with the issues?
11. If so, what are your plans for including green spaces (including parks, city forests, and forest reserves) in city design?
12. What are your ideas for designing cities so that they have adequate green spaces?
13. Is adequate allowance made for green spacing in the smart city?
14. What are the challenges faced in designing cities with adequate green spaces?
15. What are your ideas/strategies to address and solve the problems?
16. What is the total green spaces area (in hectares) in the city, including parks, city forests, and forest reserves? Will be sought only if the Corporation offices do not have the data…
17. Are there plans to increase green spaces in the city?
18. If so, what are your ideas/strategies to expand the green areas?
19. What are the challenges in creating new green areas?
20. What are challenges faced in maintaining presently existing green areas?
21. What are the challenges faced in expanding the green areas?
22. What future trends do you foresee in urban planning, design, and development?
23. What possible environmental issues and solutions do you foresee?

Table A8. Questionnaire for Municipal/City Corporation Office

1. Smart city concept initiation year
2. Vision statement
3. Ideas of “smart” city
4. Associated Departments
5. List of new urbanization projects
6. Probable dates of planned for implementation
7. Services the department providing to the city residents
8. Major challenges faced in providing the services
9. New services planned and provided after the smart city concept
10. Environmental concerns and issues
11. Steps taken by the department to address and dealt with the concerns
12. Challenges faced in addressing and dealing with the issues
13. New/additional environmental issues anticipated, and solutions thought of
14. Total green spaces area (in hectares) in the city,
    1. Parks
    2. Holy/sacred groves
    3. Avenue plantations
    4. Plant nurseries
    5. Forest reserves, if any
15. Challenges faced in expanding the green areas
16. Challenges faced in maintaining existing green areas
17. Information/details of plans to increase green spaces
18. Plans or ideas/strategies to expand the green areas
19. Anticipated challenges in creating new green areas
20. List of stakeholders
21. Amounts of funds allocated (if available/sharable)

Table A9 Questionnaire for Sewage Handling Department

Sewage Handling Department

1. Total number of STPs
2. Volume of sewage received at each STP
3. Frequency of effluent reception
4. Duration of treatment
5. Type of treatment
6. Frequency of chlorination
7. List of Reuse practices
8. Distribution methods at user end
9. Role of public works department
10. Frequency of treated water disposal
11. Modes of disposal
12. Types of distribution methods
13. Number of people employed to handle treatment and disposal
14. Post treatment water quality monitoring (nutrients/nitrate, phosphate, pH, dissolved oxygen, heavy metals, oil/lipid concentration, total organic carbon, turbidity)

A Few Photographs from Field Visits

Fig A1. Amanikere Park, one of the larger parks in Tumkur city. Photographed during January 2019

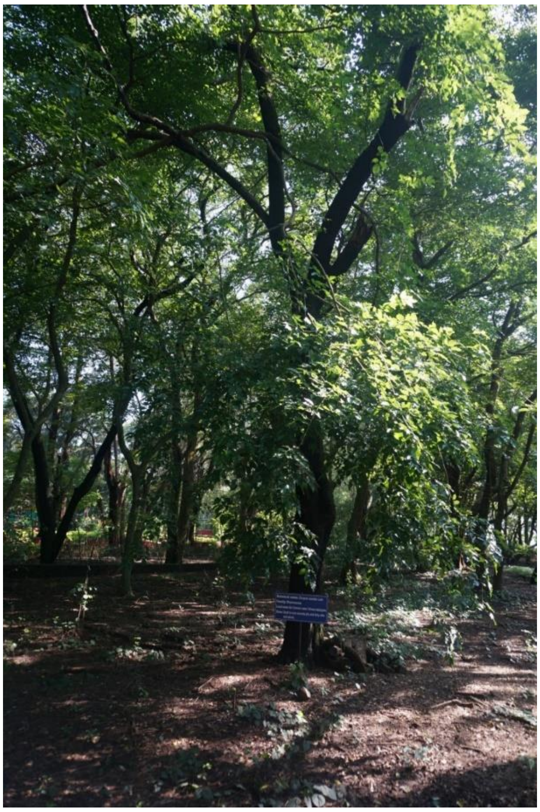

Fig A2. A view of tall trees in Mahavir Park, Panaji

Fig A3. Mahavir Park, Panaji. Walkways and a grove of Casuarina and other trees.

Fig A4. Hedgerow and lawn (groundcover) view in Mahavir Park, Panaji.
Photos taken during September 2020

Fig A5. Mahvavir Park, Panaji showing a narrow strip of paspalum grass, a hedge row and a walkway

Fig A6. View of hedge row, lawns, and a massive Rain Tree (top) in Ambedkar Park

Fig A7. View of hedgerow, lawn, and a sandalwood tree in the middle of the lawn, Joggers' Park Panaji. Photo taken during September 2020


Fig A8. Girth measurements of different trees in Ambedkar Park, Panaji.

Fig A9. Decantation tank in Tonca Sewage treatment plant. Treated wastewater of ecologically safe quality being discharged. Photo taken during October 2020