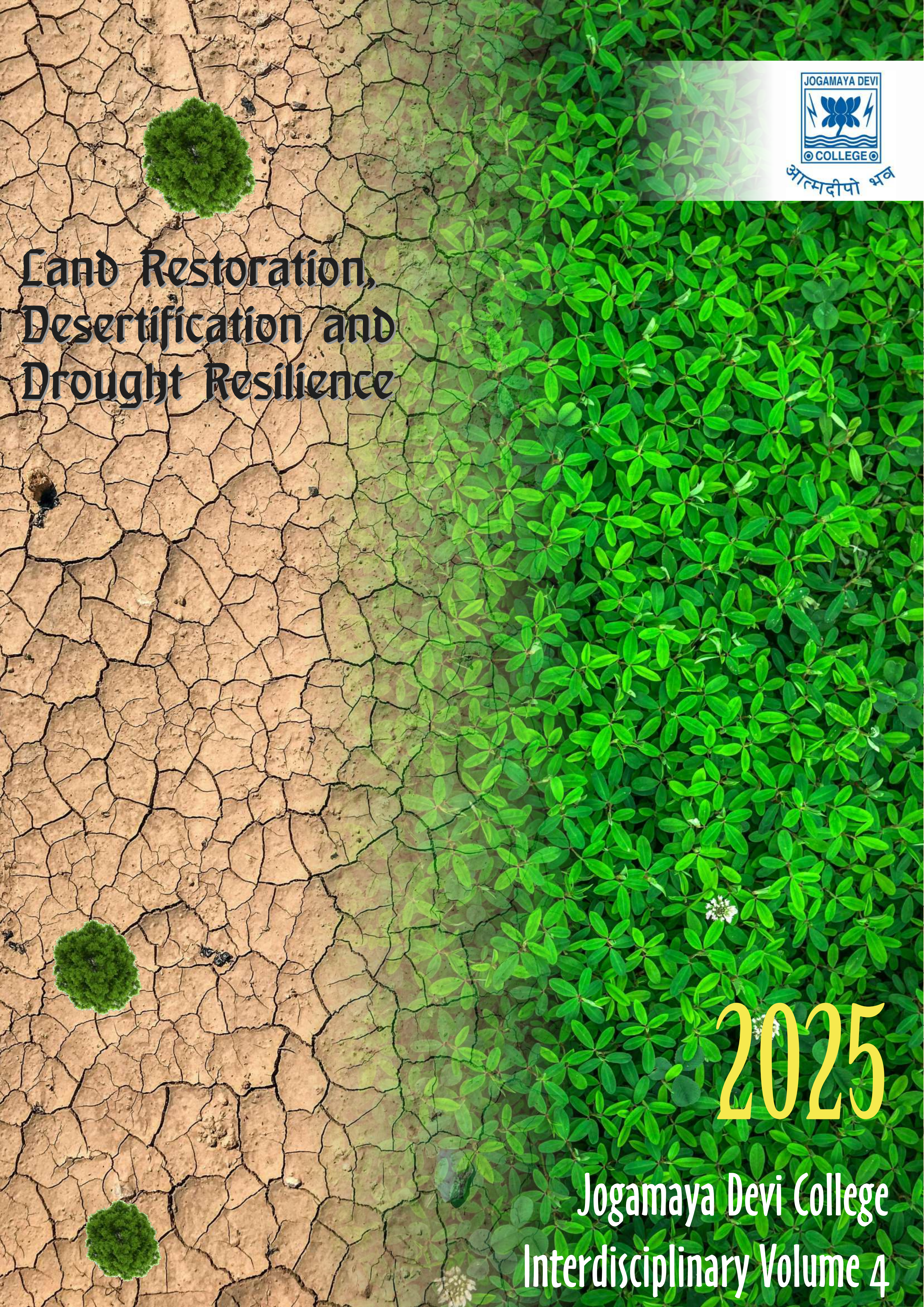


JOGAMAYA DEVI COLLEGE

आत्मदीपो भव

Land Restoration, Desertification and Drought Resilience

2025

Jogamaya Devi College

Interdisciplinary Volume 4

Land Restoration, Desertification and Drought Resilience

Jogamaya Devi College Interdisciplinary Volume 4

Jogamaya Devi College
Kolkata
2025

Kolkata Jogamaya Devi College
92, Shyama Prasad Mukherjee Road, Kolkata 700026 and
5A, Rajeswar Dasgupta Road, Kolkata 700026

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission and sources are indicated. A wide variety of references are listed. Reasonable efforts have been made to publish reliable data and information, but the editors and the publisher cannot assume responsibility for the validity of all materials or for the consequences of their use.

This publication is designed to provide accurate and authoritative information in regard to the subject matter covered.

The whole project is funded by Jogamaya Devi College and it is freely available in the website of Jogamaya Devi College.

First Publication: 15th April 2025

Publication Data:
Land Restoration, Desertification and Drought Resilience/edited by Dr. Bhaskar Ghosh, Dr. Soma Mondal & Dr. Kaushik Kiran Ghosh
(Jogamaya Devi College Interdisciplinary Volume 4)
ISBN: 999-99-999-999-0-4

Disclaimer: *The present volume is a collection of articles from varied disciplines, authored and reviewed by the specialists from a wide range of subjects. It is not possible for the publisher, the chief editor, or the editorial board to verify the originality of the works and the authenticity of the information presented therein, neither shall they assume any responsibility for the same. The authors are solely responsible for the originality of their respective works and shall have to resolve any copyright-related issues arising therefrom.*
In case of any proven infringement of copyright, the relevant article will be removed from this volume.

☺ **PLEASE CONSIDER THE ENVIRONMENT BEFORE PRINTING THIS VOLUME**

Board of Editors

Dr. Bhaskar Ghosh

Dr. Bhaskar Ghosh is presently working as an Assistant Professor in the Department of Geology at Jogamaya Devi College, Kolkata. His areas of interest include the analyses of field structures and microstructures of deformed rocks, and the studies of the compositions, structures and socio-economic applications of clay minerals. He received Ph.D. degree from the University of Calcutta for his research on stratigraphy and tectonics of Precambrian rocks of the Singhbhum Craton, Eastern India.

Dr. Soma Mandal

Dr. Soma Mandal is presently working as an Assistant Professor in the Department of English, Jogamaya Devi College, Kolkata. Her doctoral thesis was on Indigenous Roots of Ecofeminism in India. Her area of interests includes Eighteenth Century British Fiction, Ecocriticism, Ecofeminism and Postcolonial Studies.

Dr. Kaushik Kiran Ghosh

Dr. Kaushik Kiran Ghosh received M.Sc. and Ph.D. degree from the University of Calcutta, Kolkata. He is presently working as an Associate Professor of Jogamaya Devi College, Kolkata. His research interest includes banded iron formation (BIF) and related iron ore deposits of India. He has published several papers and one book in national and international journals.

PUBLISHER

Dr. Srabani Sarkar

Dr. Srabani Sarkar, Principal of Jogamaya Devi College, has an experience of 27 years of student interaction. She received her Ph.D. on Fuzzy Mathematics in 2012. Working is her favourite pastime. She loves to read too. She has a very amicable and congenial personality.

FROM PRINCIPAL'S DESK

Dear Readers!

It feels nice to announce the publication of the seventh multidisciplinary peer-reviewed E-Book by Jogamaya Devi College. The members of the Research & Development Cell of this college, who are in charge of publishing these E-Books, chose the multidisciplinary topic "*Land Restoration, Desertification and Drought Resilience*" as the theme of the present volume. My heartfelt thanks go to the members of this cell, especially the enthusiastic editors for their efforts towards fostering creativity and knowledge transfer.

I hope the readers will not only enrich their knowledge reading the articles presented here, but also will be encouraged to contribute to our future publications.

With thanks and best wishes,
Principal

FROM THE EDITORS' DESK

The Research and Development Cell (R & D Cell) of Jogamaya Devi College, previously known as the Research Committee, resolved to publish a peer-reviewed e-book on a selected interdisciplinary theme in each academic session from 2017 onwards. These volumes were expected to provide a platform for the teachers and researchers from various disciplines to present their ideas on that theme and enrich themselves through mutual interactions with the academicians from the other disciplines.

Six interdisciplinary e-books with various titles have been published so far in compliance with the above idea, highlighting a wide range of academic, environmental, socio-economic, and sustainability issues. When we were deciding the theme for the publication of the present academic session (2024 – 2025), our college celebrated the *World Environment Day, 2024.* The official theme of that event in 2024 was *Land Restoration, Desertification, and Drought Resilience*, and a highly informative discourse on this topic was presented by Dr. Supatra Sen, Associate Professor of Zoology, Asutosh College. This enlightening presentation encouraged many of us to explore this subject, and it was not surprising that the members of the R & D Cell recommended the same theme for the present interdisciplinary volume.

The ever-increasing population, urbanization and industrialization have multifaceted detrimental effects on the land resources, which call for a holistic approach from the experts from diverse fields for their comprehensive redressal. Conforming to this necessity, this volume presents eight thought-provoking articles from a wide gamut of subject areas. Following the conventions of all the publications of Jogamaya Devi College, the articles are arranged in alphabetical order of the names of the authors.

In the first article, titled "*The Role of Folktales in Combating Drought and Desertification*", Juthika Biswakarma emphasized the importance of raising mass awareness to mitigate the occurrence of droughts, and explained the applicability of folktales for this purpose. The article delves into folktales from diverse realms, including India and other countries, and describes how these narratives depict characters combating drought and desertification, highlighting the relevance of interconnecting traditional knowledge and contemporary science.

Urban drought is a relatively new term that refers to the failure of infrastructure to meet the growing demand for water in metropolitan areas. Contributing factors include automobile and industrial emissions, as well as high-rise buildings that obstruct natural airflow, leading to the formation of urban heat islands. These conditions intensify the problem by increasing temperatures, reducing per-capita water availability, and aggravating the unequal distribution of water between wealthy and impoverished communities. As a result, densely populated slums often experience human-induced (anthropogenic) drought conditions. In his article *"A General Discussion on Urban Drought,"* Kaushik Kiran Ghosh systematically analyzes the various causes and consequences of urban drought and proposes several strategies to address the issue.

Prevention of drought requires identification of the zones with more water scarcity in a given region, so that an appropriate scheme can be designed for augmentation of water supply in those zones. In the article titled "*Zonation of Agricultural Drought using Analytical Hierarchy Process in Jhargram District, West Bengal, India*", the authors Kishor Dandapat, Prasanna Mahata, Biswajit Pramanik and Namgyal Tshewang Bhutia demarcated the drought-prone zones in the Jhargram District of West Bengal and categorized them into five areas based on their susceptibility to drought: from very high-risk areas to very low-risk areas. Such a work will be immensely helpful for the future drought mitigation activities in Jhargram and surrounding regions.

The degradation of soil brought about by various natural processes and anthropogenic activities may lead to desertification. As the saying goes: "forewarned is forearmed", continuous monitoring of soil health facilitates early detection of soil degradation, and proper implementation of their mitigation processes. Soil nematodes, a group of soil-dwelling worms, can be effectively used as indicators of soil pollution caused by heavy metal, hydrocarbon, microplastic etc. Papia Das, in her article "*A Review on the Role of Soil Nematodes as Biological Indicator of Soil Health and their Contribution to Sustainable Soil Management*", documented the role of these organisms as biological indicators of soil health. The potential uses of these worms for sustainable soil management have also been discussed here.

Purulia is one of the most arid district of West Bengal, recording much higher summer temperatures and considerably lower annual rainfall than the state averages. The drought situation of this district has been comprehensively discussed by Poulami Chakraborty and Indrani Chakraborty in the article "*Exploring the Water Crisis in Purulia, West Bengal: A Brief Review*". Delving into the underlying causes of water scarcity, they have systematically explained all the geological, hydro-meteorological, topographic and anthropogenic factor that are important in this context.

Samuel Biswas and Subhra Prakash Nayak have explained the importance of land restoration for reducing drought, combating desertification, and nurturing sustainable development. In their article titled "*The Path to Recovery: Land Restoration as a Key to Combating Desertification and Drought Effects*", they have reviewed the roles of some key factors for drought and desertification, like deforestation, overgrazing, unsustainable agricultural practices etc. Then exploring different methodologies for land restoration, such as afforestation and nature-based solutions, they have evaluated the effectiveness of these processes. Finally, they have discussed the importance of involving the local populations in the restoration initiatives, and the policy framework.

In the last century, many developing countries like India had to adopt modern agricultural techniques for sustaining their ever-increasing populations, eschewing their age-old environment friendly practices of farming. However, the adverse effects of the chemical fertilisers and pesticides on human health were revealed within a few decades. Different types of pesticides affect different organs and systems of human body, and some of them cause serious damages to the reproductive health. Sumana Das studied the impacts of agricultural chemicals on female and male reproductive health and documented her findings in the article "*Land Restoration as a Remedy: Mitigating the Effects of Pesticides on Human Health*". This research indicates that a plausible solution for this problem is land restoration, which will enable the farmers to resume their traditional agricultural practices, thus decreasing their dependence on the harmful chemical pesticides.

This volume is appropriately concluded with the article contributed by Supatra Sen, based on her aforementioned lecture on the subject of World Environment Day, 2024. Titled "*Restoring Land: Combating Desertification through Drought Resilience*", this article discusses the principal causes of desertification, and its impacts on the economy of a region, rural and traditional livelihoods, climate change, carbon sequestration by vegetation, surface and groundwater resources. Considering the global crisis brought about by increasing aridity and land degradation, the United Nations General Assembly declared the decade from 2010 to 2020as the '*United Nations Decade for Deserts and the Fight against Desertification*' or UNDDD. Its objectives were to generate mass awareness on this problem, to organise financial and technical supports, to monitor the progress of the work, and finally to endorse a policy of sustainable land management. The author has described the remedial measures taken in India conforming to these objectives of UNDDD. The commonly used resilience strategies for drought have also been discussed in this article, such as aquifer recharge, reuse of water, desalination of brackish and saline water by salt tolerant algae etc. The lucid but comprehensive discussions presented in this article makes it highly recommendable to the students and any reader who want to acquire some basic knowledge on this subject.

Throughout the entire work, we have been generously assisted by several teachers and researchers from various institutions. As has already been mentioned, Dr. Supatra Sen has greatly indebted us with her judicious guidance and unstinting cooperation in different stages of the work. We gratefully acknowledge the invaluable assistances we received from Dr. Gupinath Bhandari, Department of Civil Engineering, Jadavpur University; Dr. Anasuya Bhar, Department of English, St Paul's Cathedral Mission College; Dr Sourav Madhur Dey, Department of Sociology, Burdwan University; Dr. Monalisha Mishra, Department of Geography, STRM Kalinga Institute of Social Sciences; Dr. Sruti Karmakar, Department of Environmental Science, Asutosh College; and Dr. Dola Chakraborty, Department of Geology, Sister Nibedita Govt. General Degree College for Girls.

Our respected Principal, Dr. Srabani Sarkar, deserves special thanks for her continuous inspirations, guidance, and all-round assistances.

Finally, we thank our esteemed colleagues of the R & D Cell, and all the other teachers of our college, for their encouragements and help, and hope for their continued support in all our future endeavours.

Bhaskar Ghosh
Soma Mandal
&
Kaushik Kiran Ghosh

CONTENT

		Page No
1.	Juthika Biswakarma – The Role of Folktales in Combating Drought and Desertification	01
2.	Kaushik Kiran Ghosh – A General Discussion on Urban Draught	15
3.	Kishor Dandapat, Prasanna Mahata, Biswajit Pramanik and Namgyal Tshewang Bhutia – Zonation of Agricultural Drought using Analytical Hierarchy Process in Jhargram District, West Bengal, India	53
4.	Papia Das – A Review on the Role of Soil Nematodes as Biological Indicator of Soil Health and Their Contribution to Sustainable Soil Management	73
5.	Poulami Chakraborty and Dr. Indrani Chakraborty – Exploring the Water Crisis in Purulia, West Bengal: A Brief Review	87
6.	Samuel Biswas and Subhra Prakash Nayak – The Path to Recovery: Land Restoration as a Key to Combating Desertification and Drought Effects	104
7.	Sumana Das – Land Restoration as a Remedy; Mitigating the Effects of Pesticides on Human Health	130
8.	Supatra Sen – Restoring Land: Combating Desertification through Drought Resilience	141

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 01-14

The Role of Folktales in Combating Drought and Desertification

Juthika Biswakarma
Assistant Professor, Department of English, Jogamaya Devi College,
juthika.chat@gmail.com

Abstract: The United Nations Convention to Combat Desertification suggested that raising awareness of the problem is the first step to mitigate the occurrence of drought. Storytelling can make complex environmental concepts accessible and relatable, particularly for children and marginalised communities. One of the most powerful roles of folktales lies in their ability to educate and inspire people. Folktales are a reservoir of deep ecological insights, reflecting the intimate relationship between communities and their natural surroundings. These narratives can impart knowledge about water conservation, soil management, sustainable farming practices and combating drought and desertification. As global efforts to combat desertification and drought intensify, it is essential to preserve and adapt traditional folktales for contemporary audiences. While folktales are deeply rooted in tradition, they can also inspire innovative solutions to environmental challenges. This paper seeks to examine the themes and lessons embedded in these narratives from across the world, and show how these enable communities to develop context-specific strategies to combat drought and desertification. This paper shall further establish folktales as a medium to bridge the gap between traditional knowledge and contemporary science by integrating their lessons into modern efforts to combat drought and desertification. Through storytelling, we can foster a global movement rooted in empathy, creativity and resilience, qualities essential for addressing one of the most pressing environmental challenges of our time.

Key Words: Folktales, drought, desertification, traditional knowledge.

1. Introduction

"One of the themes of the Kenyan Green Belt Movement is that the desert does not come from the Sahara- it begins in our backyards."

– Dr. Daisaku Ikeda (2012)

Dr. Daisaku Ikeda, the founder of Soka Gakkai International and his mentor and founder of Soka Gakkai, Tsunesaburo Makiguchi had always regarded the local community as the world in miniature. Both had emphasised on the necessity of awakening children to the problems of the local community. The United Nations Convention to Combat Desertification, too, suggested that raising awareness of the problem is the first step to mitigate the occurrence of drought. The United Nations declared 17th June as the World Day to Combat Desertification and Drought to raise awareness and promote action to prevent desertification and drought. Stories can play a very vital role in raising people's awareness. Storytelling has the unique ability to make complex environmental concepts understandable and relatable, especially for children and marginalised communities. Folktales often carry profound ecological insights, reflecting the close relationship between communities and their natural environments. They provide valuable lessons on water conservation, soil management, sustainable farming practices and strategies to address drought and desertification. For example, a community-based initiative in Kenya uses traditional storytelling sessions to teach children about water conservation techniques. Stories about mythical creatures guarding rivers and punishing those who waste water effectively instill a sense of responsibility and reverence for natural resources. Some stories from arid regions frequently emphasise the sacredness of trees and the need to prevent deforestation. Indian folktales often feature the banyan tree as a symbol of life and sustenance, underscoring its ecological importance. These narratives can inspire community-led afforestation efforts and reinforce the value of maintaining green cover to combat desertification.

2. Significance of Folktales

Tony Judt, in his book *Ill Fares the Land*, said, “Something is profoundly wrong with the way we live today.” (Kalam & Tiwari 2013) He identified the three imminent threats to humanity as dramatic climate change and its social and environmental effects, imperial decline and rise of non-state powers with local conflicts and collective political impotence. The present environmental crisis is indeed a threat to the very existence of human beings. The 7 billion people on earth, today, face this crisis especially because humanity has taken more from nature than it has given back. To tackle this, we must embrace the principle of one planet in all human activities and enhance our understanding of the earth and the interconnected systems that sustain life. By adjusting our lifestyles and committing to nurturing and sustaining the planet, we can create a safer and more livable world for everyone (Kalam & Tiwari 2013). But we must not forget the words of Frederick Douglass, the nineteenth-century African American social reformer: “It is easier to build strong children than to repair broken men.” (Kalam & Tiwari 2015) Hence, we must foster environmental awareness and a sense of responsibility towards natural resources from an early age. Folktales are a reservoir of living wisdom, deeply rooted in the traditional knowledge, which celebrates the oneness of all life forms. These narratives are indeed living wisdom as these by their very nature are ever evolving; their oral nature subjects them to modifications to enable them address the local problems more effectively. For example, stories from arid regions frequently emphasise the sacredness of trees and the need to prevent deforestation. The Desana people of the Amazon emphasise that humans cannot exist in isolation and can only truly flourish when living in harmony with their environment. Similarly, the Iroquois of North America urge us to make decisions with consideration for not just the present but also future generations, including those yet to be born (Ikeda 2012). Dr. Ikeda says, “In this worldview, all animals and plants are seen as siblings” (2012). This principle of dependent origination can also be seen in the Buddhist tradition which forms the basis of all activities of Soka Gakkai International (SGI). We find an echo of this principle in the prayers of the SGI: “May all beings, those who can be seen and those who cannot be seen, those who live far away and those who live nearby, those who have been born and those still desiring to be born, may all living beings enjoy happiness!” (Ikeda 2012) The emphasis on the unity and connectedness of life and collective action in many folktales aligns with modern principles of community-based resource management. In educating children with these folktales, we not only honour cultural heritage and indigenous knowledge, but also build a sustainable future for generations to come. This paper now shall bring to the fore the tales of courage, devotion, selfless sacrifice and resilience in the face of great droughts and incidents of desertification from folklores across the world.

3. Indian Folktales:

3.1 Uttar Pradesh, Uttarakhand and West Bengal

The Legend of Bhagiratha and the Ganga River: Once upon a time, the earth had grown parched and lifeless, suffering from prolonged droughts and ecological devastation. The descendants of King Sagar had been reduced to ashes due to a curse, and their salvation depended on the holy waters of Ganga reaching the earth to purify their souls. But bringing Ganga down was not an ordinary task, it required immense perseverance and a deep understanding of nature's balance. Bhagiratha, a prince of great wisdom and unwavering dedication, took upon himself the mission to restore both his ancestors and the land they once ruled. He renounced worldly pleasures and embarked on a long and arduous penance, seeking the blessings of Lord Brahma and Lord Shiva. The gods, pleased with his devotion, agreed to let Ganga descend to the mortal realm. However, there was one great challenge, if the mighty river fell directly onto the earth, its force would be so great that it would destroy mountains, forests and fertile lands, causing untold ecological destruction. Understanding the delicate balance of nature, Bhagiratha turned to Lord Shiva, who caught Ganga in his thick, matted locks, allowing her waters to trickle down gently in many streams. This act was an ancient lesson in ecological wisdom- human intervention in natural systems must be mindful and gradual, ensuring sustainability rather than devastation. As Ganga meandered across the earth, she cleansed the ashes of Bhagiratha's ancestors and her waters rejuvenated dying forests, replenished dried-up rivers and turned barren lands into fertile fields. She became the lifeline of civilizations, sustaining agriculture, wildlife and entire ecosystems along her course. However, the story also carries a warning- Ganga's descent was meant to be a blessing, not an unchecked force of exploitation. Bhagiratha's efforts remind us that water is sacred and must be respected, conserved and used responsibly.

3.2 Uttar Pradesh

Throughout history, humans have devised various rituals and practices to appease nature and the gods in hopes of ensuring sufficient rainfall. The ancients recognized the crucial role of trees and mountains in attracting rain and conserving water.

The Bhagavata Purana describes the Govardhan Puja, a ritual observed in Gokulam during Krishna's childhood. This agrarian community, dependent on farming and cattle-rearing, relied on timely rainfall for its sustenance. Each year, they performed a puja or *yajna* to honour Lord Indra, the deity believed to govern rainfall. When Krishna was around seven years old, preparations for the annual Indra Puja were underway. Being curious, he questioned the elders about the purpose of the ritual. Unconvinced by their explanations, he challenged the notion that Indra controlled the rains, arguing that rainfall was a natural process governed by the laws of nature. He suggested that any scarcity of rain was a consequence of *karma* or human actions, what we might today describe as ecological mismanagement or exploitation. Krishna further pointed out that their community thrived at the foothills of Govardhan Mountain and that the mountain, along with the surrounding trees, played a vital role in bringing rainfall. He warned that ignoring the importance of these natural elements would be detrimental, and that Indra had no real influence over the process. He then proposed that instead of worshipping Indra, they should revere and honour the mountain that sustained them. His words were so compelling that the people of Gokulam embraced his suggestion. The events that followed are well known, but at its core, Krishna's message was a powerful call for environmental conservation- one that an activist would echo today. Through this story, Krishna emphasized the need to respect and protect nature, a lesson that holds even greater relevance in today's world. (The Hindu 2021)

3.3 Assam, West Bengal and some other parts of India

Across India, age-old stories and rituals highlight the deep connection between frogs and rainfall. In Assam, an ancient tale explains this link. Farmers once asked the clouds why it wasn't raining, and the clouds replied that they were waiting for the frogs to croak. Since frogs typically croak during the monsoon, their calls became a natural signal for the arrival of rain. Over time, this association became deeply rooted in folklore.

A similar belief exists in southern India, where people perform a wedding ceremony for two frogs, known as *Mandooka Parinaya*. It is believed that this ritual pleases the rain god Indra, who, in return, blesses the land with rainfall. Despite regional variations, these traditions reflect a profound reverence for nature and its cycles, emphasizing the desire to live in harmony with the environment.

Interestingly, just as humans sometimes part ways, so do the frogs. In Madhya Pradesh, a real-life frog marriage was once performed with hopes that it would appease Indra and bring much-needed rain to the drought-stricken land. The ceremony, held in Bhopal, proved successful, perhaps too much so. The resulting monsoon was so intense that it caused severe flooding across the region. To curb the relentless downpour, the villagers decided to divorce the frog couple. A symbolic separation ceremony was conducted at the Turant Mahadev temple, where two clay frog figurines were placed in a water-filled pot while priests chanted mantras, hoping to pacify the raging monsoon.

This fascinating tradition takes different names across India. In Assam, it is called *Bhekulir Biya*, in southern India, it is known as *Mandooka Parinaya*, and in Tripura and West Bengal, the ritual is called *Banger Biye*. Regardless of the name, the core idea remains the same- honouring the oneness or inter-dependence of all natural elements in the hopes of maintaining balance in the environment. (Shankar 2023)

3.4 Odisha

The Legend of Maa Samaleswari and the Great Drought: The Legend of Maa Samaleswari is deeply rooted in the cultural and spiritual traditions of western Odisha, India, where the goddess Samaleswari is revered as the presiding deity of the region. The goddess is widely associated with agricultural prosperity and the protection of her devotees. The legend intertwines with the tale of a great drought that plagued the region, leading to severe hardship for the people. The parched land and failing crops led the farmers and rulers to seek divine intervention. Seeking a solution, the king gathered priests, sages and elders to perform rituals and sacrifices to appease the goddess. Despite their efforts, the skies remained unyielding. Among the devotees of Maa Samaleswari was a young girl named Aparna, known for her unwavering devotion. One night, the goddess appeared to her in a vision, instructing her to seek the answer to her village's suffering in the Mahanadi River at dawn. Following the divine guidance, Aparna discovered a glowing stone in the river, which transformed into a shimmering fish upon her touch. The fish swam downstream, causing the river to swell and flow abundantly. Rain soon followed, ending the drought and bringing prosperity back to the village, leaving the people in awe of the goddess's miracle. This narrative highlights the goddess's role as a nurturer and protector and establishes the female as living in close proximity with nature, to be able to listen to the demands of nature. The story symbolises the harmony between humans and nature, mediated by divine power, and continues to inspire festivals like Nuakhai, which celebrate the first harvest and offer thanks to Maa Samaleswari for her blessings. The legend remains a cornerstone of faith and resilience in the collective memory of the region (Folklore Chronicles 2023).

3.5 Rajasthan

The Story of Amrita's Promise and the Rain: In the arid land of Rajasthan, a popular folktale, which is based on a real-life story, celebrates the Bishnoi community's dedication to protect nature. Nearly three hundred years ago, in the village of Khejadli near Jodhpur, Rajasthan, a young girl named Amrita deeply revered nature. The villagers, who lived in harmony with plants and animals, believed that their survival depended on protecting trees. Each day, Amrita would embrace her favorite trees, expressing her love and gratitude. One day, she discovered royal soldiers sent to cut down trees for the King's palace. Horrified, she hugged a tree, declaring that they would have to cut through her first. Despite her defiance, the soldiers carried out their orders. Inspired by her courage, hundreds of villagers, including her daughters, joined in, sacrificing their lives to protect the trees. When the King learned of this, he was deeply moved, and he visited the village. Realising the villagers' devotion to nature, he issued a decree banning tree cutting and animal harm in the region. To this day, the Bishnoi community upholds Amrita's legacy, ensuring the land remains green and wildlife thrives in the desert. (ncert.nic)

Based on this true story, over the years a folktale has evolved- once Amrita's village was suffering from a relentless drought. Amrita noticed that the few remaining khejri trees, which sustained life even in the harsh desert, were wilting under the scorching sun. Determined to save the trees, Amrita began carrying water from a distant well to nourish them. Despite her village's dire scarcity, she shared her meagre water supply with the trees, inspiring others to do the same. Moved by the villagers' devotion to preserving nature, the rain gods finally relented. Dark clouds gathered over the desert, and a heavy downpour followed, replenishing the parched land and filling the village's wells. The khejri trees thrived once again, becoming a symbol of life and resilience.

3.6 Tamil Nadu

The Story of Kannagi’s Tears: In ancient Tamil Nadu, a severe drought struck the prosperous kingdom of Madurai. Rivers dried up, and the once-fertile paddy fields turned into cracked, lifeless earth. The people believed that the gods were displeased, but no one knew the reason for their wrath. In the midst of this suffering, an old storyteller recounted the tale of Kannagi, the legendary woman who had once cursed Madurai for the unjust execution of her husband. Her fiery rage had burned the city to ashes, and her tears of sorrow had created new rivers. The storyteller suggested that the drought might be a result of Kannagi’s unfulfilled spirit still mourning her tragic fate. Moved by this insight, the villagers decided to perform a ritual in Kannagi's honour. They erected a shrine near the riverbed and offered her flowers, lamps and their sincerest prayers. They also pledged to live with integrity and justice, vowing never to let another innocent person suffer in their land. That night, Kannagi appeared in the dreams of the village elder. She was moved by their repentance and promised to release the rains once the people upheld their pledge. The next day, dark clouds gathered, and a heavy rain blessed the land. The rivers flowed once again, and the fields turned green with new crops. The story of Kannagi’s tears became a keystone of Tamil folklore, reminding people of the power of justice, compassion and honouring the divine balance of the world (The Hindu Saga 2024).

4. African Folktales

4.1 The Quest for the Sacred Water

Long ago, in a small village called Zawadi, the people faced a devastating drought. The once abundant riverbeds were dry, and the crops had withered. Desperation gripped the villagers, and one evening, they gathered under a palaver tree where the village sage Ndidi revealed an ancient prophecy that one day a warrior with a pure heart would undertake a dangerous journey to find the source of life- a sacred water spring hidden beyond mountains and deserts. In the village lived a young warrior named Temba, an epitome of bravery and honesty. He came forward to the rescue of his villagers. Temba embarked on a perilous journey, walking through the desert for several days; and met a caravan of nomadic merchants who offered him water and food. Temba shared his tragic story with Bakari, the leader of the caravan, who gave him an ancient map leading to the sacred water source. After leaving the desert, Temba reached the enchanted forest of Nyoka, a mysterious and dangerous place with strange creatures, whispering trees and many hidden traps. Defeating a group of shadow warriors, Temba met their chief Mbogo who offered him a protective talisman. Guided by the talisman, Temba reached the summit of the Moon Mountain and met an old shaman named Nyasha, who knew the legend of the sacred water and agreed to help him. On her advice he discovered the Heart of the Mountain, which is a precious stone hidden in a secret cave, to activate the secret source. With that stone Temba descended from the mountains and followed the map’s direction to reach a sacred valley, where after defeating Nia, an evil witch, he found at the centre of the cave the source of life- a fountain of crystalline water. Temba filled a gourd with this sacred water; and on his return journey, each drop of this water seemed to revive the parched land he crossed, plants blossomed and rivers began to flow again. On reaching Zawadi, Temba poured the sacred water into the village well, and immediately clear water gushed out, marking the end of the drought. The village was once again thriving with joy and life. Temba married the village chief's daughter and opened a school there teaching children the importance of nature. As years passed, Temba formed a group of young warriors and sages called the Guardians of Nature whose mission was to pass on the ancient wisdom protecting the sacred bond between nature and human beings. The legend of Temba kept on inspiring generations to revere nature and live in harmony with the environment. (Folktales of the Continent 2024)

4.2 The Spine-Chilling Tale of Oya

A West African village was once struck with a catastrophic drought. The villagers prayed to Oya, the Rain Goddess, but she remained silent, withholding her blessings. At last, Oya appeared in a swirling storm of wind and leaves. She warned the villagers to respect the spirits, otherwise be prepared to face her wrath. The next morning, rain poured from the heavens, reviving the fields and filling the rivers. But, the moment they disrespected the spirits, a devastating storm ravaged the land, turning it into a heap of ruins. This tale serves as a cautionary tale for us, teaching us about the delicate balance between nature's bounty and the respect it demands. (Kidsfolktale.videos 2024)

4.3 The Volcanic Cry of the Mountain Spiri

In a village near the Mount Kilenda, a cruel drought had turned the rivers into dry beds of stone. The people began whispering about a powerful spirit Kifaru who lived in the mountains and controlled the rains. A brave woman named Amina decided to seek his help. Amina climbed the mountain to find Kifaru, who appeared as a shadowy figure with tears of lava rolling down his eyes. He promised to summon the rains but only if the villagers would give him something of great value. Amina returned to the village and informed them about offering their most cherished possessions to Kifaru, and that should be a symbol of love, unity and selflessness. The villagers together climbed the mountain and started the ritual with their prayers. Kifaru, pleased with their prayers, appeared in front of them, and Amina offered him an intricately designed wooden figurine, a gift from her late mother and a symbol of her family's love. Tears welled up in Kifaru's eyes again, but this time these are tears of gratitude and renewal. That night, rain poured down, replenishing the rivers and fields. The molten lava got transformed into a river of crystal clear water flowing down the mountain. The drought ended and the villagers rejoiced. This tale proves that the power of love and selflessness can strike a balance between nature and human beings. The mountain in the story stands as a symbol of unity and purity of heart. (Unveiled Tales 2024)

5. Algerian Folktales

5.1 Dry Land that Became Lush and Green

An old farmer, devoted to his only daughter, worked tirelessly on a wealthy landowner's estate, transforming it into a lush paradise. He imparted his agricultural knowledge to her, teaching efficient farming and irrigation techniques, and often encouraged her to carry on his legacy. As his health declined, the daughter took over the farm's responsibilities with diligence and integrity, impressing the landowner and earning a reputation for excellence in the region. One day, a wise man warned of an impending drought, but the locals dismissed him. He said: "Do not rejoice over the prosperity you have today, for I have seen a desert that became a river and dry land that became lush and green. Our Lord is able to change misfortune into good fortune in an instant." (Bejag 2017) The worried daughter informed his father and then the landowner. The landowner promised the old man and his daughter that if they could save the farm, he would give them half of it. The resourceful daughter proposed a solution and immediately began the work, tirelessly constructing cisterns and digging holes until everything was complete. The landowner was impressed by her ingenuity. A few months later, rain filled the cisterns and holes with water. When the drought arrived, the farm remained lush and green, thanks to the efficient irrigation system. True to his word, the landowner gave her half the farm. She later married his son, and together they lived happily ever after, sustained by her clever water conservation plan. (Bejag 2017) This tale teaches us the value of conserving natural resources, and that our little efforts can even prevent the occurrence of droughts.

5.2 Conserve what you have to make it last

Sheikh Nu'man, a wise man renowned for his intellect, lived in a village reliant on gardens for sustenance. When the king announced a reward for solving the problem of an impending drought, Sheikh Nu'man promised a solution but requested for seven months. He departed on a journey but did not return in time, leading the king to strip his family of their rights. Years later, Sheikh Nu'man returned, and angered by the king's actions, refused to share his solution; instead he presented a riddle: "An ounce of prevention is worth a pound of cure." (Hamed 2017) Unable to solve it, the king embarked on a journey through seven valleys, guided by cryptic sayings and encounters that reinforced the importance of foresight, conservation and community. In the final valley, the king discovered a lush paradise sustained by reservoirs and irrigation canals. Learning that the system was based on Sheikh Nu'man's advice, the king implemented similar methods in his city. Over time, the city flourished with abundant water and greenery, and the people thrived, living happily ever after, thanks to Sheikh Nu'man's wisdom. (Hamed 2017) This tale teaches us the importance of water conservation, soil management and sustainable farming practices to combat drought and desertification.

6. American Folktales

6.1 Maidens Who Broke a Drought

A Native American tribe faced a relentless drought that dried up their land, depleted water sources and drove animals away. Desperate for rain, the tribe's chief consulted the medicine man, who revealed that to appease the gods and end the drought, the chief serpent living in a cave at the base of a high cliff must be fed the maidens of the tribe. The tribe's young girls, taught to sacrifice themselves for their people, volunteered bravely. The chosen maidens, dressed in white, were led to the cliff's edge. Just as they were about to leap, the goddess who protects young girls intervened. She transformed the maidens into white flowering bushes before they hit the rocks, sparing their lives and frightening the serpent back into his cave. With the serpent gone, the clouds returned, and rain poured down, ending the drought. The bushes, now known as bee brush or bush honeysuckle, bloom every summer in Texas and beyond, filling the air with fragrance. They provide nectar for bees, butterflies and hummingbirds, serving as a living memory of the maidens' bravery and sacrifice (Whispering Books). This tale makes us aware of the bounties of nature, which only demands our selfless devotion; and it also highlights women as living in close proximity with nature, ready to sacrifice themselves to restore the balance between nature and human beings.

7. Zoroastrian Folktale

7.1 The Battle of Tishtrya and Apaosha

In ancient Persia, a devastating drought plagued the land. The rivers dried, crops failed, and the people prayed to Ahura Mazda for relief. Ahura Mazda sent Tishtrya, the radiant star and guardian of rain, to battle the demon Apaosha, who had chained the waters of the world. Tishtrya appeared as a shining white stallion and charged into the heavens to confront Apaosha, who took the form of a monstrous black horse. Their battle was fierce and lasted for days. At first, Apaosha overpowered Tishtrya, forcing the rain-bringer to retreat. Weakened but determined, Tishtrya prayed to Ahura Mazda, who strengthened him with the faith and prayers of humanity. Renewed, Tishtrya returned to the fight and struck Apaosha with his divine light, shattering the demon's hold on the waters. As Apaosha fled, rain poured down across the parched land, reviving the rivers and crops. The people rejoiced and offered thanks to Tishtrya, who became a symbol of perseverance and divine justice in the face of adversity. This story is still told in Zoroastrian tradition to remind believers of the eternal struggle between good and evil. (9 World Chronicles 2022)

8. Mesopotamian Folktales

8.1 Enki's Sacred Waters

In the ancient land of Mesopotamia, a terrible drought struck the kingdom of Sumer, leaving the mighty Tigris and Euphrates rivers as dry as deserts. The people turned to Enlil, the god of storms, but he remained silent, believing that the humans had grown arrogant and forgotten the gods. Desperate, the goddess Inanna approached Enki, the god of wisdom and freshwater, to plead for his help. Enki, moved by Inanna's compassion for humanity, devised a plan to release the Abzu, the underground reservoir of water. Disguising himself as a mortal, Enki traveled to the parched fields and struck the ground with his staff. From the earth gushed streams of water, which flowed into the dry riverbeds. However, Enki's actions angered Enlil, who sent scorching winds to evaporate the water. Enki cleverly summoned the Seven Sages, divine beings who taught the people how to dig canals and construct irrigation systems. Through their wisdom, the rivers were restored, and the drought ended. The people offered thanks to both Enki and Inanna, vowing to respect the gods and care for the waters.

The story highlights the importance of wisdom, compassion, and ingenuity in overcoming adversity and maintaining harmony with the divine forces of nature. (default whispers 2023)

8.2 Pazuzu: The Demon of Drought

In ancient Mesopotamia, the people of a bustling city faced a devastating drought. Crops failed, livestock perished, and the Euphrates River, the city's lifeline, shrank to a trickle. The priests declared that the cause of their suffering was Pazuzu, the demon of drought and famine. Pazuzu, with his lion-like face, taloned feet and wings, was known to bring scorching winds and plague to those who angered him. Desperate to save their city, the people turned to Ishtar, the goddess of fertility and life, for guidance. She instructed a young priestess named Ninsun to travel to the mountains where Pazuzu dwelled and offer him a powerful amulet of protection. This amulet would bind Pazuzu's destructive power and redirect it to safeguard the city. Ninsun, guided by Ishtar's wisdom, journeyed to the demon's lair. Pazuzu appeared in a whirlwind of fire and sand, demanding to know why a mortal dared disturb him. Ninsun knelt and presented the amulet, chanting a prayer that praised Pazuzu's might but pleaded for his mercy. Intrigued by her courage and flattery, Pazuzu took the amulet and placed it around his neck. Bound by its magic, he could no longer harm the city. Instead, his fierce winds were transformed into gentle breezes that brought rainclouds to the parched land. The drought ended, and the city prospered once more. To this day, Pazuzu is remembered as both a bringer of destruction and a protector, a reminder of the duality of nature's forces and the importance of balance in the world. (ScaryBoxx 2024)

9. Aztec Folktale

9.1 Tlaloc’s Fury:

Long ago, in the highlands of the Aztec Empire, the rains were plentiful, and the lands flourished under the watchful gaze of Tlaloc, the mighty god of rain and fertility. His shimmering blue crown and jaguar-toothed mouth struck awe into the hearts of all. Tlaloc provided the life-giving rain that turned the fields green and filled the rivers with fresh water. But Tlaloc was not a god to be trifled with. He was known for his temper, and his fury could bring devastating droughts or torrential storms that destroyed entire cities. To honour him, the Aztecs held great ceremonies, offering sacrifices of maize, flowers and even human lives to ensure his blessings. One year, however, the people grew complacent. The rains had been steady for many seasons, and the harvests were bountiful. Believing they were secure, the priests decided to scale back the offerings to Tlaloc, thinking he would not notice. The ceremonies became less grand, the sacrifices fewer, and the songs less fervent. When Tlaloc looked down from his mountaintop palace of Tlalocan and saw the meager offerings, his fury boiled like a storm cloud. "Do they forget who feeds their rivers and fills their fields?" he thundered to the wind and skies. With a single motion of his hand, Tlaloc commanded the clouds to retreat and the rains to cease. Days turned to weeks, then months, and not a single drop of rain fell. The rivers dried, the maize withered, and the once-lush valleys turned to cracked, barren wastelands. The people realized their folly too late. They prayed and pleaded, but Tlaloc’s ears were deaf to their cries. Desperate, they sought the wisdom of the priests, who consulted the sacred codices and decreed that a grand offering must be made- a sacrifice unlike any before. Among the people, a young girl named Xochitl was chosen. She was known for her purity and her voice, which was said to rival the song of the quetzal bird. Though her heart trembled with fear, Xochitl agreed, believing her sacrifice would save her people. On the day of the ceremony, Xochitl was adorned with flowers and painted with the sacred blue of Tlaloc. As she stood before the altar, she sang a haunting melody, pleading with Tlaloc to forgive her people. Her voice carried to the heavens, reaching Tlaloc's ears. Hearing her song, Tlaloc's heart softened. He saw her courage and the sincerity of her people's remorse. A single tear fell from his jaguar eyes, and as it struck the earth, it unleashed a deluge. Rain poured from the skies, soaking the parched land and filling the rivers once more. The people rejoiced, vowing never again to take Tlaloc's gifts for granted. Xochitl's name was forever remembered in songs and stories, and each year, the people honoured her sacrifice with a festival dedicated to Tlaloc. From that day on, the Aztecs knew that Tlaloc's blessings came not just from ritual but from gratitude, respect and the balance of nature. They lived in harmony with the rain god, always mindful of the power he held. This story reflects the Aztec reverence for balance and their deep connection to nature and the divine. Tlaloc's fury serves as a reminder of the consequences of neglecting that balance. (TimelessTalesWithX 2024)

10. Conclusion

In all these folktales we can find deep ecological insights, reflecting the importance of a fine balance between humans and environment. These narratives uphold the heart wrenching tales of misery of people during drought, and how small changes in our way of living can prevent such catastrophes in future. In the face of mounting environmental challenges, traditional wisdom encoded in these narratives can serve as a vital tool for fostering sustainable practices. We can recall here the words of the Little Prince from the eponymous novella of Antoine de Saint-Exupery: "What makes the desert beautiful is that somewhere it hides a well." (Brady) This, perhaps, gives us the message that a desert teaches us to live in harmony, taking only what is needed from nature and repaying our debts to nature in whatever way we can. Indeed, a desert can be turned into a land of opportunities with our little efforts, at least that is what Baba Bhadariya Maharaj has shown in transforming Bhadariya, a barren and deserted village, into a thriving community with lush green pastures, a large cow shelter and a library which is an architectural marvel, maintaining a natural cool temperature in the scorching heat of the desert and housing more than 200,000 books. The transformation of Bhadariya highlights the role of community initiatives, and hence, it is of paramount importance that we learn the spirit of oneness of all living beings. Folktales drive home the themes of resourcefulness and collaboration in times of scarcity more effectively. As Kofi Annan, the UN Secretary General (1997-2006) said, "The human community faces an array of choices about the quality of our lives and the state of the global environment. Each of those choices will help to determine what kind of world our children and grandchildren will live in". (Brady) Folktales can serve as powerful tools for motivating us to make the right choice, complementing scientific approaches to environmental management. It is our duty to ensure the preservation and dissemination of these narratives to future generations to make them global citizens, based in traditional values, and this world a better place. Therefore, it is essential to preserve and adapt traditional folktales for contemporary audiences. Digital platforms, animation and multimedia storytelling offer innovative ways to keep these narratives alive and relevant. Websites like FolkloreChronicles, StoryWeaver, GlobalGiving and UNESCO's Intangible Cultural Heritage Platform archive and share folktales related to environmental themes. Podcasts like 'Myths and Legends' and 'Indigenous Earth Community' retell folktales on desertification and climate resilience. Gamified storytelling apps like 'Forest Legends' and 'Water Warrior' use folklore-inspired quests to teach children about drought prevention. Old and young people alike are making extensive use of social media platforms like YouTube, Facebook and Instagram to share their stories and cultural heritage with the larger world. These digital representations of traditional folktales, no doubt, appear more appealing to the present generation. Thus collaborations between storytellers, environmental organizations and technology developers can help amplify the reach of folktales and their messages. For instance, animated adaptations of folktales that highlight the importance of planting trees or conserving water can engage younger generations in urban and rural areas alike. Interactive apps that incorporate storytelling with practical advice on combating desertification could also be developed, providing users with both entertainment and knowledge.

REFERENCES

[01] Bejag, F., 2017. Dry Land that Became Lush and Green. Water Stories from the Maghreb. 46-55. URL: https://www.pseau.org/outils/ouvrages/giz_oss_contes_du_maghreb_sur_l_eau_en_2019.pdf. Last visited on 30th December 2024.

[02] Brady, F. Combating Desertification. Development Education Department, Concern Worldwide. URL: https://developmenteducation.ie/media/documents/Desertification.pdf. Last visited on 30th December 2024.

[03] Folktales of the Continent, 2024. The Courageous Expedition for Sacred Water to Rescue the Village from Drought and Famine. YouTube. URL: https://www.youtube.com/watch?v=d9RAw7fyTHI. Last visited on 31st December 2024.

[04] Hamed, K., 2017. Conserve what you have to make it last. Water Stories from the Maghreb. 56-69. URL: https://www.pseau.org/outils/ouvrages/giz_oss_contes_du_maghreb_sur_l_eau_en_2019.pdf. Last visited on 30th December 2024.

[05] Ikeda, D., 2012. Soka Education: For the Happiness of the Individual. Eternal Ganges, New Delhi.

[06] Kalam, A.P.J.A., Tiwari, A., 2013. Squaring the Circle: Seven Steps to Indian Renaissance. Universities Press, Hyderabad.

[07] Kalam, A.P.J.A., Tiwari, A., 2015. Transcendence: My Spiritual Experiences with Pramukh Swamiji. Harper Element, Uttar Pradesh.

[08] Kidsfolktale.videos, 2024. The Spine-Chilling Tale of Oya the Storm Warrior. YouTube. URL: https://www.youtube.com/shorts/tyTz2-Do1QU. Last visited on 31st December 2024.

[09] Maidens Who Broke a Drought. Whispering Books. URL: https://whisperingbooks.com/Show_Page/?book=Native_American_Legends&story=Maidens_Who_Broke_A_Drouth. Last visited on 31st December 2024.

[10] Default Whispers, 2023. How Enlil and Enki Wiped Out the Human Race: Revealing the Truth. YouTube. URL: https://www.youtube.com/watch?v=jN4ExStVkOM. Uploaded on: Jun 27, 2023. Last visited on 31st December 2024.

[11] NCERT. The Story of Amrita. https://ncert.nic.in/textbook/pdf/deap104.pdf. Last visited on 10th February 2025.

[12] Patnaik, L., 2023. The Legend of Maa Samaleswari and the Great Drought. Folklore Chronicles. https://folklorechronicles.com/the-legend-of-maa-samaleswari-and-the-great-drought/. Last visited on 31st December 2024.

[13] ScaryBoxxx, 2024. The Demon of Drought: Uncovering the Fearsome Mythology of Pazuzu. YouTube. https://www.youtube.com/shorts/MrLUn0hwUDU. Last visited on 31st December 2024.

[14] Shankar, S., 2023. From ponds to pheras- The tradition of frog marriages in India. URL: https://www.savaari.com/blog/frog-wedding-for-rain-in-india/. Last visited on 10th February 2025.

[15] The Hindu, 2021. The striking tales the rain tells: The universal truths and some age-old lessons of water management. URL: https://www.thehindu.com/opinion/open-page/the-striking-tales-the-rain-tells/article28732940.ece. Last visited on 10th February 2025.

[16] The Hindu Saga, 2024. Story of Kannagi Amman. YouTube. URL: https://www.youtube.com/watch?v=I1TL_9x1QmY. Last visited on 31st December 2024.

[17] TimelessTalesWithX, 2024. How Tlaloc’s fury was calmed by Citalic. YouTube. URL: https://www.youtube.com/shorts/UFx3YoQTlk4. Last visited on 31st December 2024.

[18] Unveiled Tales, 2024. The Volcanic Cry of the Mountain Spirit. YouTube. URL: https://www.youtube.com/watch?v=JD_C642eNi0. Last visited on 31st December 2024.

[19] 9 World Chronicles IG, 2022. Apaosha the Drought Demon of Zorastrianism. URL: https://www.youtube.com/watch?v=CI-SfQxwKH8. Last visited on 31st December 2024.

Juthika Biswakarma

Juthika Biswakarma is an Assistant Professor of English Literature at Jogamaya Devi College, affiliated with the University of Calcutta. With over fourteen years of teaching experience, she holds a Master's degree in English Literature from Visva Bharati University and another in Public Administration from Indira Gandhi National Open University. Currently, she is also a research scholar at Adamas University and her work focuses on ecological memories. Her academic interests span American and Indian English literature, postcolonial studies, environmental literature and memory studies. She has several national and international publications to her name.

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 15-52

A General Discussion on Urban Draught

Kaushik Kiran Ghosh
Associate Professor of Geology, Jogamaya Devi College, Kolkata
kaushikkghosh@gmail.com

Abstract: Drought is one of the most complicated natural hazards, with a slow onset, long-lasting impacts, and a gradual but catastrophic impact on communities, economic sectors, and the environment. Urban drought refers to a water scarcity crisis in cities caused by excessive water extraction, poor water management, and climate change. As urban populations grow, water demand increases, leading to unsustainable consumption. Water sources like rivers, lakes, and underground aquifers in many cities are depleting faster than they can naturally replenish, resulting in severe shortages. A major challenge of urban drought is the unequal distribution of water. Rapid urbanization contributes to the expansion of impervious surfaces like concrete, which reduces water infiltration and increases runoff during rainfall, further limiting groundwater replenishment. In India, urbanization accelerated after independence, driven by the adoption of an open economy that spurred private sector development. This discussion provides a comprehensive analysis of urban drought in India and globally, exploring various strategies for mitigating water resource shortages in a holistic manner.

Key Words: Urban areas, hydrogeological drought, meteorological drought, urban drought vulnerability.

1. Introduction

Urban drought indicates a condition in which the total water available to meet the demand for the urban ecosystem, industry, and municipal water supply is less than the adequate amount. The situation may arise due to below-average rainfall for consecutive years, overconsumption and excess exploitation of surface and groundwater, and substandard water management. Cumulative pressure due to urbanisation, population growth, industrial development and ultimately, climate change creates more burden on the water crisis.

Drought, in general, refers to a water-stressed condition in a particular area during a particular period of time. It is different from the natural condition prevailing in a desert, in which usual precipitation is less than evaporation, and hence, scarcity of water is a perpetual problem throughout the area. Depending on their causative factors, the drought may be classified into three different categories, namely climatic drought, hydrological drought and agricultural drought.

2. Causes of Urban Drought

A major problem in urban drought is related to the gap between demand for water in the region and the available water for consumption. Like other water-stressed conditions, any urban drought can be linked to the meteorological, hydrological and agricultural drought or any combination of them. Majority of the people of urban settlements are not involved in primary production sectors such as agriculture or farming. They are, rather, engaged in industrial production and tertiary work sectors related to white-collar jobs like teaching, engineering, practicing law and medicine etc. So, in an Indian urban setup, agricultural drought might not be so important for further consideration.

Table 1. Growth of global urban population in last 50 years.

Continent	Urban Population in terms of % of Total population						
	1970	1980	1990	2000	2010	2020	2023
World population	37	69	43	47	51	56	57
North America	74	74	75	79	81	83	83
South America (& Caribbean islands)	57	65	71	75	79	81	82
Europe & Central Asia	61	65	68	69	71	73	73
Central Europe & the Baltics	51	58	61	61	62	63	63
European Union	64	68	69	71	73	75	76
Euro Area	67	70	71	73	75	77	78
East Asia & Pacific	25	28	34	41	52	61	63
South Asia	19	22	25	27	31	35	36
Middle East & North African	42	49	54	58	62	65	66
Sub-Saharan Africa	18	22	28	31	37	41	43
Australia	84	86	85	84	85	86	87
<u>Special Interest Groups</u>							
Arab World	38	44	49	52	56	58	59
Heavily indebted poor countries (HIPC)	16	21	25	29	32	37	39
UN classified less developed countries	13	17	22	25	29	35	36
OECD members	67	70	73	76	79	81	82
Pacific island countries	26	29	31	34	37	39	40
<u>Countries of different income groups</u>							
High Income Countries	67	71	74	76	79	81	81
Upper Middle-Income Countries	28	33	40	48	58	66	79
Middle-Income Countries	21	25	28	31	35	39	41
Lower Middle-Income Countries	21	25	28	31	35	39	41
Low & Middle-Income Countries	25	29	34	39	45	51	52
Lower Income Countries	18	21	25	27	30	34	35

Data Source: Urban population (World Bank Group) (WB 2023)

The problem of urban drought is not solely related to the shortage of water due to any weather event, especially the less rainfall or sluggish water flow in the nearby river source. The main problem is associated with the gap between demand and supply. Demand usually increases in the summer. At that pre-monsoon time, sources like rivers, lakes, reservoirs, groundwater or desalination plants can not meet the rising demand for water. This phenomenon is a common occurrence during this period, particularly in urban areas. However, if the agricultural drought ensures crop failure, farmers from the periurban areas are compelled to migrate to nearby towns and cities to get jobs as unskilled labour in unorganised sectors. These migrants require the provision of excess water. The availability of cheap labour encourages permanent residents to opt for gardening, car washing, and backyard and terrace cleaning, which all require huge amounts of water. Hence, the major factors involved are anthropogenic, which are mainly concerned with over-extraction of natural water, incompetent urban planning and poor water management.

India's urban population was approximately 488 million in 2020, accounting for about 34.93% of the total population. The country is experiencing the fastest rate of urban population growth, with an average annual increase of 4.1% based on the 2011 Census of India. A United Nations survey projects that by 2030, approximately 40.76% of India's population will reside in urban areas (Wikipedia 2024). Approximately 4.4 billion individuals, or roughly 56% of the global population, reside in urban areas (see Table 1). Urbanization is expected to continue and reach its peak, with 70% of the global population living in urban areas by 2050. This trend is supported by rising incomes and a shift away from agricultural work. Currently, nearly 1% of the world's land is designated for urban infrastructure, which supports the growing population. Over 80% of the world's GDP is generated in urban areas. While urbanization can drive sustainable progress in productivity and economic development, it often falls short in meeting the basic needs of the population. As a result, urban droughts are inevitable – not due to a lack of water, but because of the reduced availability of water and other resources per capita due to population growth (UD 2023, Ritchie et al. 2024). In India, an urban locality is considered to be an area of more than 5000 inhabitants in which population density is > 400 persons/sq. kilometres and at least 75% of the male workers are engaged in work other than agriculture (Ritchie et al. 2024).
The article employs this definition of an urban area.

Unplanned and rapid urbanization accelerates the development of water-stress conditions. Urbanisation itself promotes the construction of roads, buildings and other infrastructural facilities, which creates impervious surfaces over the land. After a heavy shower, a component of rainwater infiltrates into the ground and the rest flows over the surface. Impervious surfaces, such as asphalt and concrete, hinder the natural groundwater recharge. So, a drought situation develops in the underground aquifer. On the other hand, flowing surface water creates a temporary flood situation just after a precipitation, which is commonly known as an 'urban flood'. This water does not have any suitable use. The enough land for the construction of reservoirs is not freely available in highly populated settlements and retaining the flood water for future use, especially in drought situations, is not possible. Plants with thick, broad foliage drip the splash of sudden rainfall throughout the day and allow more time for groundwater infiltration. It is not possible in metropolitan areas due to a lack of adequate vegetation.

Another important issue is the stress in the infrastructure of urban water supply. A prolonged period of below-normal water availability would leave the system unprepared. Water becomes precious with a shortage of supply. Economically weaker sections of society either face inequality in accessing clean water or they are to spend more money on drinking water. Social unrest would develop in the community if the condition prevailed for a long time. Conflicts are obvious amongst the different stakeholders who are the beneficiaries of the common water resource.

Global climate change, deviation in rainfall patterns and other climate impacts such as heatwaves, volcanic explosions, earthquakes etc., aggravate the drought situation. Heat waves increase evapotranspiration from soil and reservoirs. Volcanic activity increases heavy metals in the environment and contaminates surface and groundwater with arsenic and fluoride. Arsenic is a carcinogenic element and may cause skin cancer and, in extreme cases, cancer of the bladder and lung. Intake of excess fluoride may cause dental and skeletal fluorosis. Access to drinking water during the period of volcanic activity is an acute problem and supplying water in nearby municipal areas becomes challenging. The problem is witnessed in volcanic island countries like Iceland and Japan and several other countries having active volcanoes in their territory (Linhares et al. 2020, Parrone et al. 2018).

The obvious problem related to water shortage is the availability of less water for industrial, domestic and recreational use. Surface water levels and groundwater tables are declining. Reduced recharge of groundwater and slow river flow lead to degradation of the quality of water. The generation of huge municipal solid waste (MSW), liquid from sewerage, and chemicals from nearby industries pollute the urban natural resources. Excess presence of water in the environment flushes out the pollutants from point sources and their concentration comes close to or even below the permissible level. In a drought situation, the general condition of hygiene deteriorates due to water pollution and waterborne diseases (Kovats et al. 2003).

It is evident from Table 1 that migration from rural to urban areas is gradually increasing. It is an eternal tendency of people to migrate from rural villages to urban municipal setups to get access to more opportunities. Limited scope and declining income from the agricultural sector, market fluctuation and intrusion of middlemen, make the segment less attractive. On the other hand, opportunities other than farming are insignificant in village areas. The economic problems coexist with poverty. Essential services in remote areas are not adequate due to lack of resources. Rising cost of living and the uncertainty of production in farming due to erratic weather and climate change compel the common people to move towards nearby towns. Rural life is difficult due to insufficient communication networks, roads, electricity, and the internet. Inadequate schools and colleges and a lack of modern healthcare facilities attract the solvent sector of the rural community to set up another residence in the nearby municipal areas. Professional experts of different fields and their services are not available in the countryside. Whereas the society in the area is divided into caste, creed etc. and differentiated by gender and ethnicity. So, the general public is interested in moving to urban areas. Overcrowding creates different problems in the absence of sufficient resources, especially surface and groundwater.

Apart from the '*push factors*' of the rural area, some urban attractions are assurance of better income and living, modern amenities, reliable transportation, proper housing and higher standard of living. Community services like eldercare, childcare, psychotherapy and other consulting services are available only in urban areas. Rising wealth and opportunities for people; favourable government policies towards encouraging urbanisation and developing industrial hubs open up new opportunities for a productive workforce. However, optimum utilisation of resources and no surplus budget make the system inefficient for emergency situations. Social and cultural adjustment becomes difficult for the newcomer in the absence of enough resources, especially water. Overcrowding causes strain on the infrastructure, and as a result, slums expand in the areas.

Socioeconomic factors and improper policy decisions are often responsible for the human-induced water problem in towns and cities. Poor water storage, unequal distribution of water in different localities, overconsumption of water in nearby commercial farms and industrial sectors, and finally, lack of drought preparedness make the situation worse. A standard dam and reservoir system should support a large city or a cluster of towns. The reservoir retains water either from neighbouring streams or from heavy showers during the monsoon and provides it throughout the year. Inadequate storage space in the reservoir and improper management fail to supply water during droughts. Marginalised urban societies may suffer from improper water allocations and faulty water supply systems. Different stakeholders of the society are taking water from a single source. Hence, high consumption of water in the industrial units and business houses creates pressure on supplies, especially during dry months and drought situations. Finally, the absence of a blueprint for drought mitigation makes the situation more vulnerable. Instant decisions, enforcement of laws on water use, releasing financial aid from government grants and activities of NGOs do not make the situation congenial unless an adequate supply of water from the other sources is ensured.

Metropolitan areas often experience higher temperatures compared to the surrounding countryside, a condition intensified by drought conditions. Close-spaced buildings and infrastructures in combination with a lack of vegetation and open water sources enhance this *urban heat island effect*. Intensified heat, increased demand for water and a higher rate of evaporation deteriorate the drought condition. During periods of water stress, urban vegetation often declines, reducing evapotranspiration – an effective natural cooling process. As a result, the urban environment absorbs more solar radiation, which enhances the further rise of temperature. Water scarcity becomes more acute and extreme heatwave aggravates heat stress among vulnerable communities. Dependence on air coolers and air conditioning machines is evident; that raises the demand for excess power. Concrete structures retain more heat than greenery, amplifying the heat island effect, while industrial activities and poor urban planning further contribute to the issue. Implementing solutions like reflective paints and materials for rooftops can help to mitigate the impact of high temperatures in urban settlements.

Like other drought events, the recurrence of urban drought depends on several other global factors, such as abnormal sea surface temperature (SST) and ENSO (El Niño Southern Oscillation). El Niño, or ENSO, refers to periods of warming in the central and eastern equatorial Pacific Ocean. El Niño shifts air masses over the ocean and thus, the places, usually wet, become dry. The extensive droughts in Asia, South America and other parts of the world are linked with the recent El Niño and many cities are suffering from water problems in the recent past. A significant correlation between El Niño and urban drought has been reported in more than 43% of cases. The percentage is likely to be higher, as there is no response strategy for urban drought and the response is masked by several other metropolitan and strategic management factors (Singh & Sharma 2019). El Niño events lead to higher winter precipitation and increased summer temperatures in the Southwestern United States, significantly affecting the local ecosystem (McPhaden et al. 2006, Alftine et al. 2003). Apart from El Niño and La Niña, the North Atlantic Oscillation (NAO) plays a significant role in creating a high-pressure belt, which is responsible for the water crisis in US cities (Nagarajan 2009).

Indian towns and cities face the drought based on their geographic location and the global factors of climatic oscillation. The Indian monsoon is more susceptible to drought when El

Niño events occur during warm Pacific decadal oscillation (PDO) phases. The effects of ENSO on Indian climate depend on season, region, and sea surface temperature anomalies. Researchers have quantified the influence of ENSO events on droughts using drought indices (Kiladis & Díaz 1989, Halpert & Ropelewski 1992, Trenberth 1997, Krishnan & Sugi 2003, Philander & Fedorov 2003). Periodic climatic factors like ENSO, Indian Ocean Dipole (IOD), Quasi Biennial Oscillation (QBO), Atlantic Multidecadal Oscillation (AMO) and Equatorial Indian Ocean Oscillation (EQUINOO) influence the variation in rainfall in the Indian subcontinent (Krishna Kumar et al. 1999, Gadgil et al. 2004, Goswami et al. 2006, Kumar et al. 2006). Irregular oscillation of SST is observed in IOD (Saji et al. 1999), which influences precipitation in Australia, India and eastern Africa (Vinayachandran et al. 2009). Wind blows from east to west on peninsular India due to atmospheric convection that develops when the Arabian Sea becomes warmer and the Bay of Bengal becomes colder.

Table 2. Different factors that cause Urban Drought

Meteorological Factors	Reduced Precipitation	Periods of significantly lower than average rainfall, leading to decreased water availability.
	Increased Temperatures	Higher temperatures increase evaporation rates, exacerbating water loss from soil and surface water sources.
	Changes in Atmospheric Circulation	Shifts in weather patterns, such as altered jet streams or El Niño/La Niña events, can disrupt normal rainfall patterns.
	Climate Change	Global warming intensifies extreme weather events, including droughts, and alters precipitation patterns.
Hydrological Factors	Depletion of Surface Water	Decreased water levels in rivers, lakes, and reservoirs due to reduced rainfall and increased evaporation.
	Groundwater Depletion	Over-extraction of groundwater for urban water supply, leading to declining water tables.
	Reduced Soil Moisture	Prolonged dry periods lead to decreased soil moisture, impacting vegetation and increasing runoff.
	Reduced Reservoir Levels	Lack of rainfall, excessive water withdrawal, sediment accumulation
Human Factors	Increased Water Demand	Rapid urbanisation and population growth increase water demand for domestic, industrial, and commercial use.
	Urbanisation and Impervious Surfaces	Increased paved areas and buildings reduce rainwater infiltration, leading to higher runoff and decreased groundwater recharge.
	Poor Urban Planning	Uncontrolled urban sprawl and development without considering water resource limitations also increase impervious surfaces, reducing groundwater recharge and increasing runoff and urban flooding.
	Urban Heat Island Effect	Increased populations lead to higher ambient temperatures, which in turn increase evaporation. This, in turn, increases water loss, thereby intensifying the effects of urban drought. Industrial processes can increase localised heat, increasing evaporation that increases localised water loss, increasing urban drought.
	Better lifestyle	A mandatory swimming pool in a gated society and the use of a bathtub in a personal bathroom require more water.

	Deforestation	Removal of vegetation reduces evapotranspiration, which decreases atmospheric moisture and rainfall. It also increases runoff.
	Water Infrastructure Leaks	water pipe infrastructure that is old, and or poorly maintained, can leak large amounts of water, causing water waste.
	Agricultural water use	water used for agriculture near urban centres, can deplete water resources. Overuse of water in agriculture and landscaping (gardening) leads to unnecessary depletion of resources.
	Industrial growth	High water consumption, pollution of freshwater sources. Usually industries consume large amounts of water without sustainable management strategies.
	Water waste	inefficient water usage by urban populations.
	Pollution	Contaminants from industries, sewage and waste disposal reduce the availability of clean water. Result is contaminated water sources, reduced availability of clean water.
	Greenhouse Gas Emissions	Greenhouse gas emissions from automobiles and industries contributes to global warming, which intensifies drought frequency and severity.
Socioeconomic Factors	Population Density	High population density in urban areas increases water demand and stress on water resources.
	Economic Development	Economic activities, tourism and better office ambience increase water consumption.
	Overuse of Shared Water Resources	Competing demands among households, industries and agriculture intensify scarcity.
	Inequitable Water Distribution	Unequal access to water resources can exacerbate drought impacts in vulnerable communities.
Innovation and Regulatory Issues	Lack of policies	Lack of policies, poor enforcement of water-use laws.
	Failure in Demand Management	No measures to promote efficient water usage, such as water pricing, rationing, or public awareness.
	Pricing Policies	Water prices that do not reflect the true cost of water can increase water waste and therefore increase the likeliness of urban drought. Subsidy in this essential item should be withdrawn for higher consumption.
	Insufficient Water Conservation Policies	Weak or unenforced policies regarding water conservation in residential, commercial, and industrial sectors which contributes to excessive water consumption and wastage of water, depleting resources.
	Lack of Investment in Water Recycling	Limited efforts in wastewater treatment and reuse increase reliance on freshwater sources.
	Inadequate Rainwater Harvesting	Failure to implement rainwater collection methods leads to wasted potential water sources.
	Lack of Drought Preparedness Plans	Failure to have plans in place for water rationing, alternative water sources, and public awareness campaigns which increases the negative effects of the drought, when it occurs.

The discussion becomes endless as millions of factors are involved in urban drought and those influence several attributes of hydrogeological and meteorological factors that govern the severity and nature of drought. Table 2 provides a comprehensive overview of all the factors that contribute to the drought problem.

3. Relation between urbanisation, urban flood and urban drought.

From the previous discussion, it is already clear that sealing the ground surface with the help of impervious materials such as concrete and bitumen restricts the downward flow of water. During rainfall in the urban area, most of the water flows over the ground, creating a flood condition. In Figure 1A, the purple line shows the preurban flood discharge curve. One component of rainfall recharges groundwater through infiltration. Hence, the total surface discharge is less in amount and that too reaches the stream gradually, taking a longer period of time. Lag time refers to the interval between the peak of rainfall and the peak discharge in a stream. In this scenario, the lag time is notably prolonged, resulting in a relatively low discharge peak, with water consistently flowing through the channel below the danger level. However, following urban development, the reduction in vegetation enhances water flow, leading to significantly higher discharge peaks (red curve). Overflow from the sewer system contributes to waterlogging issues.

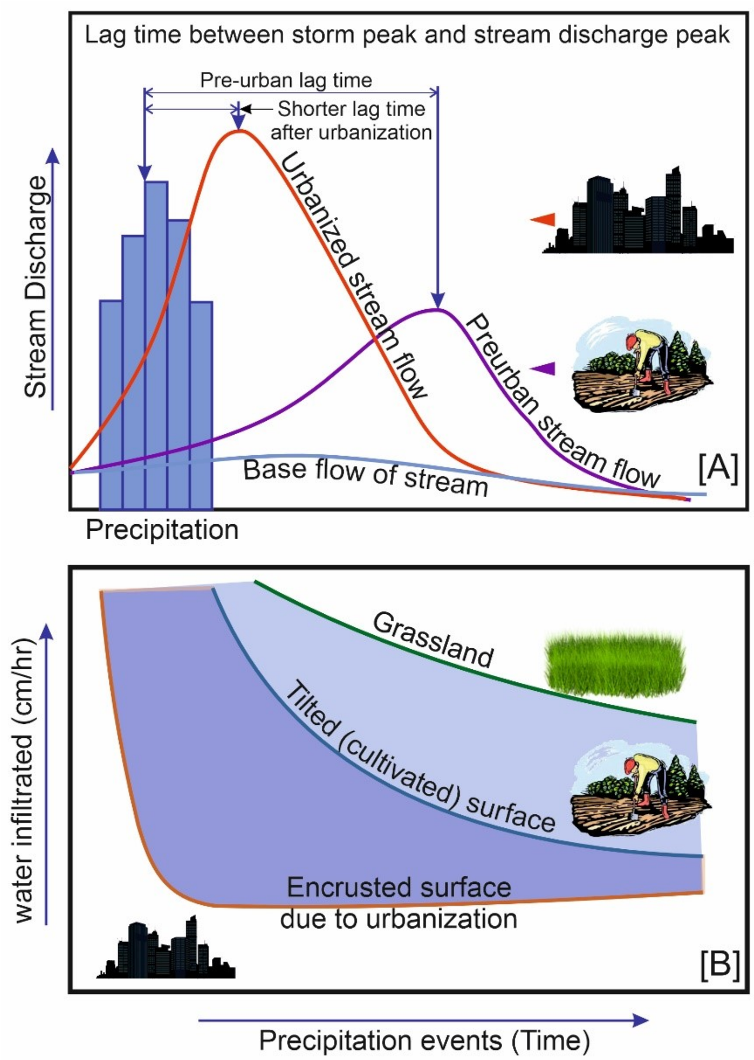


Figure 1: Schematic diagrams showing the effects of urbanisation on urban flood and groundwater recharge. (A) Graph showing the relative effects of urbanisation on surface runoff (after Marsalek et al. 2006 and Duan et al. 2016). (B) Impact of surface sealing (by asphalt and concrete) on infiltration rates (after Maidment 1993)

Below the surface of a metropolitan area, the opposite problem becomes apparent. Asphalted surfaces break groundwater percolation. In Figure 1B, the green curve indicates the groundwater infiltration with respect to time just after a heavy rainfall. Thick grass cover restricts surface movement and allows water more time for downward movement. Underground flow decreases with cultivation because rainfall directly hits the bare farmland surface, causing rapid runoff and reducing the time available for groundwater recharge.The situation becomes worse due to urban growth, where the artificially encrusted surface restricts water to entering into the ground. It is obvious that with the change of land use pattern, huge amounts of water can not reach the aquifer for groundwater recharge (see the coloured area of Figure 1B). It is usual practice to draw water from underground aquifers through pumps to meet the additional demand for water. The water table declines due to constant exploitation of groundwater without having any scope for further recharge (Figure 2A & B). Sometimes, the cone of depression on the water table becomes permanent. Cone of depressions of very close-spaced tube wells in a metropolitan setup often join to form a regional depression of the water table, causing failure of shallow tube wells (Figures 2A & 3). It might be responsible for land subsidence in the long run.

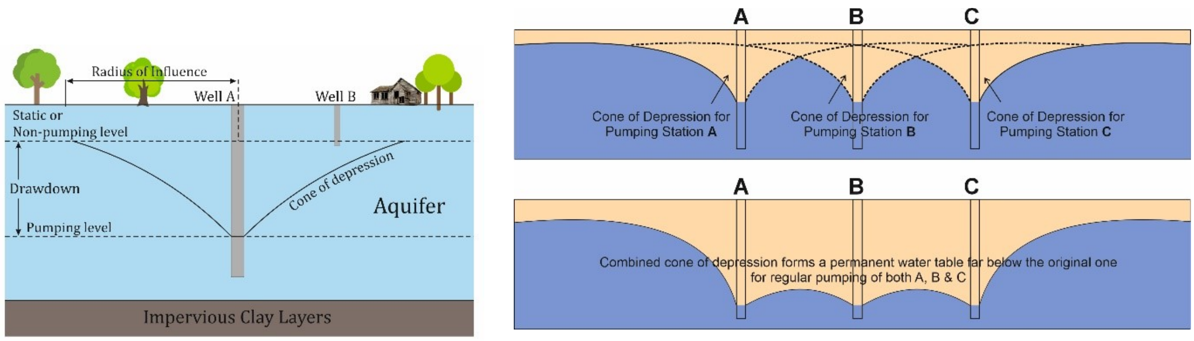


Figure 2. A: Drawdown in an unconfined aquifer. Note that extensive pumping of Well A causes a cone of depression such that the Well B becomes dry. B: Regular operation of pumping array (A, B and C) causing depletion of groundwater and lowering of water table in urban locality.

4. Urban drought categorisation framework

Urban drought is depicted in terms of drought vulnerability, with water scarcity as its central concern. Four main hydrogeological factors impact urban drought: local soil moisture, local groundwater, nearby surface water sources (such as canals, ponds, and wetlands), and surface or groundwater reservoirs that provide drinking and industrial water to the city. These reservoirs are usually located outside the urban areas. These reservoirs are typically situated outside the built environment of the city. Based on these components, urban droughts can be categorised into four types: Soil Moisture Drought (SMD), Groundwater Drought (GD), Open Water Drought (OWD), and Water Supply Drought (WSD). These drought types may result from insufficient water availability or degraded water quality, rendering it unsuitable for its intended purposes. Different types of urban droughts may occur in a particular area. (Machairas & van de Ven 2023).

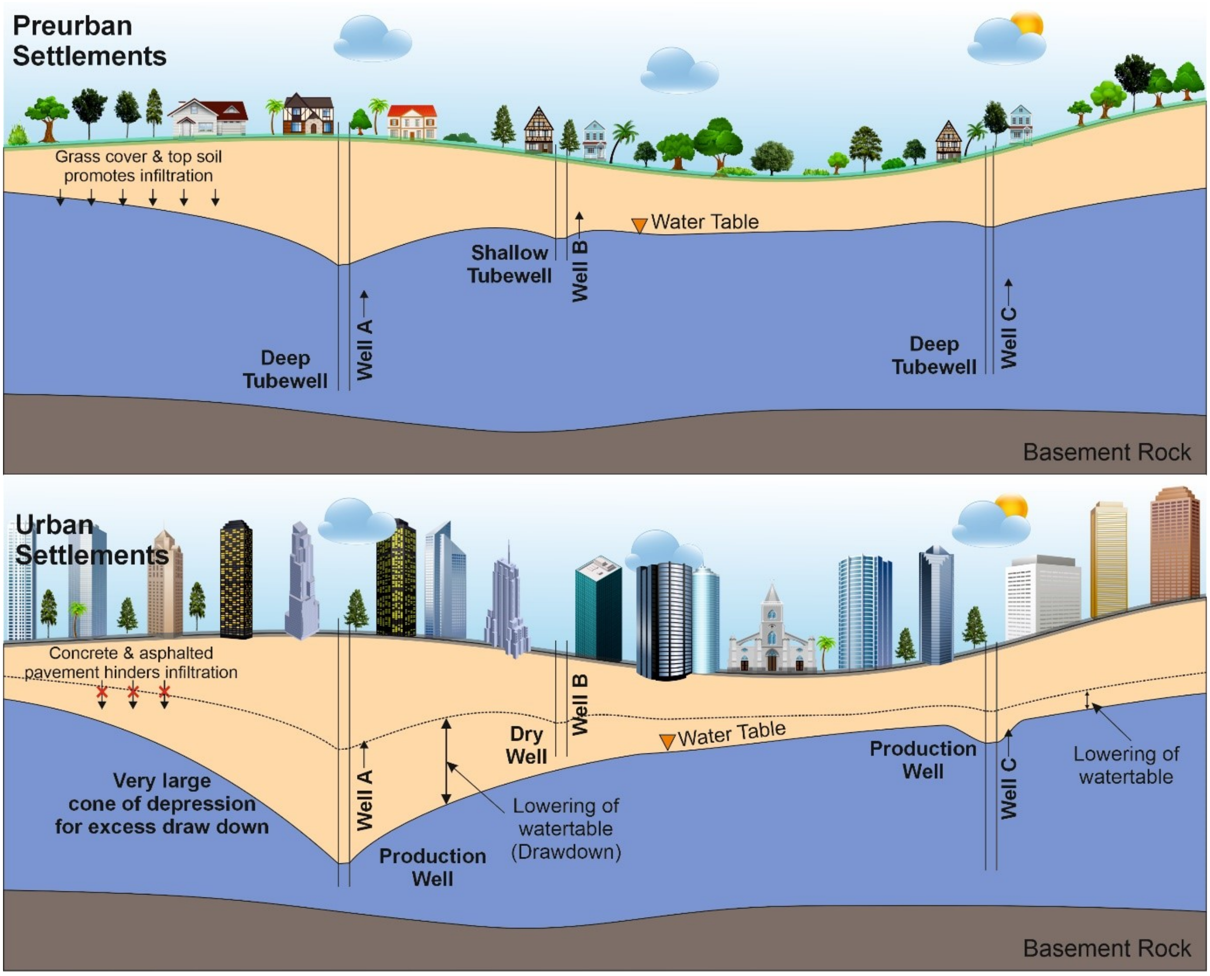


Figure 3. Three wells, namely A, B and C are drawing water for a growing urban community. Wells A and C are deep tube wells and B is shallow one. Figure indicates drying up of well B, due to overexploitation of water through well A.

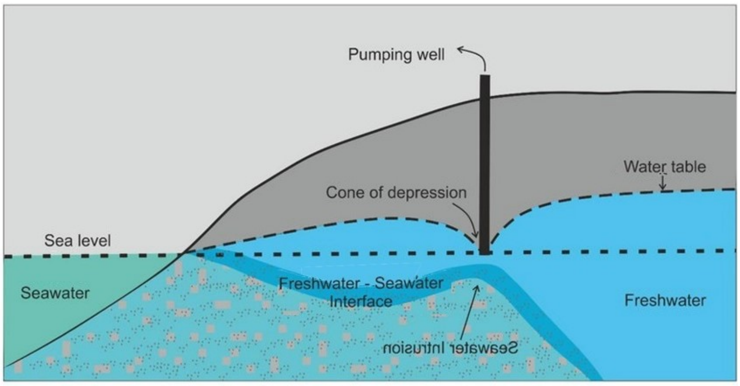


Figure 4. Schematic diagram illustrating seawater encroachment in a coastal aquifer.

The urban area suffers visible and tangible damage as a result of the integration and reflections of these drought components. SMD turns the grass and green cover of parks and islands into golden yellow and intensifies ambient temperature due to the reduced rate of evapotranspiration. As SMD takes more moisture during groundwater infiltration, GD starts with the initiation of SMD, which is observed by the lowering of the water table, reduced supply from groundwater and finally a ground subsidence for a long-duration problem. GD can root for OWD in a season with less precipitation. OWD reduces the spread of surface water and is responsible for the destruction of wetlands in coastal cities and saltwater intrusion in the estuary and underground aquifer (Figure 4). Finally, in the absence of a good amount of freshwater, hindering municipal water supply creates WSD (Machairas & van de Ven 2023).

Szalińska et al. (2018) considered both hydrological and meteorological factors for describing urban drought hazards. In this study, urban spells and parameters are grouped under different names based on ambient temperatures. The ***extreme events*** are described according to their decreasing severity:

- *Extreme hot days (EHD)*: EHD can denote a solitary day with maximum temperature (T_{max}) exceeding a certain threshold value or the hottest day in a span of one month or one year (Perkins, 2015; Frölicher et al., 2018). It was defined as days when the daily maximum temperature exceeds the 98th percentile of long-term temperature observations (Szalińska et al. 2018). While working at Madrid, co-workers of Garcìa (2002) considered a Tmax = 36.5◦C, which was equivalent to the 95th percentile. However, a day with a T_{max} exceeding the 90th percentile, calculated within a 5-day window for the 1961–1990 base period in each grid, was considered an EHD. Several studies commonly use this method (e.g., Karl et al., 1999; Peterson et al., 2001). EDH thus recurs many times in a year. The Indian Meteorological Department (IMD) announces early warnings for unusual EHD with 90, 95, and 98 percentile temperatures for every month under Heat Action Plans (HAP) from 2016 (IMD 2025).

- *Heat waves (HW)*: Heat waves indicate a period of unusually high temperature compared to other days in that region. The unusual temperature indicates an abnormally higher temperature that varies from place to place depending upon the climate and historic temperature record of the region. The usual value of temperature is considered to be more than 40°C for plains and 30°C for hilly terrain. IMD considers HW based on the departure from the normal average temperature of the day and on the basis of the actual maximum temperature. An anomalous increase of local temperature from 4.5°C to 6.4°C, is considered as HW and if it is more than 6.4°C, it is declared as severe HW. When the recorded $T_{max} \geq 45$°C for two consecutive days, HW is declared by IMD as HW and it is declared as 'severe' when Tmax ≥ 47°C. In coastal belts, an average deviation of more than 4.5°C towards the higher end ensures a temperature of 37°C or more, which is considered to be HW of the region (IMD 2025). Perkins and Alexander (2012) used five qualifiers (indices) for HW. These are – HWM: the average daily magnitude of all heat wave events in a year; HWA: the hottest day of the hottest event in a year; HWN: the number of heat wave events; HWD: the total length in days; and HWF: the total number of heat wave days.

- *Hot and Humid Weather (HHW):* HHW at a station is defined when the observed maximum temperature is 3°C or more above normal, accompanied by higher-than-normal relative humidity (IMD 2025).

- *Long-lasting dry spells (LLDS):* LLDS are extended periods of insignificant rainfall that can continue for a week to several months. For a common definition, LLDS can be defined as a period of consecutive days with either no precipitation or daily rainfall amounts of ≤1 mm, lasting for more than 10 days (Szalińska et al. 2018, Mathlouthi & Lebdi 2021).

Different tools are used to quantify the thermal condition of urban households. The discussion below describes some of the important factors.

- ***Cooling degree days (CDD):*** CDD represents the accumulated deviation of the air temperature over the days with the temperature exceeding the assumed threshold value to provide information on the local cooling energy demand. It is a weather-based technical index that can contribute to the correct interpretation of energy consumption for cooling a building or characterise the annual required cooling degrees for an average household. The value depends on the local weather condition and hence, the threshold value is very crucial (Christenson et al. 2006, Selvanathan & Migdalska 2015, EPA 2025). The unit of Cooling Degree Days (CDD) is simply degrees, as it represents the number of degrees that a day's average temperature is above a set base temperature (typically 65°F or 18°C) (Scott 2022). In India, CDDs are usually considered for base temperature within a range between 18°C and 26°C. The CDD for Poland is calculated for a base temperature from 18°C to 28°C. The average annual values of CDD_{18} for Indian cities are: CDD_{18} for Chennai is 4108, for Kolkata CDD_{18} = 3360, for New Delhi CDD_{18} = 3015, for Mumbai CDD_{18} = 3469 and for Mangalore CDD_{18} = 3449. The average annual value of CDD_{18} for the Polish city of Warsaw is CDD_{18} = 182 (Selvanathan & Migdalska 2015). Heating degree days (HDD) are opposite to CDD, which are designed to describe the energy requirements of buildings in terms of heating (HDD) and are obviously considered in the cold countries.

  The simple equations that express CDD and HDD are (Fraisse & Paula-Moraes 2018) as follows:

Temperature expressed in °F	Temperature expressed in °C
$CDD = \left(\frac{T_{max} + T_{min}}{2}\right) - 65$	$CDD = \left(\frac{T_{max} + T_{min}}{2}\right) - 17$
$HDD = 65 - \left(\frac{T_{max} + T_{min}}{2}\right)$	$HDD = 17 - \left(\frac{T_{max} + T_{min}}{2}\right)$

- Low flow index (LFI): represents the period of the river flows below the assumed threshold value. It is an indicator of hydrological drought that reflects the total water deficit of river discharge from the limiting value (EDO 2018, WF 2020).

- *Standardized Precipitation Index (SPI):* It is a meteorological index devised by McKee and others (1993), which indicates the cumulative value of precipitation in a given interval of time, i.e., for a month, quarter or year. The SPI is determined using the following equation, expressed as: $SPI = \frac{(X_{ij} - X_{im})}{\sigma}$,
  where, X_{ij} is the seasonal precipitation of j^{th} observation at the i^{th} rain-gauge station and, X_{im} is its seasonal mean of long-term data and σ is its standard deviation. The index name is usually modified to include the period of accumulation; for example, SPI-3 refers to an accumulation period of three months. The input variable precipitation for a spatial resolution of 5 km should be considered for a time period of one month (SPI-1) to one

year (SPI-12). It determines anomalies of precipitation at a given time period for a particular location, comparing the observed total precipitation amounts with the historic long-term precipitation record for that period (WMO 2012, ADO 2025). As a ratio, zero value indicates a normal condition and other figures refer to different drought and wet conditions, which is depicted in the dataset presented in Table 3 (WMO 2012, EDO 2020, ADO 2025).

Table 3. Table representing the relation between drought severity and standardized Precipitation Index (SPI)

SPI values	Category	Probability of Event (%)	Number of times In 100 years	Severity of event
< –2.00	Extreme dryness	2.3	2.5	1 in 50 yrs.
–1.99 to –1.5	Severe dryness	4.4	5	1 in 20 yrs.
–1.49 to < –1	Moderate dryness	9.2	10	1 in 10 yrs.
– 1 to < 0	Normal to mild dryness	68.2	33	1 in 3 yrs.
0 to < 0.99	Normal to mild wet			
1.0 < SPI < 1.49	Moderately wet	9.2		
1.5 < SPI < 1.99	Very wet	4.4		
SPI > 2.00	Extremely wet	2.3		

Source: WMO, 2012 and EDO, 2020.

It is a widely used normalised index; it is used both for expressing drought and monsoon. It can be used in multiple time frames but is limited to a certain extent, as it depends solely on precipitation (WMO 2012).

- *Standardized Runoff Index (SRI):* SRI is a hydrological indicator used to assess and monitor runoff anomalies in a given drainage basin. It quantifies the deviation of runoff from the long-term average, expressed in standard deviation units, similar to the Standardized Precipitation Index (SPI).

  The SRI is calculated using observed runoff data over a defined time scale (e.g., 1 month, 3 months, or longer), allowing for the evaluation of both short-term and long-term hydrological conditions. Negative SRI values indicate below-average runoff (dry conditions or drought), while positive values signify above-average runoff (wet conditions). The SRI is particularly useful both for assessing hydrological droughts and monitoring flood risks during periods of excess runoff. It has wide use in the field of water resource management and planning by providing insights into runoff variability due to climate and land-use changes (Shukla & Wood 2008, Kartika & Wijayanti 2023).

5. Impacts of Urban Drought

Drought as a natural hazard is unique in nature. It has a very slow onset and the problem has been realised after a long period of the event. It is sometimes observed that people may not feel the effect of drought at its initiation but suffer from the agricultural and economic crisis after the end of the drought period. This unusual attribute is completely absent in urban drought. Since water is a limited resource in this case, the negative impact manifests immediately after the onset of the problem. It is better to classify the problem as a hydrological drought where the availability of clean water for drinking, industry, and household use is decreasing.

- In underserved areas, children and women face more challenges for fetching water. Heart problems and dehydration are more common in aged members of the vulnerable populations. The situation compels the marginalised people to migrate to the core urban areas with a sufficient supply of water. Thus, a metropolis experiences the second level of seasonal uprooting. Occasionally, it escalates into a refugee crisis, creating significant problems for the local urban authorities.

- The economic losses linked to urban water shortages include higher costs of water production, reduced productivity in both large-scale and cottage industries, and agricultural losses in peri-urban areas. Additionally, hydropower generation is impacted by reduced water levels, leading to decreased availability of running water. This results in higher per-unit electricity production costs, ultimately affecting energy supply.

- Urban droughts can cause severe environmental impacts. Degradation of water bodies, drying of ponds and wetlands and fall of water table in aquifers are the major hydrological problems. Groundwater abstraction through diesel and electric pumps may cause ground subsidence, which may cause groundwater head depletion in shallow tube wells and damage to buildings and properties (Logar et al. 2013). Subsidence leads to ground compaction in unconsolidated sediments that reduces the accumulation spaces (intergranular pore spaces) and storage capacity of the aquifers. Subsidence is often gradual but can occasionally be severe, as observed during California's drought from 2008 to 2010, when subsidence in certain areas reached rates of up to 270 mm per year (Faunt et al. 2016). The sinking is continuing in the San Joaquin Valley and the Sacramento Valley till today due to over-extraction of groundwater (McNabb & Swenson 2023).

- Over-pumping not only leads to subsidence but also contributes to seawater intrusion into aquifers in coastal cities. The controversy centres on whether saltwater intrusion in coastal deltas is caused by subsidence due to water extraction, silt starvation resulting from the construction of dams and reservoirs in the upstream region of adjacent rivers, or the recent rise in mean sea level (Gies 2022). In 1976, Northern Europe, particularly from Scandinavia to France, experienced an unprecedented 3-month drought. In the UK, longer duration of drought is responsible for widespread subsidence resulting in failure of building foundations (Nagarajan 2009). Subsidence due to groundwater exploitation has been noted from Mexico City (Figueroa Vega, 1984). The subsidence problem in the lowlands of the Netherlands has deteriorated the wooden foundation of heritage buildings (Machairas & van de Ven 2023). Overdrawing of water in the islands of Taiwan causes land subsidence upto two metres below sea level in the southern and central parts of the island. A very high rate of subsidence was reported in Taipei during the period between 1955 and 1975, which was later checked by implementing strict regulations during the 1970s. Synthetic Aperture Radar Interferometry (InSAR) technology indicates that some areas of Taipei are still sinking and the maximum rate is 9mm/year (Chang & Tseng 2025, Narvaez et al. 2022).

- Evaporation increases with high heat flow, which is the result of a lack of vegetation. The process reduces soil moisture and less moisture in soil intensifies soil erosion and reduces soil fertility. These two processes then reduce further vegetative cover. The whole system runs in a positive feedback cycle. Hence, soil degradation is a pertinent problem, though soil cover is not enough in metropolitan areas. Problems related to infrastructure and water distribution systems in urban setup are very common.

- Water supply systems and sewerage in older sections of an established city, such as north Kolkata, have leakage that creates significant problems. Lack of proper drawing of older laying enhances the problem manifold.

- Poor water pressure can disrupt essential services such as firefighting and sanitation. In January 2025, three significant wildfires destroyed a few places in Los Angeles, which were beyond control due to the failure of fire engines due to low water pressure in hydrants (ET 2025). Conflict over limited water resources among the stakeholders occasionally generates unprecedented problems. For example, US president Donald Trump blamed other departments of government for not providing additional water to Los Angeles to preserve an endangered species of fish, popularly known as Delta Smelt (Yurcaba 2025). Water uncertainty creates tension and anxiety among the residents and disputes between the communities sharing the same water resource become evident.

6. Vulnerability Assessment of Urban Drought

Vulnerability assessment involves identifying, quantifying, prioritising and ranking various types of vulnerabilities within a system (p.399 of Şen 2015). It serves as a framework for uncovering the social, economic, and environmental factors driving drought impacts. By focusing on the root causes of vulnerability rather than solely addressing the resulting negative impacts triggered by events like drought, vulnerability assessment bridges the gap between impact evaluation and policy formulation (Wilhite & Pulwarty 2018). It can be measured based on factors like drought exposure, its extent and the adaptive capacity of the victims. Based on the assessment, policymakers develop a balanced solution that prioritises mitigation and boosts resilience. Identification of vulnerable people and systems is important and the solution for them should be effective, up-to-date and economical.

IPCC (2012, 2014) defines exposure as the presence of people, communities, livelihoods, ecosystems, environments, resources, infrastructure, or economic and cultural assets that may be negatively impacted by hazards. The most important key component of *Vulnerability Assessment* is the exposure, which can be quantified by hydrogeological and climatic data of the affected region. The intensity, duration and frequency of drought can portray a general model for urban drought, specific to a particular town or a group of urban settlements, situated in a particular geographic region. Patterns of precipitation shows a trend, the deviation of which, especially lesser rainfall, might be an alarm for the drought. For the proper assessment, patterns of urbanisation, especially population density, urban stretch and external sources of water, are vital issues. Many coastal cities of India consume water far away from the coastline.

Sensitivity and resilience towards adaptation is another parameter for assessment. It basically indicates the degree to which the urban area and community have been affected. The survey on vulnerable groups, such as the effect of drought among children, aged and retired people and low-income sections, reflects the extent of drought. The migration trend in search of water and better livelihood reflects the condition of drought. Production and economic activities that heavily depend on water might be affected. Wetlands and ecosystem services may be affected in the absence of soil moisture and groundwater. Measuring these parameters, we can develop an idea of the degree of drought.

The competence of an urban community to cope with the situation or recover from negative drought impact indicates the adaptive capacity of that urban area. Procuring water from alternative sources and good water resource management and conservation practices with the help of recycling, water treatment and desalination (in case of coastal cities) can alleviate the drought situation. Capacity building through institutional initiatives may play a bigger role in affected societies. Implementing a governance framework through regulations and policies would change the situation. Investment and incentives on drought preparedness and mitigation programmes. Funds may be released for developing innovative technologies that monitor the water loss, provide predictive models based on real-time conditions; and encourage the people to use smart water systems. Community awareness programmes through seminars and symposiums would often provide positive feedback. Public participation in effective knowledge percolation, drought preparedness and water conservation also provides operative solutions to the problems. Measuring all of these aspects for efficient results and quantifying efforts provides a clear picture of urban drought, which will serve as the doctrine for future challenges and solutions.

After defining an objective, the second step for vulnerability assessment is to collect data on hydrogeology, climate, infrastructure, socioeconomic parameters and the spectrum of the population. The selection of appropriate indicators and parameters to measure drought exposure and sensitivity, and the adaptive capacity of vulnerable communities and regions is crucial. Based on the predictive model and historical trend of drought, a map showing highly vulnerable zones has to be prepared. A composite vulnerability score on existing and extrapolated data can be considered, which can be used for contouring to develop high-resolution hazard zonation maps in relation to drought. At the final stage, all the stakeholders, that is, the involved communities, government agencies, NGOs and experts, should be consulted to validate the result. Based on the findings, recommendations and action plans should be developed to enhance resilience and reduce vulnerability.

7. Tools and Approaches for Vulnerability Assessment

For the *vulnerability assessment*, real-time monitoring of hydrological, hydrogeological and meteorological factors should be considered. The engaged machinery produces a huge amount of data. Proper tools and approaches should be adopted to interpret the data and get inference for long-term sustainable urban development. A large number of parameters for handling those data have already been discussed in the previous sections (see Section 4).

For real-time monitoring of drought, the best way is to observe the situation through Remote Sensing (RS) and Geographic Information Systems (GIS). Land Surface Temperature (LST), Normalized Difference Vegetation Index (NDVI) etc. are developed from the RS and GIS dataset (Han et al. 2010). These indices are used to monitor plant growth and thus used as a tool to understand agricultural drought. Wang et al. (2003) devised the Vegetation Temperature Condition Index (VTCI) with the help of a scatter plot of LST and NDVI, which is effective for monitoring real-time drought situations. Remote sensing images are primarily utilised to monitor and detect land cover changes that frequently occur in urban and suburban areas due to continuous urbanisation (Karanam 2018). Change of land use and urban growth can be examined by the Normalized Difference Built-Up Index (NDBI) and Urban Index (UI) in association with NDVI (Ali et al. 2019). The change of urban character in drought situations can be studied by remote sensing techniques. Drought forecasting is a key component of drought hydrometeorology, which plays a vital role in drought preparedness, mitigation and overall risk management. The development of different predictive models and their success depend on the availability of authentic databases. Meteorological observation post provides ground data. RS and GIS provide a series of data that change with time. These static and dynamic data, along with the empirical dataset predicted through mathematical models, can provide better solutions for drought control.

Environment and ecosystems change with the climatic conditions, especially the availability of water. So, the earliest effort was to use the Environmental Vulnerability Index (EVI) to study vulnerability. The index includes 50 biophysical or natural environment indicators categorised into three sub-groups (hazards, resistance and damage), ignoring the human systems (Kaly et al., 2004). The index was effective in analysing the environmental vulnerabilities of *Small Island Countries* (Wikipedia 2025) but fails to quantify an urban drought.

Health issues as a societal problem emerge just after any natural hazard and urban drought is not an exception. Vulnerability indicates the “propensity or predisposition to be adversely affected” (IPCC, 2012). Social vulnerability measures a community's susceptibility to the adverse impacts of natural hazards and stressors, including loss, injury, death, or disruption of livelihood. In other words, it reflects the resilience of communities in responding to and recovering from threats to public health, livelihoods, and property. To measure socioeconomic factors that contribute to vulnerability, Social Vulnerability Index (SVI) can be used as an indicator. SVI is used in the preliminary survey to identify the groups of people from different genders, ages and castes and creeds who are more or less vulnerable. Initially, Cutter et al. (2003) created a Social Vulnerability Index (SVI) using 30 socio-economic characteristics that hamper a community's capacity to prepare for, respond to, and recover from disasters throughout the whole United States at the county level. Later, it was modified for the requirement of the US Government. Presently, it is used by other survey agencies working outside US territory. SVI is measured based on 15 variables or proxies that are grouped into four different categories, such as (a) socioeconomic status, (b) household composition and disability, (c) minority status and language and finally, (d) housing and transportation of an ethnic group. Generally, SVI score varies from 0 (least vulnerable) to 1 (most vulnerable). (TEPHI 2021, SEDAC 2023, DHHS-NS 2024)

During vulnerability assessment, SVI is utilised to identify and classify weaker people that will deserve continued care and support to recover from natural disasters. Using the SVI, the Emergency Response Team (ERT) can estimate the amount of food, medicine, water or bedding required to support the affected persons. Finding out the effective evacuation route, identifying the best area for emergency shelter and taking decisions for how many emergency personnel are required to handle the problem situation – all these crucial decisions can be taken by ERT studying the value of SVI.

To predict the future scenario in relation to hydrogeological problems, it is a general practice to develop an empirical mathematical model based on atmospheric-hydrological interlinked phenomena (Mishra and Singh, 2011). Lots of such hydrological models are depicted to understand the peak flow of a stream channel or to improve the flood condition. Flood forecasting focuses on short-term higher flows, but drought forecasting emphasises lower stream flows for a long and extended period of time. Forecasting drought is quite unconventional, as most of the studies emphasise the simulation of peak flow rather than low flow conditions (Yu et al. 1999, Mishra and Singh 2011). Another problem is that the studies usually deal with a single drought event, which is not suitable for evaluating drought occurrences of different spatial and temporal frames. An ideal model has the ability to classify a locality based on the manifestation of non-drought vs. drought periods. The efficacy of hydrological models depends on their ability to accurately mimic the timing, amount, and variability of streamflow during drought periods, as well as their capacity to predict drought duration, intensity, and severity using the available normalised data (Simeone et al. 2024). The United States Geological Survey (USGS) has adopted the National Water Model (NWM) and National Hydrologic Model with Precipitation-Runoff Modeling System (NHM-PRMS) for predicting flood and drought events.

Integrated Water Resource Management (IWRM) is used to manage all types of surface, stream and groundwater in a holistic manner. The Global Water Partnership (GWP) defines IWRM as:

> *"IWRM is a process which promotes coordinated development and management of water, land and related resources in order to maximise the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems."* (GPW 2000)

It is a systematic and sustainable approach to managing water resources, acknowledging their limited availability and addressing the impact of negative influences on this vital resource.

The IWRM concept, as a part of the Dublin Statement on Water and Sustainable Development, was adopted on 31st January in 1992 at the International Conference on Water and the Environment (ICWE) held in Dublin, Ireland. The declaration emphasised the misappropriation and shortage of global water resources and recommended four guiding principles to address the escalating threats to environmental preservation, sustainable development concerning ecosystems, human health, food security, and industrial advancement (SIWI 2020, Biswas 2004).

IWRM focuses on the "three E's": **E**conomic Efficiency, **E**nvironmental Sustainability, and Social **E**quity. Its foundation rests on three key pillars: an *enabling environment* supported by appropriate policies and laws, a well-defined *institutional framework and roles*, and effective *management instruments* for institutions to implement in daily operations. The Government of India has implemented the National Water Policy (2012) following IWRM. In this guideline, "*Flood and drought warning and development of emergency works; drought preparedness and coping mechanisms*" have been proposed under the head "*Preparedness against water disasters*" (GOI 2016). IWRM recognises the significance of the entire water cycle, including its natural processes and interactions with other ecological cycles within the natural ecosystem (SIWI 2020). The IWRM approach is effective, as successful water resource management leads to the elimination of water stress and drought events.

The outcome of a vulnerability assessment can be employed in urban planning, policy development and resilience building against water stress. The implementation of vulnerability assessment ideas will be accomplished by (a) incorporating drought risk into development and land use plans; (b) developing effective water distribution and conservation plans; and (c) implementing emergency response policies and enhancing community preparedness. An effective *Urban Drought Vulnerability Assessment* supports proactive and sustainable management of urban water resources, reducing risks to people, the economy, and the environment.

8. Urban Drought Mitigation Strategies

Mitigating urban drought involves a combination of proactive planning, efficient water management, infrastructure development, community engagement, and environmental conservation. To find out the feasible solution to drought, the demand for water for a particular community in a particular area for a certain period of time has to be estimated. The data should be corroborated by the probable and possible resources available in the area, which can be freely accessed by the said community during that period. To determine the available resources and assess the severity of the situation, we must evaluate the potential water supply from natural sources, including surface water and groundwater. This information should guide the response level and the measures needed to mitigate the drought's impact on the community and the system. Therefore, careful observation of groundwater levels, well pump performance, and monitoring of surface streamflow should be carried out.

Water demand can be estimated by considering the number of regular users within a population and analysing data on the community's monthly and annual water consumption. From the understanding of community level, impact minimisation with the help of reduction on demand and appropriate supply augmentation is very important.

To improve the supply of water, both short-term and long-term measures can be taken care of. To increase the supply of water, wells may be deepened; finding out new sources or developing a new water supply are the options for the supply augmentation. Reducing water pressure in the supply line to the existing municipal and irrigation supply, the same amount of water can be distributed to a greater pool of consumers. The water supply system should be equipped for the use of reclaimed water to address certain future water needs. Educating people on water conservation can create awareness that reduces the stress, anger and water-conflict during drought season. For the long-term benefit, a drought contingency plan can be adopted and a water conservation programme can be implemented with the help of a health-engineering report and long-term water usage plan.

A rationing system that limits the amount of water each consumer can use (say, 500 litres per person per day (L/p/d)) could be implemented, along with an "excess use charge" for those exceeding the set limit. Revenues earned in this way can be utilised to improve the water supply. This approach would not only reduce the strain on the municipal water supply (MWS) but also minimise wastewater generation, benefiting the urban sewerage system. However, setting appropriate water usage limits is crucial and depends on factors such as the situation, demand and supply of water. According to the UN Refugee Agency's Annual Report 2021 (UNHCR, 2022), a standard minimum provision is 20 litres per person per day (L/p/d), with a minimum threshold of 15 L/p/d even in emergencies. The World Health Organization (WHO) recommends a supply of water between 50 and 100 L/p/d to ensure the basic needs of a citizen (UNW-DPAC, 2010). In India, the Ministry of Housing and Urban Affairs has proposed 135 L/p/d as the standard for urban water supply, while the Jal Jeevan Mission sets a minimum supply of 55 L/p/d for rural areas (PIB, 2020). Efforts should focus on maintaining enhanced levels of domestic water supply above these minimum recommended values.

Imposing use-restrictions on certain gadgets and appliances can play a vital role in water conservation in connection to drought management. A ban on using water hoses and sprinklers, washing cars, fitting fountains and establishing swimming pools is an effective method to save water during dry seasons of arid regions. Watering in the garden on either odd or even days may save a certain amount of water. Restricting new water connections and encouraging hotels and guesthouses to avoid daily washing of linens and bedsheets can help to conserve water.

As hydrogeological problems create urban drought, efficient water management is the best way to overcome the situation. The effective solution involves three different strategies, such as: (a) Finding new sources of water that provide the excess demand for water in a growing urban setup; (b) developing a smart and efficient distribution with minimum wastage; and (c) encouraging people to install water-saving gadgets in households (such as low-flow faucets or water-saving toilets) and water-efficient machinery in industry and business houses. As already discussed, water-leakage problems in old cities of India and abroad (e.g. North Kolkata) are acute. An alternative approach or laying completely new pipelines might be helpful. The approach is not cost-effective and the delay to adopt this approach is obvious. Leakage and wastage from the consumer end can be possible with the help of water metering and multi-tier pricing schemes. Installing smart meters to regulate and monitor water provides efficiency in water use. Implementing tiered pricing and enforcing more levies from excess water use might discourage people from additional use of water in swimming pools, bathtubs and other luxuries.

Developing alternative water sources is another effective approach. Apart from sourcing additional water, saving water through water recycling and rainwater harvesting (RWH), reduces the stress on the distribution line. Community-level system can be developed to collect clean rainwater from rooftops for future use or groundwater recharge. The *'3-R'* principle of 'reuse, reduce and recycle' can be adopted to save water. The most effective way to manage water in urban communities includes: Reusing wastewater from one process in a different application. For instance, recycled water can be utilised for non-potable purposes such as gardening, toilet flushing, or industrial use. When wastewater from a process is reused for the same process, it is referred to as "recycling". For example, water used as a coolant in heat-generating industries can be reused multiple times after being treated with an efficient radiator. Reducing water usage at the point of consumption can be achieved with smart appliances, such as ultra-low-flow toilets (ULFT), that use less water for specific tasks (Gleick 2003). Rainwater harvesting is becoming popular and is considered as one of the major components of smart cities. Big cities and towns all over India are now placing the system in new constructions (Raghavan 2005, Patki 2011, Mitra & Banerji 2018, CPWD, 2019). In India, RWH is not an eventual solution, as eighty percent of the rainfall in India is restricted within the four months of the monsoon period. Apart from RWH, low-cost water treatment plants can be commissioned in the riverside towns to procure additional water from nearby streams. Additional water would be sourced after developing desalination plants to convert seawater into freshwater, particularly for coastal cities.

Water storage facilities in urban localities are a big problem. These large reservoirs may be natural or artificial and can store either surplus monsoon water or it may dam a river. The major problem is the challenge related to the management of the reservoir, especially during the less rainy years as it happened in Chennai in 2019, which is discussed later in this discussion. Excess drawdown from groundwater can be replenished by Managed Groundwater Recharge (MAR), in which excess and wastewater water is sent to a recharge pond or spread over a recharge bed for ground absorption. The technology is simple but effective. With maximising the storage, MAR also enhances water quality, hydraulic gradient, and river base-flows (Murray 2025, Maxwell et al. 2019). However, floodwater from the rainy season can have a negative impact on MAR systems, as it leads to clogging of the infiltration bed, thereby reducing the infiltration rate into the aquifer (Ward et al., 2020). Aquifer Storage and Recovery (ASR) is another water management strategy where surplus water is injected into an aquifer during periods of abundant supply and later retrieved for use when demand is high. This method essentially functions as an underground water reservoir, allowing for water extraction during droughts or peak usage periods while utilising the same well for both injection and withdrawal. According to a report by the International Groundwater Resources Assessment Centre (IGRAC) in Delft, Netherlands, over 1,200 MAR projects are successfully operating across 62 countries. Groundwater recharge through such water management systems is a widely adopted practice in various cities and towns in Southern California and Arizona (Gies 2022). Uncontrolled aquifer recharge in urban areas can occasionally lead to basement flooding due to an excess rise of the water table above the basement level (Ward et al., 2020).

Urban planning and designing is very crucial for drought mitigation. The construction of green roofs, parks and wetlands can improve infiltration and reduce surface runoff and thus, helps to reduce intermittent flooding and drainage problems. To enhance the infiltration, permeable surfaces should be replaced with asphalt and concrete by permeable materials. Perforated precast concrete slab might be one of the beneficial options. Roadside artificial recharge points can effectively capture and replenish significant amounts of water from metal road runoff. Implementing zoning regulations is essential to control urban sprawl and protect water-sensitive areas.

The water table in near-surface aquifers sometimes rises to ground level due to excess recharge, leading to wetland conditions in low-lying slum areas, especially during the rainy season. On the other hand, excessive groundwater extraction by water vendors and soft drink manufacturers from specific locations results in local depletion. These issues can be addressed through advanced monitoring technologies. Real-time tracking of water levels, consumption, and quality can be achieved using sensors and IoT devices. AI tools, predictive models, and data analysis play a crucial role in forecasting drought conditions and enabling proactive planning. Additionally, weather and soil moisture data can help optimise water usage in public spaces and gardens (Chang & Wang 2013, Zhang et al. 2019, Lo et al. 2020, Amanambu et al. 2022).

As previously discussed, strengthening governance and policy frameworks is essential at this stage. The role of IWRM is crucial, and its principles have already been outlined. By promoting sustainable water use and conservation practices, IWRM ensures that urban areas have sufficient water supplies even during periods of drought. This approach ensures a balance between water supply and demand, making cities more resilient to drought conditions (GPW 2000 SIWI 2020 GOI 2016). Offering subsidies or tax incentives for adopting drought-resilient technologies and practices helps raise public awareness. In fact, combining drought preparedness plans with policy incentives enhances the success of urban projects while also fostering community awareness and engagement.

Collaboration and partnerships play a crucial role in addressing knowledge gaps and resource constraints. Regional cooperation, such as partnerships with neighbouring areas to share water resources and best practices, enhances cost-effective and efficient water management. A few decades ago, Central and Eastern Europe (CEE) began experiencing increasingly prolonged and severe droughts. In response, countries in the region, including Bulgaria, Romania, Moldova, Slovenia, and Hungary, established the Drought Management Centre for South-Eastern Europe (DMCSEE) in 2006, supported by the WMO and UNCCD, that helps them to solve the socio-economic challenges associated with water shortages, emphasising the urgent need for drought mitigation measures (Bokal et al. 2014). Global Water Partnership (GWP), a UN initiative, is a network of 2800+ water organisations (registered partners) from 180 countries that promotes the effective, efficient, and sustainable management of water resources around the world. The estimated budget for water and sanitation activities (USD) in the network is around 10-20 million USD (UN 2025, GWP 2025). A seminar on regional cooperation for addressing drought-related challenges was organised during the Climate Symposium 2013 of the Asia-Pacific Economic Cooperation (APEC). The event brought together nearly 100 participants from academia and the private and government sectors, who presented research on innovative techniques for seasonal prediction of climate, drought monitoring and risk reduction, and related policymaking (Rhee et al. 2015). Such meetings are highly effective and play a crucial role in developing solutions to drought-related issues.

Allocating sufficient funds for removing water stress in urban areas can be possible through Public-Private Partnerships (PPP), a popular current idea to engage private companies in funding and commissioning water projects. PPP is an arrangement between a private (non-government) entity and a government entity, where services typically provided by the government are instead delivered by the private entity under a set of agreed terms and conditions established at the outset. Governments may lack certain expertise within their workforce, and in the PPP model, the private partner can supply the necessary skills and technology. While the private entity takes on the operational responsibilities, accountability to the public usually remains with the government. PPP in urban drought mitigation is observed in the collaboration between the California Government and different partners from the fields to install, improve and monitor the urban water projects (BACEI 2018). Los Angeles Department of Water and Power's (LADWP) develops partnership projects related to storm-water capture, and wastewater reuse to reduce reliance on external water sources and manage water during drought periods (LADWP 2025). On a practical level, the PPP model has significant potential. However, if the wrong partners are selected or the partnerships are poorly designed, they can end up with the blending of the worst aspects of both the public and private sectors.

In India, public-private partnerships (PPPs) have not gained widespread popularity, primarily because the returns on investments in sectors like urban water supply, sewerage, sanitation, and drainage are often uncertain. Additionally, there is a lack of a strong culture around levying and collecting adequate user charges to even cover the costs of operation and maintenance. However, the Jawaharlal Nehru National Urban Renewal Mission (JNNURM), under the Ministry of Urban Development, recognises PPPs as a key mechanism for the management, development, and financing of urban infrastructure (GOI 2025).

In recent years, Bangalore, India, has been grappling with a water crisis. To address this water-stressed situation, the municipal water supply (MSW) system can be upgraded through the following measures: (a) replacing old distribution pipelines to minimise water loss; (b) forming a dedicated task force for continuous leak detection in the water supply system; (c) implementing water metering to prevent misuse; (d) developing new water supply sources; and (e) establishing agreements with other agencies and providers. To fund these initiatives, adopting a Public-Private Partnership (PPP) model could be a viable approach.

Research and development (R&D) plays a crucial role in driving innovation for drought-resistant technologies and solutions. The UN Convention to Combat Desertification (1994) highlights the importance of R&D in addressing desertification, with a strong focus on scientific and technical collaboration, particularly in meteorology, climatology, and hydrology. This includes efforts to establish networks for data collection, assessment, information sharing, and project monitoring. The solutions identified should cater to the specific needs of local communities, ultimately aiming to enhance the living conditions of those in affected regions (ASIL 1994).

Integrated R&D should also address different aspects of environmental conservation, especially watershed protection, reforestation and urban pollution control. Watershed protection plans restore and conserve upstream watersheds and improve water availability in cities located downstream. Local hydrological conditions can be improved through planting trees along the roadside and wastelands. Pollution control prevents the contamination of existing water sources to maximise their usability.

The convergence of science, culture and religion often leads to indigenous solutions for local challenges, with successful experiences in one region offering sustainable solutions for drought management elsewhere. Across various mythologies, freshwater is represented by different deities. In Hinduism, *Varuna* is the god of water, while *Indra* governs rain, storms, and thunder. In Greek mythology, *Poseidon* rules over the sea, rivers, and earthquakes, whereas *Zeus* is associated with the sky and rain. Similarly, in Roman mythology, *Neptune* is the god of freshwater and the sea. In almost all religions, water holds a divine status. When natural practices like RWH are implemented alongside religious restrictions on water misuse, these initiatives become more effective. Community-based water management succeeds when water is regarded as a sacred resource, and conservation efforts are integrated with cultural rituals and ceremonies that honour water and invoke blessings for rainfall.

The best two examples of the integration of science and religion are Water Temples in Bali, Indonesia and The Pushkar Lake in Rajasthan, India. Bali's Subak irrigation system, a UNESCO-recognised practice, is linked to Hindu water temples, promoting sustainable water management through equitable distribution, preventing overuse, and maintaining groundwater levels, reducing drought risks. Pushkar Lake, sacred in Hinduism, is maintained through rituals and conservation efforts, reducing drought impact in Rajasthan's arid climate.

Some religious occasions are deeply connected to water, promoting both spiritual significance and water conservation efforts. In India, *Kumbh Mela*, celebrated in Prayagraj (Allahabad), Ujjain, Haridwar, and Nashik, witnesses millions taking a holy dip in sacred rivers like the Ganga, Yamuna, and Godavari. This festival is accompanied by large-scale awareness campaigns for river cleaning, pollution control, and sustainable water use before and during the festival. Similarly, *Inti Raymi*, a significant Incan festival celebrated in Peru, Ecuador, Bolivia, and Colombia, includes rituals that honour water sources with indigenous communities actively advocating for sustainable water management in the Andean region. *Nowruz* or the Persian New Year festival, is celebrated in Iran, Central Asia and the Middle East. In some dry regions, Nowruz involves cleaning water sources and irrigation canals, emphasising the sacredness of water. The *Wattah* Festival of San Juan City, Philippines, highlights the importance of water in religious ceremonies and community bonding. The effort to develop bonding between these festivals and the water conservation strategies can bring success to reduce water-stress conditions in highly populated areas. Jal Utsav (India) is one of such festivals with a modern conservation approach. The 15-day festival is organised by NITI Aayog all over India and is intended to raise awareness about water management, conservation, and sustainability. It involves community participation and school students in various water management activities (PIB 2024). Gen Z's young community trusts social media and so-called viral information. Developing popular videos, catchy information on water conservation and management, therefore, turned them into responsible citizens.

March 22 is globally observed as "World Water Day", an initiative established by the United Nations to raise awareness about water-related issues. On this day, governments and NGOs worldwide organise campaigns, cleanup drives, and water management initiatives to promote sustainable water use. Leveraging this significant occasion, a dedicated campaign can be launched to combat urban drought, fostering widespread awareness and collective action.

Finally, it is evident that scarcity of water is the first indicator of drought. So, drought might be controlled by the following measures: (a) collecting information about the source of water, especially finding new sources of groundwater; (b) finding out the total water demand and preparing data and furnishing a table on water-use patterns. (c) An operative ordinance should be issued to restrict water use (or rather misuse) and proper rationing of water would be implemented. (d) Community awareness and education programmes can be adopted to address the problem. The professional bodies, especially schools, colleges and higher learning centres, might be engaged to handle the situation. (e) Finally, policy and decision-making are very crucial in the final blueprint of the solution. A positive approach and effective governance can serve as better drivers for drought mitigation, even when natural resources are limited.

9. Global Scenario of Urban Drought: Some Specific Examples

Some major cities from all over the world came into the limelight in the last few decades because of the acute water crisis around the metropolitan area. Cape Town in South Africa, São Paulo in Brazil, Los Angeles in the USA, Barcelona in Spain and Beijing in China are some notable examples (Zhang et al. 2019, C40 2022, Stolte et al. 2023).

- In Cape Town, severe drought was observed from 2015 to 2018, which reached its acme in the year 2018 when municipal water supply failed and it was declared “Day Zero”. The drought was a result of below-average rainfall for three successive years coupled with poor water management and rising population growth. Restriction was imposed on water use with a maximum of 50 litres per person per day. Two revenue sectors, namely agriculture and tourism, were drastically affected. The reliance on water tankers grew significantly, leading to an increase in regular household expenses. The drought was supposed to be the effect of climate change and thus, long-term planning and preparation is required for mitigation. However, to solve the local demand, temporary desalination plants were installed and a slogan campaign, “Save Like a Local” was introduced. An effort was made to drill additional boreholes to tap into aquifers, but it did not gain the required success (Zhang et al. 2019).

- São Paulo, Brazil, faced a severe drought during 2014-15, with reservoir levels in the Cantareira System dropping below 4%. The crisis was deteriorated by Amazon deforestation, urban expansion, and insufficient investment in water infrastructure. Both industries and households felt the impact – residents experienced intermittent water supply, with some areas receiving water for only a few hours daily, while water-intensive industries faced disruptions. Social unrest and protests were very common during the period due to unequal water distribution. In response, water was urgently diverted from other reservoirs to the Cantareira System, and residents were urged to conserve water. Additionally, rainwater harvesting was promoted for residential and commercial use as a long-term solution (C40 2022).

- Los Angeles has experienced recurring droughts, with significant water scarcity during the California drought of 2011-2017. Climate change, over-reliance on imported water, and inefficient water use contributed to the crisis. As an impact, strain on agriculture in

California's Central Valley, a key food supplier for the U.S., was generated. Wildfires increased due to dry conditions. The area has witnessed a similar wildfire in the month of January 2025 (ET 2025). Mandatory water restrictions had been imposed for residents and commercials. The city installed desalination plants and a large-scale wastewater treatment setup with public-private partnership. The urban authority tried to get rid of this situation through public awareness campaigns, water conservation programs and announcing attractive rebates on water-efficient appliances (Zhang et al. 2019, LADWP, 2025).

- Mexico City witnesses recurring water shortages due to rapid urbanisation, obsolete set-up, and over-extraction of groundwater. The water distribution system with outdated infrastructures suffers from high levels of leakage. Many residents have limited or no access to clean water for days or weeks. Over-exploitation of groundwater leads to significant land subsidence, damaging buildings and infrastructure. Upgrading infrastructure is crucial, but it is a cost-intensive process (Figueroa Vega 1984, Stolte et al. 2023).

- Insufficient rainfall and high water demand were major contributors to the urban drought of the Spanish city of Barcelona. In 2008, Barcelona faced one of its worst droughts, with reservoirs falling below 20% capacity. The problem was so acute that the city imported drinking water by ship from France. Recurring Water Shortages were very common in the city of London in the last decade. The city relies heavily on the River Thames, which is vulnerable to droughts and pollution. Major key issues of Athens in Greece are the water scarcity, particularly during summer months due to low rainfall and over-extraction of water (WB, 2019).

- The Australian city Perth faces water shortages due to a long-term decline in rainfall since the 1970s, leading to a reduction in water supplies from surface water sources. Sydney, the city on the eastern coast of Australia, faced long-term water stress, particularly during the Millennium Drought (1997-2009), which severely affected the region’s water supply (Jones 2017). Both cities are affected by climate change, population growth, and a decline in reservoir inflows. On the other hand, the Chinese city, Beijing, experiences chronic water crisis due to overpopulation, pollution of water sources, and desertification. Here, per capita water availability is significantly below the global water scarcity threshold. China is trying to improve the situation through the South-to-North Water Diversion Project; – a massive project to transfer water from the Yangtze River Basin to northern China (WB, 2019, Zhang et al. 2019).

- The cities like Jakarta, Kuala Lumpur, Ho Chi Minh City and Hong Kong in Southeast Asia need to explore solutions for the urban water crisis. Frequent water shortages due to the depletion of groundwater and rising demand from a fast-growing population are the problems common to the cities of Jakarta in Indonesia, Ho Chi Minh City in Vietnam and Kuala Lumpur in Malaysia. Water scarcity further accentuates in Kuala Lumpur due to shortages during prolonged droughts (such as in 2014), pollution of rivers and over-reliance on surface water. The problem is manifested in Jakarta by land subsidence, whereas saltwater intrusion and pollution of water sources are observed in Ho Chi Minh City. Water shortages during periods of low rainfall, exacerbated by climate change and over-reliance on imports, pose more challenges for Hong Kong. The major problems of this Chinese city are its insufficient local freshwater resources, vulnerability to drought, and inefficient water use. Bangalore, India, has made newspaper headlines in recent years due to groundwater depletion, poor water management, and inadequate infrastructure (C40 2022).

- Another group of metropolises located in the desert areas clearly records a water crisis. Notable examples include Addis Ababa, Ethiopia; Cairo, Egypt; Dubai, UAE; Riyadh, Saudi Arabia; Tehran, Iran; Nairobi, Kenya; and Istanbul, Turkey. Severe water stress due to its arid climate is common to all. Dubai and Riyadh highly depend on the desalination of water, which involves high energy consumption. As a financially struggling nation, Ethiopia faces poor water infrastructure, inefficient distribution, contamination, and excessive groundwater use. In Addis Ababa, frequent droughts and rapid population growth further worsen the issue. The Nile River is called the lifeline of Egypt. Cairo city also depends on the Nile River for water, which is threatened by upstream developments, population growth, and pollution. Climate change and upstream damming in the Nile reduce the water flow to Egypt, along with pollution in the river. Lima, Peru, faces water scarcity due to over-extraction from rivers fed by glaciers, which are rapidly shrinking due to climate change. Over-reliance on water from glaciers and limited local water sources make the town more vulnerable (C40 2022, Peregrina González, E.D., 2022).

- Problems come from depletion of the shallow aquifers and their arsenic contamination in Dhaka, Bangladesh. Karachi (Pakistan) is experiencing water stress as a result of intermittent rainfall, high dependence on groundwater, improper distribution systems and inadequate water supply infrastructure (C40 2022, Peregrina González, E.D., 2022).

10. Urban Drought in Indian Cities

Several Indian cities, such as Bengaluru, Chennai, Hyderabad, Jaipur, Mumbai and Pune, have faced significant urban drought conditions due to rapid urbanisation, poor water management, and climate change. Below are some notable case studies:

Chennai (Tamil Nadu) experienced a severe urban drought in 2019, commonly referred to as "Day Zero," when its four main reservoirs ran almost completely dry. The crisis resulted from delayed and insufficient monsoon rainfall, excessive groundwater extraction, and poor water management. Bengaluru (Karnataka) is popularly known as the "Silicon Valley of India”. It has faced rapid urbanisation in the last few decades due to its strong infrastructure in the IT sector. However, it failed to overcome the reliance on groundwater and to prevent pollution of surface lakes. Insufficient water infrastructure can not cater to the overcrowded metropolis and acute water shortages forced many residents to depend on private water tankers. In 2014 and 2016, Mumbai (Maharashtra) experienced drought-like conditions as the water levels in its reservoirs drastically dropped due to insufficient monsoon rainfall. A similar problem is found in Jaipur, an important city in a semi-arid region of Rajasthan. Hyderabad (Telangana) and Pune (Maharashtra), after Bengaluru, are becoming the next two destinations of IT companies and manufacturing industries. Erratic monsoons and fluoride problems in the granite aquifer are major problems in Hyderabad, whereas Pune faced urban drought conditions in 2016 due to deficient monsoons and over-reliance on the Khadakwasla reservoir (Gaur et al. 2007, Zhang et al. 2019, C40 2022, Peregrina González, E.D., 2022, Bhatia 2024).

The mitigation of water stress is focused on water conservation and efficient usage. In addition to raising public awareness, the major efforts to address the issue include RWH, water audits, water recycling, and sourcing water from alternative sources. Mumbai and Chennai plan to invest in desalination plants. Bengaluru initiated efforts to restore lakes like Bellandur and Varthur. Mission Kakatiya is accepted in Hyderabad as a lake rejuvenation project aimed at improving water storage capacity. Interlinking water projects, such as the diversion of water from the Krishna and Godavari rivers, has been proposed to meet the demand in Hyderabad. Several parts of Mumbai and Pune have implemented water rationing. Bengaluru and Hyderabad deploy private water tankers to offset the water shortage (Srinivasan 2019, Zhang et al. 2019, Bhatia 2024).

A significant number of other Indian cities have recently experienced water crisis, particularly as a result of rapid urbanisation. Some other factors also increase problems. The list incorporates Delhi; Chandigarh; Ahmedabad and Surat (Gujarat); Jodhpur (Rajasthan); Lucknow, Kanpur and Varanasi (Uttar Pradesh); Nagpur (Maharashtra); Indore and Bhopal (Madhya Pradesh); Raipur (Chhattisgarh); Coimbatore (Tamil Nadu); Kolkata (West Bengal); Bhubaneswar (Odisha); Visakhapatnam (Andhra Pradesh); Kochi and Thiruvananthapuram (Kerala) and Mysuru (Karnataka). High reliance on the contaminated Ganges River creates problems for the cities of Uttar Pradesh. Excess drawdown from aquifers, reliance on local rivers and seasonal reservoirs, unequal distribution of water, inadequate water conservation measures, water pollution and poor water recycling; – all are responsible for the urban drought of Indian cities (Srinivasan 2019, Stolte et al. 2023, Bhatia 2024).

11. Future Trend of Urban Water Management

As populations in urban areas continue to grow, the demand for water will escalate, and water systems will face increased pressure. To meet this demand and ensure the sustainability of urban water resources, it is crucial to rethink and innovate how water is managed in cities. Here are key trends and strategies that will define the future of urban water management:

A. Integrated Water Management Systems: *Integrated Urban Water Management* (IUWM) should be introduced in the modern cities, which combine the management of all water sources – rainwater, groundwater, surface water, and wastewater – within a single framework.
B. Water use must be optimised through *Smart Water Grids*, which incorporate smart sensors, real-time data collection, and AI-driven analysis into urban water distribution networks for the prevention of wastage and leakage from distribution systems.
C. To prevent contamination and to ensure better public health, *Water Quality Monitoring* should be carried out using sensors and IoT.
D. Water Recycling and Reuse: Households and businesses will increasingly adopt technologies that allow for the recycling of greywater (from sinks, showers, and washing

machines) for non-potable uses such as irrigation, toilet flushing, and industrial processes. To prevent pollution and contamination, industrial wastewater should be treated properly before sending it to the local water bodies, such as lakes and rivers.

E. Global warming and climate change are becoming the major issues nowadays. Along with drought resilience, the urban systems should be equipped with flood protection and storm-surge management.
F. Present urban water management systems are usually constructed with one or two central pumping stations and treatment plants. Decentralised water systems with RWH and community-based water systems should be the eventual solution to the urban water crisis of the near future.
G. *Nature-Based Solutions* will become an important aspect of urban water management. Constructed or restored wetlands can provide natural filtration, help manage stormwater, and support local wildlife. They also offer recreational space for residents and improve air and water quality.
H. Trees and vegetation in cities can help absorb excess rainwater, reduce surface runoff, and provide cooling effects in hot urban environments. Green spaces will be integrated into urban water management systems to help mitigate the impacts of floods and droughts.
I. Governments and organisations will increasingly invest in public education campaigns to encourage water conservation at the individual, household, and business levels.
J. Water Pricing and Incentives: Cities may implement tiered pricing or introduce incentives to promote water-saving practices and discourage overconsumption.
K. Digitalisation and data-driven decision-making should be incorporated in the water sector, which will be done by incorporating data analytics, machine learning, and artificial intelligence (AI) into the system. Predictive analytics and handling "Big Data" are the other two most effective technologies for tracking usage patterns and developing strategies to improve water management.
L. Ensuring fair and inclusive access to water for all residents, especially marginalised and vulnerable communities, contributes to a smarter water system. Embracing concepts like ‘zero waste water systems’ and ‘treating water as a valuable resource’ can play a crucial role in preventing extreme urban drought.
M. Lastly, given the global scale of water challenges, the future will see increased international collaboration to combat water scarcity, exchange best practices, and implement joint solutions. Local policies must align with global frameworks such as the Sustainable Development Goals (SDGs), particularly Goal 6 (Clean Water and Sanitation).

12. Conclusion

Urban drought is a problem interlinked with water security, economic infrastructure, public health and the betterment of the environment. A proactive integrated approach incorporating factors such as scientific water management, a good distribution network, water conservation, rooftop rainwater harvesting, building resilience; – all these can help us to understand and eliminate urban drought.

REFERENCE

[01] ADO, 2025. SPI: Standardised Precipitation Index. Alpine Drought Observatory. Available at: https://raw.githubusercontent.com/Eurac-Research/ado-data/main/factsheets/SPI_4.pdf. [Accessed on 22 Jan. 2025].

[02] Alftine, K.J., Malanson, G.P., & Fagre, D.B., 2003. Feedback-driven responses to multidecadal climatic variability at an alpine treeline. *Physical Geography,* 24, pp.520–535.

[03] Ali, M.I., Hasim, A.H., and & Abidin, M.R., 2019. Monitoring the built-up area transformation using Urban Index and Normalized Difference Built-up Index analysis. *International Journal of Engineering (IJE), IJE Transactions B: Applications*, 32(5), pp.647-653.

[04] Amanambu, A.C., Mossa, J., & Chen, Y.-H., 2022. 'Hydrological drought forecasting using a deep transformer model', *Water*, 14(3611), pp:1–19. DOI: 10.3390/w14223611.

[05] ASIL, 1994. *United Nations: Convention to Combat Desertification in Those Countries Experiencing Serious Drought and/or Desertification, Particularly in Africa*. International Legal Materials, 33(5), pp. 1328-1382. American Society of International Law. Available at: http://www.jstor.org/stable/20698382 [Accessed on January 22, 2025].

[06] BACEI, 2018. Public-Private Partnerships in California, 2018. Bay Area Council Economic Institute, San Francisco, CA. 52p. Available at: https://www.bayareaeconomy.org/files/pdf/P3inCaliforniaWeb.pdf [Accessed on 07 Jan. 2025]

[07] Bhatia B, 2024. India Cities That Will Face Water Shortage in the Near Future, Last Updated: May 29, 2024. Available at: https://flotaa.com/indian-cities-facing-water-shortage-in-the-near-future/. [Accessed on January 22, 2025].

[08] Biswas, A.K., 2004. Integrated water resources management: A reassessment – A water forum contribution. *Water International*, 29(2), June 2004, pp.248-256.

[09] Bokal, S., Grobicki, A., Kindler, J., & Thalmeinerova, D. 2014. From national to regional plans – the Integrated Drought Management Programme of the Global Water Partnership for Central and Eastern Europe. *Weather and Climate Extremes*, 3, pp. 37–46. doi:10.1016/j.wace.2014.03.006

[10] C40, 2022. Water Safe Cities – Technical Report, June 2022. *C40 Cities Climate Leadership Group, Inc*. 27p. Available at: https://www.c40.org/water-safe-cities/ [Accessed on January 22, 2025].

[11] Chang, Y.-C. & Tseng, K.-H., 2025. Measuring surface subsidence in Taipei, Taiwan with Sentinel-1 data using PS-InSAR. *Proceedings of SPIE*, 13263, Land Surface and Cryosphere Remote Sensing V, 1326308. DOI: 10.1117/12.3045967 [Accessed on 5 January 2025].

[12] Chang, F.-J., & Wang, K.-W., 2013. A systematical water allocation scheme for drought mitigation. *Journal of Hydrology, 507, 124–133.* doi:10.1016/j.jhydrol.2013.10

[13] Christenson, M., Manz, H. and Gyalistras, D., 2006. Climate warming impact on degree-days and building energy demand in Switzerland. *Energy Conversion and Management*, 47, pp. 671–686.

[14] CPWD, 2019. Rainwater Harvesting & Conservation Manual 2019. *Central Public Works Department (CPWD)*, Ministry of Housing and Urban Affairs, New Delhi, 77p.

[15] DHHS-NS, 2024. Social Vulnerability Index: An Emergency Response Tool. *The New Hampshire Department of Health and Human Services (DHHS); New Hampshire State Government*. Available at: https://www.dhhs.nh.gov/sites/g/files/ehbemt476/files/inline-documents/sonh/svi-factsheet-2024.pdf [Accessed on 22 Jan. 2025].

[16] Duan, W., He, B., Nover, D., Fan, J., Yang, G., Chen, W., Meng, H., & Liu, C., 2016. Floods and associated socioeconomic damages in China over the last century. Natural Hazards, 82, pp. 401–413.

[17] EDO, 2018. Low-Flow Index (LFI): EDO Indicator Factsheet. Copernicus European Drought Observatory (EDO). pp. 1-5 Available at: https://drought.emergency.copernicus.eu/data/factsheets/factsheet_spi.pdf. [Accessed on January 22, 2025]

[18] EDO, 2020. Standardized Precipitation Index (SPI): EDO Indicator Factsheet. Copernicus European Drought Observatory (EDO). pp. 1-6 Available at: https://drought.emergency.copernicus.eu/data/factsheets/factsheet_lowflowindex.pdf. [Accessed on January 22, 2025]

[19] EPA, 2025. Technical Documentation: Heating and Cooling Degree Days. U.S. Environmental Protection Agency. Available at: https://www.epa.gov/sites/default/files/2021-03/documents/heating-cooling_td.pdf. [Accessed on January 22, 2025]

[20] ET 2025. How Los Angeles ran out of water amid devastating wildfires. The Economic Times, Last Updated: Jan 09, 2025, Available at: https://economictimes.indiatimes.com/news/international/global-trends/how-los-angeles-ran-out-of-water-amid-devastating-wildfires/articleshow/117073374.cms [Accessed on January 22, 2025].

[21] Faunt, C.C., Sneed, M., Traum, J., & Brandt, T.J., 2016. Water availability and ground subsidence in the Central Valley, California, USA. *Hydrogeology Journal*, 24, pp. 675–684. DOI: 10.1007/s10040-015-1339-x.

[22] Figueroa Vega, G.E., 1984. Case history No. 9.8: Mexico, D.F., Mexico. In: Poland, J.F. (ed.) *Guidebook to studies of land subsidence due to ground-water withdrawal*. Studies and Reports in Hydrology 40, prepared for the International Hydrological Programme, Working Group 8.4, UNESCO, Paris, France, pp. 217–232.

[23] Fraisse, C.W. and Paula-Moraes, S., 2007. Degree-Days: Growing, Heating, and Cooling. *Department of Agricultural and Biological Engineering, UF/IFAS Extension*, University of Florida. Original publication date: July 2007. Revised December 2010 and April 2018. Available at: https://edis.ifas.ufl.edu/publication/AE428 [Accessed on 22 Jan. 2025].

[24] Frölicher, T.L., Fischer, E.M. and Gruber, N., 2018. Marine heatwaves under global warming. *Nature*, 560(7718), pp. 360–364. DOI: 10.1038/s41586-018-0383-9.

[25] Gadgil, S., Vinayachandran, P.N., Francis, P.A., & Gadgil, S., 2004. Extremes of the Indian summer monsoon rainfall, ENSO, and equatorial Indian Ocean oscillation. *Geophysical Research Letters,* 31, L12213. doi:10.1029/2004GL019733.

[26] Gaur, A., McCornick, P.G., Turral, H. and Acharya, S., 2007. Implications of drought and water regulation in the Krishna Basin, India. *International Journal of Water Resources Development*, 23(4), pp.583-594. doi: 10.1080/07900620701488513

[27] Gies, E., 2022. *Water Always Wins: Thriving in an Age of Drought and Deluge.* The University of Chicago Press, Chicago. ISBN 978-0-226-71960-3 (cloth); ISBN 978-0-226-71974-0 (e-book). DOI: 10.7208/chicago/9780226719740.001.0001.

[28] Gleick, P.H., 2003. *Waste Not, Want Not: The Potential for Urban Water Conservation in California*. Oakland, CA: Pacific Institute for Studies in Development, Environment, and Security. 165p. ISBN 1-893790-09-6.

[29] GOI, 2016. Guidelines for Integrated Water Resources Development and Management. Government of India. Ministry of Water Resources; River Development and Ganga Rejuvenation; and Central Water Commission Basin Planning and Management Organization, New Delhi. 2016, 30p.

[30] GOI, 2025. Note on PPP in Urban sector. Ministry of Housing & Urban Affairs, Government of India. Available at: https://mohua.gov.in/upload/uploadfiles/files/Note%20on%20PPP%20in%20Urban&%20sector04.pdf [Accessed on 22 Jan. 2025].

[31] Garcìa, R., Prieto, L., Dìaz, J., Hernàndez, E. and del Teso, T., 2002. Synoptic conditions leading to extremely high temperatures in Madrid. *Annales Geophysicae*, 20, pp. 237–245. European Geophysical Society.

[32] Goswami, B.N., Madhusoodanan, M.S., Neema, C.P., & Sengupta, D., 2006. A physical mechanism for North Atlantic SST influence on the Indian summer monsoon. *Geophysical Research Letters,* 33, L02706. doi:10.1029/2005GL024803.

[33] GWP. 2000. Integrated Water Resources Management. TAC Background Paper No. 4. Global Water Partnership, Stockholm.

[34] GWP, 2025. Homepage: Global Water Partnership, Stockholm. Available at: https://www.gwp.org/ [Accessed on 22 Jan. 2025]

[35] Halpert, M.S., & Ropelewski, C.F., 1992. Surface temperature patterns associated with the Southern Oscillation. *Journal of Climate,* 5(6), pp.577–593.

[36] IMD, 2025. FAQ on Heat Wave. India Meteorological Department; 16p. Available at: https://internal.imd.gov.in/section/nhac/dynamic/FAQ_heat_wave.pdf. [Accessed on January 07, 2025]

[37] IPCC, 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation*. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

[38] IPCC, 2014. 'Summary for policymakers', in Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. and White, L.L. (eds.) *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press, pp. 1-32.

[39] Jones, R. 2017. Slow Catastrophes: Living with Drought in Australia. Monash University Publishing, Clayton, Victoria, Australia, 403p. ISBN: 978-1-925495-43-0 (paperback)

[40] Kaly, U., Briguglio, L., McLeod, H., Schmall, S., Pratt, C. & Pal, R., 2004. Environmental Vulnerability Index (EVI) to summarize national environmental vulnerability profiles. *SOPAC Technical Report*, 275.

[41] Karanam, H.K., 2018. Study of Normalized Difference Built-Up (NDBI) Index in automatically mapping urban areas from Landsat TM imagery. *International Journal of Scientific Research and Review*, 7(1), pp.1-8. Available at: https://www.researchgate.net/publication/339230287. [Accessed on January 22, 2025].

[42] Karl, T.R., Nicholls, N. and Ghazi, A., 1999. Clivar/GCOS/WMO workshop on indices and indicators for climate extremes: Workshop summary. In: *Weather and Climate Extremes*. Dordrecht: Springer, pp. 3–7. DOI: 10.1007/978-94-015-9265-9_2.

[43] Kartika, F.D. and Wijayanti, P., 2023. Drought disaster modeling using drought index: A systematic literature review. *ICOAGPG-2022, IOP Conference Series: Earth and Environmental Science*, 1190(1), pp. 1–10. DOI: 10.1088/1755-1315/1190/1/012026.

[44] Kiladis, G.N., & Díaz, H.F., 1989. Global climatic anomalies associated with extremes in the Southern Oscillation. *Journal of Climate,* 2, pp.1069–1090.

[45] Kovats, R.S., Bouma, M.J., Hajat, S., Worrall, E., & Haines, A., 2003. El Niño and health. The Lancet, 362(9394), pp. 1481–1489. DOI: 10.1016/S0140-6736(03)14695-8.

[46] Krishnan, R., & Sugi, M., 2003. Pacific decadal oscillation and variability of the Indian summer monsoon rainfall. *Climate Dynamics,* 21, pp.233–242.

[47] Krishna Kumar, K.B., Rajagopalan, B., & Cane, M.A., 1999. On the weakening relationship between the Indian monsoon and ENSO. *Science,* 284, pp.2156–2159.

[48] Kumar, K.K., Rajagopalan, B., Hoerling, M., Bates, G., & Cane, M., 2006. Unravelling the mystery of Indian monsoon failure during El Niño. *Science,* 314, pp.115–119.

[49] LADWP, 2025. Los Angeles Department of Water and Power. Available at: https://www.ladwp.com/ [Accessed on January 22, 2025].

[50] Linhares, D.P.S., Garcia, P.V., & Rodrigues, A.d.S., 2020. Fluoride in volcanic areas: A case study in medical geology. *Environmental Health - Management and Prevention Practices*. IntechOpen. DOI: 10.5772/intechopen.86058 [Accessed on January 07, 2025].

[51] Lo, H.-C., Hsu, S.-M., Chou, P.-Y., & Ke, C.-C. 2020. 'Mitigating drought and landslide simultaneously for mountain tribes of Taiwan: hydrogeological investigation, modelling, and development of an intelligent hazard prevention system', Natural Hazards. DOI: 10.1007/s11069-020-04121-6.

[52] Logar, I. & van den Bergh, J.C.J.M., 2013. Methods to assess costs of drought damages and policies for drought mitigation and adaptation: review and recommendations. *Water Resources Management*, 27, pp. 1707–1720. DOI: 10.1007/s11269-012-0119-9.

[53] Marsalek, J., Jiménez-Cisneros, B.E., Malmquist, P.-A., Karamouz, M., Goldenfum, J., & Chocat, B., 2006. Urban water cycle processes and interactions. IHP-VI Technical Documents in Hydrology No. 78. The International Hydrological Programme (IHP), United Nations Educational, Scientific and Cultural Organization (UNESCO), Paris, pp. 1-87.

[54] Machairas, I. & van de Ven, F.H.M., 2023. An urban drought categorization framework and the vulnerability of a lowland city to groundwater urban droughts. *Natural Hazards*, 116, pp. 1403–1431. DOI: 10.1007/s11069-022-05767-0.

[55] Mathlouthi, M. and Lebdi, F., 2021. Comprehensive study of the wet and dry spells and their extremes in the Mediterranean climate basin, Northern Tunisia. *SN Applied Sciences*, 3:850. DOI: 10.1007/s42452-021-04834-8.

[56] Maxwell, C.M., Langarudi, S.P. and Fernald, A.G., 2019. Simulating a watershed-scale strategy to mitigate drought, flooding, and sediment transport in drylands. *Systems*, 7(4), 53, pp. 1–33. DOI: 10.3390/systems7040053.

[57] McNabb, D.E. & Swenson, C.R., 2023. *Water Crises in the West.* In: McNabb, D.E. & Swenson, C.R. (eds.) *America's Water Crises: The Impact of Drought and Climate Change.* Palgrave Macmillan, pp. 179-201. ISBN 978-3-031-27379-7; eBook ISBN 978-3-031-27380-3. DOI: 10.1007/978-3-031-27380-3_9.

[58] McPhaden, M.J., Zebiak, S.E., & Glantz, M.H., 2006. ENSO as a unifying concept in Earth science. *Science,* 314, pp.1740–1745.

[59] Mishra, A.K. & Singh, V.P., 2011. Drought modeling – A review. *Journal of Hydrology*, 403, pp.157–175.

[60] Mitra, D. & Banerji, S., 2018. Urbanisation and changing waterscapes: A case study of New Town, Kolkata, West Bengal, India. *Applied Geography*, 97, pp.109–118. DOI: 10.1016/j.apgeog.2018.04.012.

[61] Murray, K. (2021) 'What is Managed Aquifer Recharge (MAR) and How Does it Work?', *Groundwater and Earth Sciences (GEOSS), South Africa (Pty.) Ltd.* Posted on 8 February 2021 under Interesting Groundwater Topics, Knowledge Hub. Available at: https://geoss.co.za/what-is-managed-aquifer-recharge-mar-and-how-does-it-work/ [Accessed on 22 Jan. 2025].

[62] Nagarajan, R., 2009. *Drought Assessment.* Springer, Dordrecht, and Capital Publishing Company, New Delhi. 429p. ISBN 978-90-481-2499-2 (HB); ISBN 978-90-481-2500-5 (e-book).

[63] Narvaez, L., Janzen, S., Eberle, C., & Sebesvari, Z., 2021/2022. Taiwan drought: Technical report. United Nations University (UNU-EHS), 23p. DOI: 10.53324/UJZW5639. e-ISBN: 978-3-944535-78-4. e-ISSN: 2304-0467.

[64] Parrone, D., Ghergo, S., Frollini, E., Rossi, D. & Preziosi, E., 2018. Arsenic-fluoride co-contamination in groundwater: background and anomalies in a volcanic-sedimentary aquifer in central Italy. *Journal of Geochemical Exploration*. Available at: 10.1016/j.gexplo.2020.106590 [Accessed on January 07, 2025].

[65] Patki, P., 2011. Rainwater harvesting in urban areas. International Conference on Healthy Cities – Perspectives on Asian Concerns, Pune. Available at: https://www.researchgate.net/publication/376601197_Rain_Water_Harvesting_in_Urban_Areas [Accessed on 22 Jan. 2025].

[66] Perkins, S.E., 2015. A review on the scientific understanding of heatwaves – their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research*, 164, pp. 242–267. DOI: 10.1016/j.atmosres.2015.05.014.

[67] Perkins, S.E. and Alexander, L.V., 2012. On the measurement of heatwaves. Journal of Climate, 25, pp. 4500–4517.

[68] Peterson, T., Folland, C., Gruza, G., Hogg, W., Mokssit, A. and Plummer, N., 2001. Report on the Activities of the Working Group on Climate Change Detection and Related Rapporteurs. Geneva, Switzerland: World Meteorological Organization.

[69] Philander, S.G., & Fedorov, A., 2003. Is El Niño sporadic or cyclic? *Annual Review of Earth and Planetary Sciences,* 31, pp.579–594.

[70] PIB, 2024. 15 Days Jal Utsav Begins Tomorrow: A Celebration of Water by NITI Aayog in Partnership With DDWS, Jal Shakti. NITI Aayog, Press Information Bureau, Delhi, Government of India. Posted on: 05 NOV 2024

[71] PIB 2020: Per Capita Availability of Water. (Press Release: Press Information Bureau, Delhi) Ministry of Jal Shakti, Government of India. Release ID: 1604871 Posted On: 02 MAR 2020. Available at: https://pib.gov.in/PressReleasePage.aspx?PRID=1604871 [Accessed on 22 Jan. 2025].

[72] Peregrina González, E.D., 2022. Urban drought hazard assessment using global open data and water balance model. *Master's Thesis, Master Water Science and Management*. Utrecht: Universiteit Utrecht, July 2022, p.71.

[73] Raghavan, S., 2005. Rainwater harvesting in India with special reference to urban areas and the Chennai experience. Paper presented at the *Tokyo Asia Pacific Sky Water Forum*, Sumida City, Tokyo, 1–7 August 2005. Available at: https://www.raincentre.net/downloads/pdf/RAIN_HARVESTIN_1.pdf [Accessed on 22 Jan. 2025].

[74] Rawls, W.J., Ahuja, L.R., Brakensiek, D.L., & Shirmohammadi, A., 1993. Infiltration and soil water movement. In: Maidment, D.R. (ed.) *Handbook of hydrology*. McGraw-Hill, New York, Chapter 5.

[75] Rhee, J., Cai, W., Plummer, N., Sivakumar, M., Horstmann, N., Wang, B. and Kirono, D., 2015. Regional cooperation on drought prediction science for disaster preparedness and management. *Bulletin of the American Meteorological Society*, 96(4), pp. ES68–ES70. DOI: 10.1175/BAMS-D-14-00049.1.

[76] Ritchie, H., Samborska, V. and Roser, M., 2024. Urbanization, *Our World in Data*, first published in September 2018, and last revised in February 2024. Available at: https://ourworldindata.org/urbanization [Accessed on 22 Jan. 2025].

[77] Saji, N.H., Goswami, B.N., Vinayachandran, P.N., & Yamagata, T., 1999. A dipole mode in the tropical Indian Ocean. *Nature,* 401, pp.360–363.

[78] Scott, G., 2022. Cooling Degree Day (CDD): How to Calculate Energy Demand. *Investopedia*. Updated 29 May 2022. Available at: https://www.investopedia.com/terms/c/colddegreeday.asp [Accessed on 22 Jan. 2025].

[79] SEDAC, 2023. Documentation for the U.S. Social Vulnerability Index Grids, Revision 01. *NASA Socioeconomic Data and Applications Center (SEDAC)* Documentation for the U.S. Social Vulnerability Index Grids, v1.01 (2000, 2010, 2014, 2016, 2018, 2020) Date of revised publication: November 2023 through Center for International Earth Science Information Network (CIESIN), Columbia University. Pp.1-11. Available at: https://sedac.ciesin.columbia.edu/downloads/docs/usgrid/usgrid-us-social-vulnerability-index-rev01-documentation.pdf [Accessed on 22 Jan. 2025].

[80] Selvanathan, S.P. and Migdalska, J., 2015. Cooling degree day analysis as a climate impact indicator for different locations of Poland and India. *International Journal of Advances in Science Engineering and Technology*, Special Issue-4, October, ISSN: 2321-9009, pp. 43–51.

[81] Şen, Z., 2015. Applied Drought Modeling, Prediction, and Mitigation, Elsevier, Amsterdam, 472p.

[82] Shukla, S. and Wood, A.W., 2008. Use of a standardized runoff index for characterizing hydrologic drought. *Geophysical Research Letters*, 35, L02405, pp. 1–7. DOI: 10.1029/2007GL032487.

[83] Simeone, C., Foks, S., Towler, E., Hodson, T. & Over, T., 2024. Evaluating hydrologic model performance for characterizing streamflow drought in the conterminous United States. *Water*, 16, p.2996, pp.1–22. DOI: 10.3390/w16202996.

[84] Singh, S., & Sharma, V.K., 2019. Urban droughts in India: case study of Delhi. In: B. Ray & R. Shaw, eds. *Urban Drought: Emerging Water Challenges in Asia.* Singapore: Springer Nature, pp. 155–167. DOI: 10.1007/978-981-10-8947-3_10. ISBN 978-981-10-8946-6 ISBN 978-981-10-8947-3 (eBook)

[85] SIWI, 2020. MANUAL 1: Principles and Practices of Integrated Water Resources Management (Workplace-based Professional Training). Stockholm International Water Institute (SIWI), Stockholm, 23p. Available at: https://siwi.org/wp-content/uploads/2020/06/IWRM_Manual1_final.pdf [Accessed on 22 Jan. 2025].

[86] Srinivasan V., 2019. Water is getting scarce in India, but not for everyone. *India Development Review*. Posted on: August 16, 2019. Available at: https://idronline.org/water-is-getting-scarce-in-india-but-not-for-everyone/. [Accessed on January 22, 2025].

[87] Stolte, T.R., de Moel, H., Koks, E.E., Kwens, M.L., van Veldhoven, F., Garg, S., Farhad, N. and Ward, P.J., 2023. Global drought risk in cities: present and future urban hotspots. *Environmental Research Communications*, 5, 115008. [Online] DOI: 10.1088/2515-7620/ad0210.

[88] Szalińska, W., Otop, I. and Tokarczyk, T., 2018. Urban drought. *E3S Web of Conferences*, 45, 00095: INFRAEKO 2018, pp. 1–8. DOI: 10.1051/e3sconf/20184500095.

[89] TEPHI, 2021. Social Vulnerability Index (SVI) – Texas. *Texas Epidemic Public Health Institute (TEPHI) Vulnerable Populations*, pp.1-11. Available at: https://tephi.texas.gov/docs/tephi-social-vulnerability-index-report-texas.pdf [Accessed on 22 Jan. 2025].

[90] Trenberth, K.E., 1997. The definition of El Niño. *Bulletin of the American Meteorological Society,* 78, pp.2771–3277.

[91] UD, 2023. Urban Development, *World Bank Group*, Last Updated: Apr 03,2023. Available at: https://www.worldbank.org/en/topic/urbandevelopment/overview [Accessed on 22 Jan. 2025].

[92] UN, 2025. Global Water Partnership (GWP) United Nations. Available at: https://www.unwater.org/about-un-water/members-and-partners/global-water-partnership-gwp. [Accessed on 22 Jan. 2025].

[93] UNHCR, 2022. Annual Report 2021 on Water, Sanitation and Hygiene. *United Nations High Commissioner for Refugees (UNHCR)*.

[94] UNW-DPAC, 2010. The Human Right to Water and Sanitation Media brief. *UN-Water Decade Programme on Advocacy and Communication (UNW-DPAC) and Water Supply and Sanitation Collaborative Council (WSSCC)*. Available at: https://www.un.org/waterforlifedecade/pdf/human_right_to_water_and_sanitation_media_brief.pdf [Accessed on 22 Jan. 2025].

[95] Vinayachandran, P.N., Francis, P.A., & Rao, S.A., 2009. Indian Ocean dipole: Processes and impacts. *Current Trends in Science,* pp.569–589.

[96] Ward, P.J., de Ruiter, M.C., Mård, J., Schroter, K., Van Loon, A., Veldkamp, T., von Uexkull, N., Wanders, N., AghaKouchak, A., Arnbjerg-Nielsen, K., Capewell, L., Llasat, M.C., Day, R., Dewals, B., Di Baldassarre, G., Huning, L.S., Kreibich, H., Mazzoleni, M., Savelli, E., Teutschbein, C., van den Berg, H., van der Heijden, A., Vincken, J.M.R., Waterloo, M.J. and Wens, M., 2020. The need to integrate flood and drought disaster risk reduction strategies. *Water Security*, 11, 100070, pp. 1–14.

[97] WB, 2019. *Assessing Drought Hazard and Risk: Principles and Implementation Guidance.* Washington, DC: World Bank. 69p.

[98] WB, 2023. Urban population. *World Bank Group*. Available at: https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS [Accessed on 22 Jan. 2025].

[99] WF, 2020. Factsheet: DROUGHT. *The Water Forum*, (Looking after Ireland's Water Resources), pp.01-06. Available at: https://thewaterforum.ie/app/uploads/2021/06/AFU-Factsheet-Drought_v4.pdf. [Accessed on 22 Jan. 2025].

[100] Wikipedia, 2025. Environmental Vulnerability Index. *Wikipedia – the Free Encyclopedia*. Last edited on 21 January 21 2025. Available at: https://en.wikipedia.org/wiki/Environmental_Vulnerability_Index [Accessed on January 22, 2025].

[101] Wikipedia, 2024. Urbanization in India. *Wikipedia – the Free Encyclopedia*. Last edited on 20 November 2024. Available at: https://en.wikipedia.org/wiki/Urbanization_in_India [Accessed on January 22, 2025].

[102] Wilhite, D.A. & Pulwarty, R.S., 2018. *Drought and Water Crises: Integrating Science, Management, and Policy*. 2nd ed. CRC Press (Taylor & Francis Group), Boca Raton. 541p.

[103] WMO, 2012. Standardized Precipitation Index: User Guide. WMO-No. 1090. World Meteorological Organization, Geneva. 16p. Available at: https://www.droughtmanagement.info/literature/WMO_standardized_precipitation_index_user_guide_en_2012.pdf. [Accessed on 22 Jan. 2025].

[104] Yu, Z., Lakhtakia, M.N., Yarnal, B., White, R.A., Miller, D.A., Frakes, B., Barron, E.J., Duffy, C. & Schwartz, F.W., 1999. Simulating the river-basin response to atmospheric forcing by linking a mesoscale meteorological model and a hydrologic model system. *Journal of Hydrology*, 218, pp.72–91.

[105] Yurcaba J. 2025. Conservatives blame California wildfires on a small fish, DEI and more. NBC News, Last Updated: Jan 10, 2025, Available at: https://www.nbcnews.com/news/us-news/conservatives-play-blame-game-california-wildfires-pointing-fingers-de-rcna186983. [Accessed on January 22, 2025].

[106] Zhang, X., Chen, N., Sheng, H., Ip, C., Yang, L., Chen, Y., Sang, Z., Tadesse, T., Lim, T.P.Y., Rajabifard, A., Bueti, C., Zeng, L., Wardlow, B., Wang, S., Tang, S., Xiong, Z., Li, D., & Niyogi, D. 2019. 'Urban drought challenge to 2030 sustainable development goals', *Science of the Total Environment*, **693**, 133536. Pp. 1–11. DOI: 10.1016/j.scitotenv.2019.133536.

Dr. Kaushik Kiran Ghosh

Dr. Kaushik Kiran Ghosh is an Associate Professor in the Department of Geology at Jogamaya Devi College, Kolkata. He earned his M.Sc. and Ph.D. degrees from the University of Calcutta. His research interests encompass geochemistry, iron ore mineralization, and environmental studies. His scholarly contributions include numerous publications in peer-reviewed journals, reflecting his dedication to advancing geological sciences. In addition to his teaching responsibilities, Dr. Ghosh has authored the book *Environmental Oceanography and Coastal Dynamics*, published by Springer. This comprehensive work delves into various aspects of oceanography, including physical, chemical, geological, and biological discussions, emphasizing the significance of oceanographic studies in the context of contemporary climate change challenges.

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 53-72

Zonation of Agricultural Drought using Analytical Hierarchy Process in Jhargram District, West Bengal, India

Kishor Dandapat[1], Prasanna Mahata[2]
Biswajit Pramanik[3] and Namgyal Tshewang Bhutia[4]
[1,4]Department of Geography, Jogamaya Devi College, Kolkata 700026.
[2,3]Department of Geography, Sadhu Ram Chand Murmu University, Jhargram, 721507.
[1]kishordandapat@gmail.com, [2]prasannamahata75@gmail.com
[3]biswajit190510@gmail.com, [4]bnamgyal79@gmail.com

Abstract: The study aims to demarcate agricultural drought zones in Jhargram district, West Bengal, India, using Analytic Hierarchy Process (AHP) and Geographic Information System (GIS) approaches. The Climatic, geological, and hydrological factors, including temperature, rainfall, slope, drainage density, geology, soil type, land use, NDVI, are integrated within a GIS environment to delineate drought-prone areas. The study reveals the spatial distribution of drought vulnerability across the region. The result shows that the district has been divided into four agriculturally drought-prone zones: High (8.96 %), Moderate (56.86 %), Low (32.92 %), and Very Low (1.26 %). The northern part of Binpur II and western part of Gopiballavpur I block are classified as Very High and High Drought Prone Areas, indicating a high risk of frequent and severe droughts. Moderate Drought Prone Areas, represented by yellow, are distributed across the district, posing a moderate risk of drought. Areas classified as Low and Very Low Drought Prone Areas have a lower risk of drought due to better access to water resources or favourable soil and climatic conditions. Areas with high drought vulnerability require urgent attention for implementing drought-resilient agricultural practices and improving water management.

Keywords: Agricultural Drought. AHP. GIS. Jhargram District.

1. Introduction:

Agriculture, as a fundamental pillar of human sustenance and economic stability, heavily relies on predictable and adequate water availability. When drought strikes, its repercussions are far-reaching, disrupting food production, livelihoods, and ecological balance. Drought is a progressive and recurrent natural disaster that occurs almost everywhere in the world, making it one of the most devastating natural disasters (Yao et al., 2018). It's a long-term condition of imbalance between precipitation and evapotranspiration in a specific region, which is influenced by the timely onset and intensity of the monsoon season, (Haile, et al. 2020). Agricultural drought reflects the extent to which soil moisture is lower than the least requirement of plants by analysing the characteristics of soil moisture and morphology of plants during growth, (Bodner et al. 2015). Agricultural drought primarily revolves around the insufficient water supply to crops due to reduced soil moisture resulting from decreased precipitation. The initial manifestation of this condition is the depletion of soil moisture levels. As transpiration continues, crops are unable to meet their essential physiological needs, leading to stunted growth and ultimately causing a decline in crop yield or even complete crop failure. This underscores how diminished soil moisture, stemming from decreased precipitation, directly impacts crop health and productivity, emphasizing the critical role of water availability in agricultural success. Agriculture sector is most affected by the onset of drought as it is highly reliable on the weather, climate, soil moisture etc, (Zhou et al. 2021).

Agricultural drought exerts profound impacts that reverberate from the global stage down to local communities, affecting food security, economic stability, social well-being, and environmental sustainability in diverse and interconnected ways. Globally, regions heavily reliant on rainfed agriculture, such as sub-Saharan Africa, South Asia, and parts of Latin America, face heightened vulnerability. Reduced crop yields and livestock productivity lead to food shortages, price volatility, and humanitarian crises, affecting global food supply chains and market stability. Environmental degradation, including biodiversity loss and increased carbon emissions from land-use changes and deforestation, amplifies the global impact of agricultural drought, exacerbating climate change feedback loops. Historically drought monitoring and investigation predominantly relied on ground-level observations or interpolated grids. These methods were extensively utilized to track and analyse drought conditions, forming the cornerstone of research into its spatial and temporal patterns, (Park et al. 2022). The dataset based on observation could not effective in capturing drought-related characteristics in agriculture at a regional scale. At present, Remote Sensing technology has the advantages of wide coverage, strong data continuity, objectivity, and timeliness, making it the most promising technology in drought monitoring., a series of indices have been developed which overcome the shortcoming of spatial monitoring ability of in-situ indices (Park et al., 2017). Normalized Difference Vegetation Index (NDVI) (Kogan, 1995a), Land Surface Temperature (LST) (Kogan, 1995a), Vegetation Condition Index (VCI) (Kogan, 1995b), Temperature Condition Index (TCI) (Kogan, 1995a), Soil Moisture Condition Index (SMCI) (Zhang & Jia, 2013) and other related indices based on remote-sensing data have been widely used to monitor and assess agricultural drought worldwide. With the increase of remote sensing satellites, the quality of remote sensing data is constantly improving, providing a rich source of information for drought monitoring using multi-source remote sensing data (AghaKouchak et al., 2015; Kalisa et al., 2020).

2. Study area:

Jhargram, located in the southwestern part of West Bengal, India, was established as the 22nd district on April 4, 2017, following the bifurcation of Paschim Medinipur district. Spanning an area of 3,037.64 square kilometres, Jhargram had a population of 1,136,548 according to the 2011 census. Geographically, Jhargram is situated between latitudes 21°45' N to 22°42' N and longitudes 86°42' E to 87°16' E (See Figure. 1). The district's terrain is characterized by the dissected Chhotanagpur plateau and Ranchi plain, which are prominently visible in the western part. Demographically, the district has a predominantly rural population, with 96.52% of the total population residing in rural areas, while 3.48% live in urban areas. The average annual rainfall in Jhargram is 1,430 mm, with the temperature reaching up to 45°C in May and June. December and January are the coldest months, with a humid and tropical climate prevailing throughout the year. The Chhotanagpur Plateau is mainly composed of Precambrian rocks, including metamorphic rocks, granite and gneiss. These rocks have undergone numerous alterations and alterations over millions of years. The plateau is covered in forest and the vegetation varies from moist tropical deciduous to dry deciduous. The peneplains of Ranchi are characterized by relatively flat and gently rolling landscapes resulting from the erosion of previously elevated areas. They often have low relief with residual hills. The Ranchi Peneplanes have been shaped by long-term erosional processes and represent a phase of the erosional cycle during which the terrain approaches a base state, achieving a more attenuated topography. The general slope of the entire region is from northwest to southeast. The hard and rocky crystalline rocks are responsible for the lack of adequate development of the aquifer in the northwestern part of the district (K. Dandapat et al. 2024). The geological characteristics of hard crystalline rocks can pose challenges for aquifer development in terms of low permeability, limited porosity, and possible absence of well-connected fractures and fissures. Understanding the geological conditions is essential for effective water resource management and the development of sustainable sources of groundwater in these areas. Agricultural drought in Jhargram district leads to severe crop loss, impacting the livelihood of farmers and the overall economy of the region. Traditional methods of drought assessment are often insufficient in addressing the multi-faceted nature of droughts, leading to ineffective mitigation strategies. There is a need for a comprehensive analysis using a strong framework like AHP to better understand and manage agricultural drought in Jhargram. Unfavourable and prolonged dry spells cause crops vulnerable to moisture deficits, insufficient water and unfavourable weather conditions cause most cultivars to have gone obsolete, and yield reduction and crop failure become common. It is one of the motivations to reveal the vegetation conditions in various months of Kharif (June- September). Agricultural drought risks are not evenly distributed, spatially, due to variations in locations, differential exposures to the climate hazards and the vulnerability of farming to drought conditions. Besides, prioritization of adaptation and mitigation options for agricultural drought prone areas has been a major difficulty due to lack of well-defined agricultural drought prone area delineation in the country. Hence, agricultural drought assessment is a need for decision making process on drought monitoring and to avert its consequences on agricultural production and productivities. Thus, in order to adapt and/or mitigate the impact of agricultural drought through generating different and improved drought resistant agricultural technologies, agricultural drought assessment through remote sensing and GIS is mandatory.

3. Materials and Method:

3.1. Geodatabase preparation for Agriculture Drought evaluation

The research methodology used in the study "Zonation of Agriculture Drought in Jhargram District, West Bengal (INDIA) Using GIS and Remote Sensing Applications." To prepare the rainfall map of the study area, high resolution gridded data was collected by the Climate Research Unit (crudata.uea.ac.uk) in the form of CRU monthly gridded rainfall data

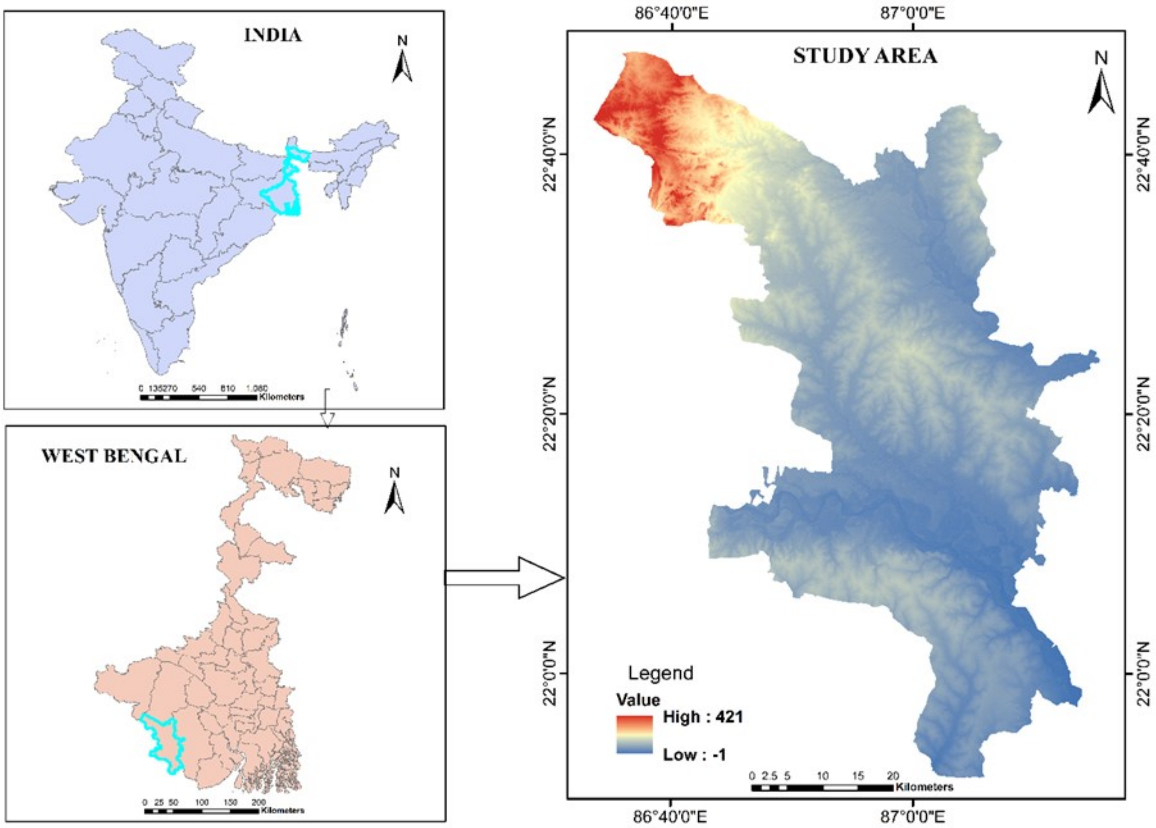


Figure 1. Location map of the study area: (a) India, (b) West Bengal and (c) Jhargram district.

(30' X 30') for everyone. After this process, the daily NETCDF file composites the interval and calculates the annual precipitation for the study area. Then convert the raster data to points and interpolate them with the IDW (inverse distance weighting) method. Inverse distance weighting (IDW) is a type of deterministic method for multivariate interpolation with a known sparse point set. The values assigned to the unknown points are calculated with a weighted average of the values available to the known points. A Shuttle Radar Topographic Mission (SRTM) digital elevation model with a resolution of 30 metres was used to generate the slope. The steepness of a slope is calculated in degrees using surface raster input in Arc-GIS. The feature map of the study area was extracted from Landsat OLI data using a linear image enhancement process. A land use/land cover (LULC) map was generated based on the maximum likelihood supervised image classification algorithm from the Thematic Mapper images with a spatial resolution of 30 m (see Table 1). The methodology employed in this study is essential in determining the final outcomes, which aim to address the research questions and offer valuable insights into zonation of agriculture drought in Jhargram District.

3.2 Function of AHP

Various techniques, classified as inductive or deductive, are used to assess the vulnerability of communities to natural hazards (Yoon, 2012). The selection of variables to infer vulnerability depends on factors such as the scale of the analysis, the extent of the study area and the availability of data (Fekete et al., 2010). This study examines communities' vulnerability to flooding using indicators from physical, socioeconomic and other sources. Separate analysis of physical and social indicators produces individual indices, which are then combined to create a composite vulnerability index (CVI). The main objective is to generate agricultural drought zonation in Jhargram District.

Table.1 Sources of data used for preparing thematic layers.

Thematic Map	Scale/Resolution	Sources of Data
Base Map (Topographical Map)	1:50000	Survey of India (SOI)
Rainfall	30 m (Spatial Resolution)	Crudata.uea.ac.uk
Geology	1:250000	Geological Survey of India (GSI)
Slope	30 m (Spatial Resolution)	USGS (https://earthexplorer.usgs.gov)
Drainage Density	30 m (Spatial Resolution)	USGS (https://earthexplorer.usgs.gov)
LULC	Landsat 8 OLI/TM	USGS (https://earthexplorer.usgs.gov)
Lineament Density	1 arc second	USGS (https://earthexplorer.usgs.gov)
Soil type	1:250000	Geological Survey of India (GSI)

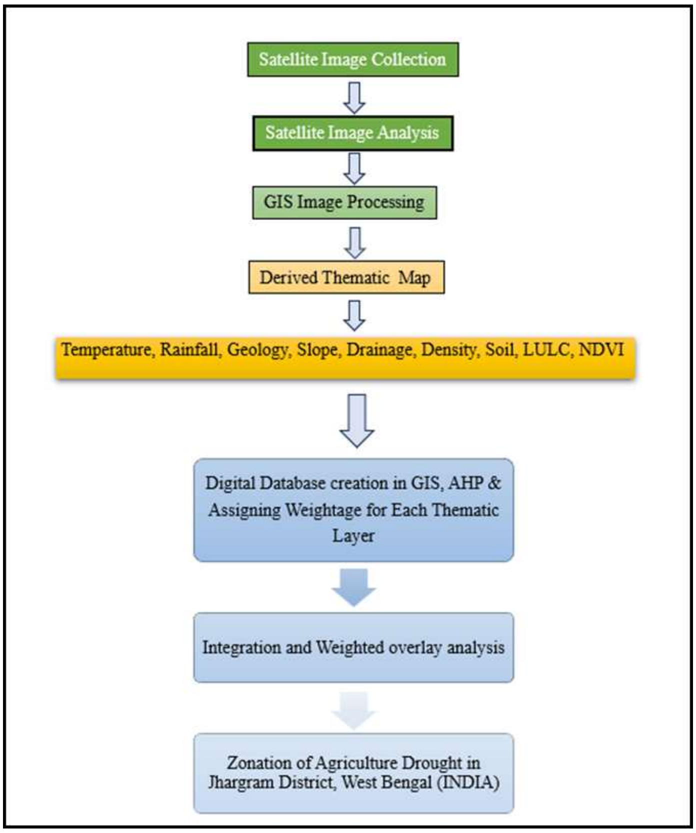


Figure 2. Graphical framework of methodology flow chart

A place-based approach is taken, integrating spatial and census data to estimate community vulnerability. Multi-criteria spatial evaluation techniques, including the analytical hierarchy process (AHP) and weighted linear combination (WLC), are used for the analysis. AHP, introduced by Thomas L. Satty (1977), is a robust and flexible technique to support prioritization and decision making in complex phenomena involving both quantitative and qualitative aspects. The AHP prioritizes the criteria identified by different stakeholder groups, guaranteeing the best decision and justifying its optimization (Satty, 1980).

The hierarchical decision model is a crucial part of the design phase of the analytical hierarchy process (AHP), where the highest level represents the overall goal of the decision. The indicators, which can constitute criteria at the highest level of the model, are divided into sub-criteria, creating a hierarchical structure. To determine the relative importance of each criterion or sub-criterion, pairwise comparisons are made on a 9-point scale, ranging from 1 (equal contribution to the objective) to 9 (strong preference for one indicator over another). This comparison process forms a matrix, as shown in Table 6.2, in which each pair of criteria or sub criteria elements is evaluated. A score of 1 indicates equal importance, while scores of 3, 5, and 7 represent weak, obvious, and strong preferences, respectively. The even numbers (2, 4, 6 and 8) provide a balance between the odd numbers, allowing for a nuanced assessment of the relative importance of each criterion and sub-criterion. This hierarchical decision model and pairwise comparison matrix allows decision makers to evaluate and prioritize indicators, ensuring a structured approach to decision making that takes into account all relevant factors. To calculate the local priority (weight) of a criterion, a pairwise comparison matrix is used. The points in each column are normalized by dividing the value of each cell by the column sum, and then the average of the normalized points in each row is calculated. This produces the local priority weighting for each criterion.

The consistency of the comparisons is assessed by the consistency index (CR), which is calculated as follows:

$$CR = Consistency\ Index\ (CI) / Random\ Index\ (RI)$$

If the CR is ≤ 0.1, the comparisons are considered consistent. Otherwise, the comparisons need to be revised. The Random Index (RI) is obtained from a table provided by Satty (1980) and is based on the size of the matrix (n). The Consistency Index (CI) is calculated using the following formula: $CI = (\lambda_{max} - n) / (n - 1)$, where λ_{max} is the maximum eigenvalue of the matrix.

Table. 2 Semantic Scale of the AHP method

Comparative Importance	Definition	Description
1	Equal importance	Two indicators equally influence the parent decision
3	Weak importance	One factor is moderately influential over the other
5	Essential or strong importance	One factor is strongly favoured over the other
7	Demonstrated importance	One decision factor has significant influence over another
9	Absolute importance	Evidence favouring one decision factor over the other is the highest order of affirmation
2,4,6,8	Intermediate	When compromise is needed, values between two adjacent judgments are used

Reciprocals	If A_i is the judgemental value when i is compared with j, then A_J has the reciprocal value when compared to A_I	A reasonable assumption

Source: Ramanathan (2001).

Table. 3 Example of a Pairwise Comparison Matrix

Infrastructure and Lifelines	Sources of Water	Sanitation	Road Density
Sources of Water	1	3	4
Sanitation	1/3	1	2
Road Density	1/4	1/2	1

Table. 4 Random average consistency indexes for various n

n	1	2	3	4	5	6	7	8	9
RI	0.0	0.0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

'n' represents the number of criteria.

Where, λ_{max} is the largest eigen value derived from the comparison matrix and n is the number of criteria. Once of the consistency is validated, the final priority of the criteria at the upper level of the hierarchy model is obtained by aggregating the local priorities of the criteria at its lower level. In addition to AHP, WLC is also used in this study. Due to its simplicity, multi-criteria decision analysis in terms of WLC is a frequently used technique within a GIS (Malczewski 1999). In GIS analysis, each indicator is treated as a data layer. A WLC is conducted by multiplying indicators by the corresponding weights and aggregating all weighted layers. In this study, the following equation was used:

$$\mathbf{VI} = \sum_{i=1}^{i} \sum_{i=1}^{i} W_i W_{ij} x \tag{1}$$

Where, VI is the Vulnerability Index for physical or social indicator, wi and wij are the weights for the ith and jth sub-criterion and x represents the value of an indicator.

3.3 Weights assignment of the parameters and Agricultural Drought Zonation Estimation (ADZE)

All the indicators (raster format) of the groundwater potential zone in the Jhargram District have been assigned through weights according to their respective role in ADZE. The total score of all indicators has been computed as –

$$\mathbf{TS} = \sum W\,X\,R \tag{2}$$

Where, TS = Total Score, W = Weight of the main indicators and R = Weight of the sub-indicators. All the weighted indicators have been integrated GIS overlay environment and obtained the Agricultural Drought Zonation Estimation of Jhargram District.

$$\mathbf{ADZE = AT + AR + S + DD + G + SS + LULC + NDVI} \quad \textbf{(2)}$$

Where, ADZE = Agricultural Drought Zone Estimation, RD = Rainfall Density, S = Slope, DD = Drainage Density, LULC = Land use land cover, LD = Lineament Density and SS = Soil Structure.

The area of groundwater potential zone has been calculated by the following formula –

$$\textbf{Area in Percentage (\%)} = \frac{\textbf{Estimated area}}{\textbf{Total area}} * \mathbf{100} \quad \textbf{(4)}$$

4. Result and discussion

4.1 Thermal Characteristics and Zonation Analysis

The temperature map of Jhargram District, West Bengal, illustrates a clear spatial variation in temperature, ranging from 32.3 to 32.8 degrees Celsius. The map reveals a predominantly warm climate across the district. The northern and eastern regions (Binpur I, Sankrail) exhibit higher temperatures, falling within the 32.6-32.8-degree Celsius range, indicating a warmer climate in these areas. In contrast, the southern and western parts (Nayagram, Gopiballvpur I) experience lower temperatures, predominantly between 32.3 and 32.4 degrees Celsius, suggesting a comparatively cooler climate (See Figure 3). The map also highlights potential temperature gradients within the district, with a gradual decrease in temperature from the northeast towards the southwest. These temperature variations likely reflect a combination of geographical, topographical, and land use factors. Further analysis with additional environmental data could provide more specific insights into these influences.

4.2 Rainfall Characteristics and Zonation Analysis

The rainfall map of Jhargram District, West Bengal, presents a clear spatial variation in annual precipitation. The district experiences a wide range of rainfall, categorized into distinct zones represented by different colours. The south-western portion (Nayagram) of the district receives the highest rainfall, with annual precipitation exceeding 1100 mm, indicated by the darkest blue colour. This suggests a humid climate with potentially lush vegetation and abundant water resources. Moving towards the northeast, the rainfall gradually decreases, with the central and eastern regions receiving between 955 and 1100 mm annually, represented by shades of green. These areas likely experience a moderately humid climate. The northernmost part (Binpur II) of the district receives the least rainfall, with annual precipitation ranging from 810 to 881 mm, indicated by the lightest orange colour (See Figure 3). This region is likely characterized by a drier climate. The map reveals a clear spatial pattern, with a general decrease in rainfall from southwest to northeast. This pattern is likely influenced by factors such as geographical location, topography, and prevailing wind patterns. The south-western region's proximity to the Bay of Bengal might contribute to its higher rainfall, while the northeaster part, being further inland, receives less moisture.

4.3 Sloping Characteristics and Zonation Analysis

The slope map reveals a diverse topography within Jhargram District. Several key observations can be made. Low Slopes (<1.74 metres): Significant portions of the district, particularly in the central and northern areas, exhibit gentle slopes. These areas are likely plains or gently undulating terrains, suitable for agriculture and development. Moderate Slopes (1.75-3.48 metres): Moderate slopes cover a substantial part of the district, interspersed with areas of low and high slopes. These areas might be rolling hills or gently inclined plateaus, offering a mix of land use possibilities. Steeper Slopes (3.49-6.81 metres): These slopes are more pronounced and occur in patches across the district, often along river valleys or hill ranges. Such areas might have limitations for agriculture but could be suitable for forestry or other land uses. High Slopes (6.82-13.10 metres): These steeper slopes are concentrated in the south-western and eastern parts of the district. They represent hilly or mountainous terrain, likely with challenging conditions for agriculture but potentially valuable for ecosystem services. Very High Slopes (>13.20 metres): These are the steepest areas, mainly found in the south-western region. They indicate hilly or mountainous terrain with significant slope gradients, likely posing challenges for human activities but crucial for biodiversity conservation. Overall, the slope map highlights the varied topography of Jhargram District (See Figure 3). The distribution of slopes has implications for land use planning, agriculture, infrastructure development, and natural resource management.

4.4 Drainage Density and Zonation Analysis

The drainage density map of Jhargram District showcases the spatial distribution of drainage networks across the region. Drainage density, a critical hydrological parameter, reflects the efficiency of a drainage basin in removing water from the landscape. Analysis of Drainage Density Patterns i.e., Low Drainage Density (0.0869-0.918 sq. km) Areas with low drainage density are primarily located in the central and northern parts (Jhargram and Binpur II) of the district. These regions exhibit a sparse drainage network, indicating a lower capacity to drain water. This might be associated with gentle slopes, low rainfall, or a higher proportion of impermeable surfaces. Moderate Drainage Density (0.919-1.75 sq. km and 1.76-2.58 sq. km) (See Figure 3). A significant portion of the district falls under moderate drainage density categories. These areas have a relatively well-developed drainage network, capable of efficiently removing water runoff. This is often observed in regions with moderate slopes, a balanced mix of land cover, and average rainfall. High Drainage Density (2.59-3.41 sq. km) High drainage density zones are primarily concentrated in the south-western and eastern parts (Nayagram, Sankrail and Binpur I) of the district. These areas have a dense network of channels, suggesting efficient water removal. This is typically associated with steep slopes, high rainfall, or permeable soils. Overall, the drainage density map offers valuable information about the hydrological characteristics of Jhargram District, aiding in water resource management, flood risk assessment, and land use planning.

4.5 Geological Characteristics and Zonation Analysis

The geology map of Jhargram District presents a diverse landscape composed of five distinct geological formations: Alluvial Plain, Flood Plain, Highly Dissected Hills and Valleys, Pediment-Pediplain Complex, and Waterbody-River.

- *Alluvial Plain* This formation primarily occupies the central and northern parts (Gopiballavpur II, Jhargram and Binpur I) of the district. Characterized by flat, fertile land, it is likely formed by the deposition of sediments carried by rivers. This area is suitable for agriculture due to its rich soil composition.
- *Flood Plain* Often adjacent to the Alluvial Plain, the Flood Plain is susceptible to periodic inundation by rivers. It is marked by fertile soils and is vital for agricultural activities. However, it also poses challenges due to its vulnerability to floods.
- *Highly Dissected Hills and Valleys* Located in the Binpur II block portions of the district; this region is characterized by rugged terrain with steep slopes and valleys. It is likely an older geological formation compared to the plains. This area might have limited agricultural potential but is rich in biodiversity and natural resources.
- *Pediment Pediplain Complex* This formation appears as a transitional zone between the hills and the plains. It is characterized by gently sloping surfaces created by erosion and deposition processes. This area might have moderate agricultural potential and is suitable for certain types of land use.
- *Waterbody-River* The map indicates the presence of a major river flowing through the district. Rivers play a crucial role in shaping the landscape, providing water resources, and influencing the distribution of other geological formations (See Figure 3).

Overall, the geology map reveals a complex interplay of geological processes that have shaped the landscape of Jhargram District. Understanding these geological formations is essential for land use planning, natural resource management, and hazard mitigation in the region.

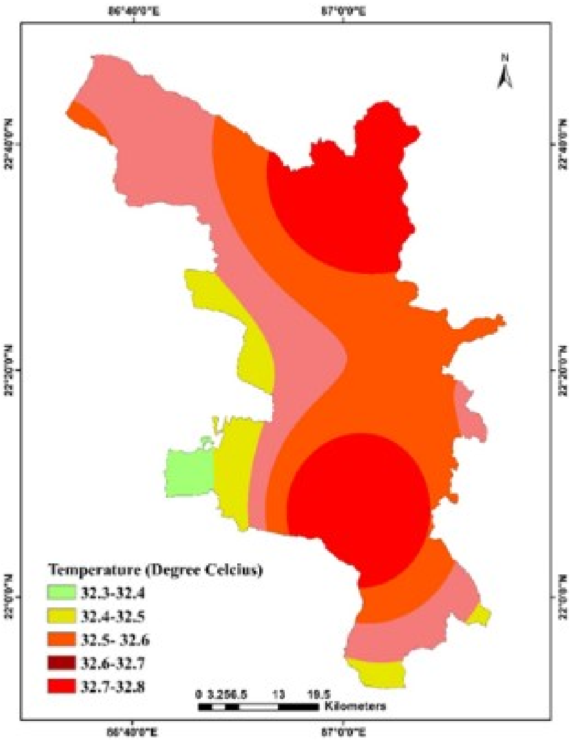
4.6 Edaphic Characteristics and Zonation Analysis

The soil map reveals a diverse soil landscape across Jhargram District. Several key observations can be made Fine Loamy Typic Paleustalfs and Fine Loamy Aeric Ochraqualfs These soil types dominate significant portions of the district, particularly in the central and northern areas. These soils, often associated with alluvial plains and river valleys, are generally fertile and suitable for agriculture. Loamy Skeletal Lithic Ustochrepts and Loamy Lithic Ustochrepts. These soils are found in scattered pockets across the district, often in areas with higher slopes or undulating terrain. They are typically less fertile and might have limitations for agriculture but could be suitable for forestry or other land uses. Fine Aeric Ochraqualfs and Fine Vertic Ochraqualfs These soils are predominantly located in the south-western region of the district. They are often associated with clay-rich deposits and might have waterlogging issues. Coarse Loamy Typic Haplustalfs and Coarse Loamy Typic Ustifluvents: These soils are found in patches across the district, often in areas with well-drained conditions. They can vary in fertility and suitability for different land uses. Fine Loamy Ulti Paleustalfs This soil type appears in smaller pockets, often associated with transitional zones between different soil groups. Rocky Outcrops As the name suggests, these areas have limited soil cover and are dominated by rocky formations. They are unsuitable for agriculture but might have ecological significance. River The map indicates the presence of a significant river system, which plays a crucial role in shaping the soil landscape through deposition and erosion processes (See Figure 3). Overall, the soil map highlights the variation in soil types across Jhargram District. This information is crucial for land use planning, agricultural practices, and environmental management.

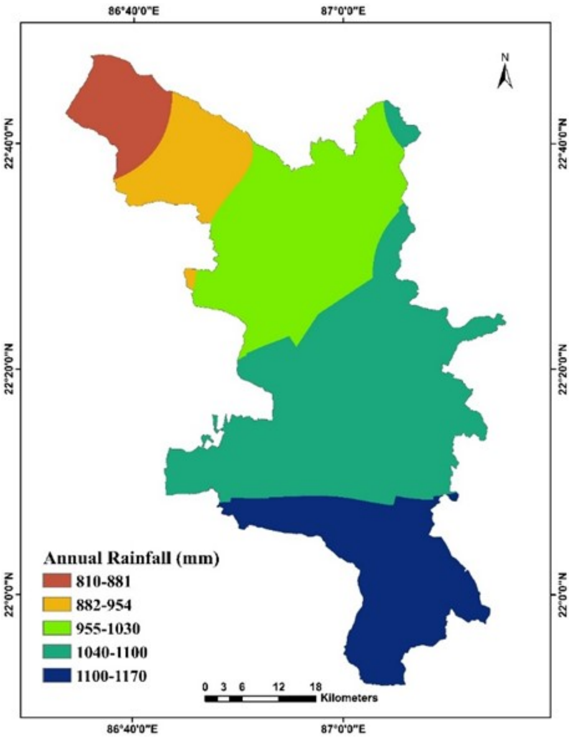
4.7 LULC and Zonation Analysis

The LULC map of Jhargram District presents a comprehensive overview of land use and land cover distribution.

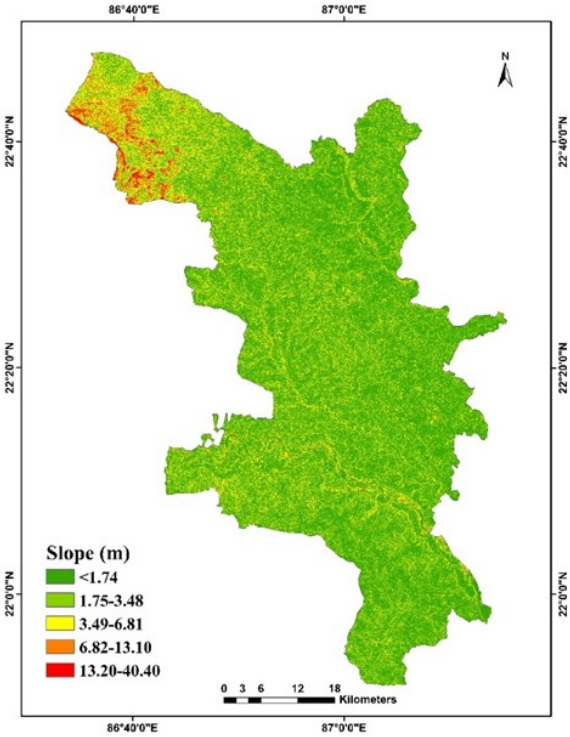
- *Dominant Land Cover, Agriculture and Vegetation* – These two categories occupy a substantial portion of the district, indicating the predominance of agricultural activities and natural vegetation cover.
- *Fallow Land* A considerable area is under fallow land, suggesting potential for agricultural expansion or land use change.
- *Built-up Land* Urban and built-up areas are relatively concentrated, primarily along river valleys and transportation corridors.
- *Spatial Distribution, Central and Northern (Binpur I, Sankrail and Gopoballavpur) Regions* These areas exhibit a higher proportion of agriculture and fallow land, suggesting intensive agricultural practices.
- *Southern and Eastern (Nayagram, Jhargram and Binpur) Regions* These regions show a greater extent of vegetation cover, indicating the presence of forests or natural grasslands.
- *River Valleys* Built-up areas and transportation networks are often situated along river valleys, utilizing the water resources for various purposes (See Figure 3).



[A]

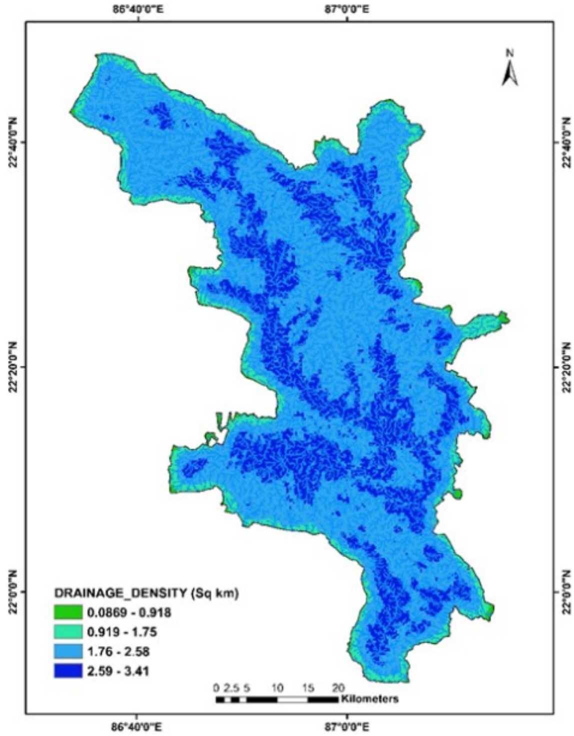


[B]



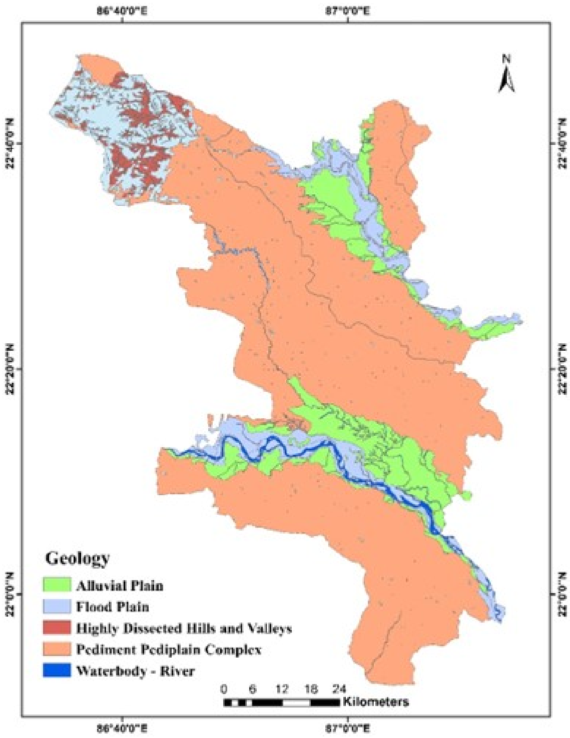
86°40'0"E
87°0'0"E
22°40'0"N
22°20'0"N
22°0'0"N
N
Slope (m)
<1.74
1.75-3.48
3.49-6.81
6.82-13.10
13.20-40.40
0 3 6 12 18
Kilometers

[C]



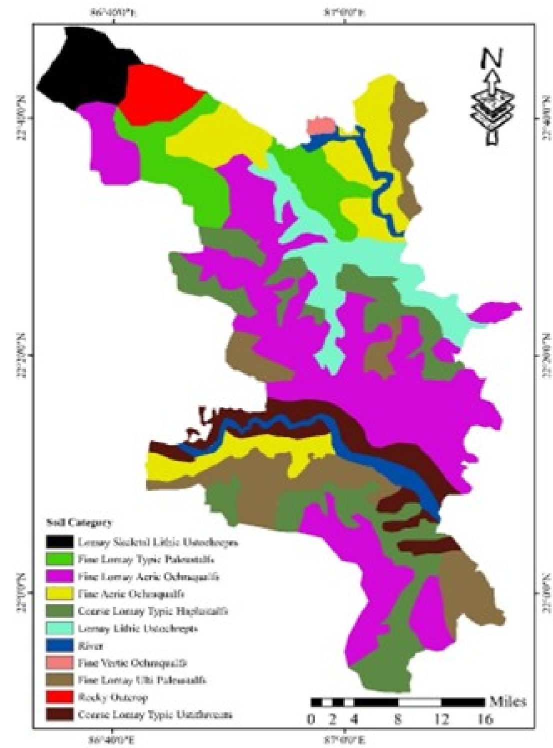
86°40'0"E
87°0'0"E
22°40'0"N
22°20'0"N
22°0'0"N
N
DRAINAGE_DENSITY (Sq km)
0.0869 - 0.918
0.919 - 1.75
1.76 - 2.58
2.59 - 3.41
0 2.5 5 10 15 20
Kilometers

[D]



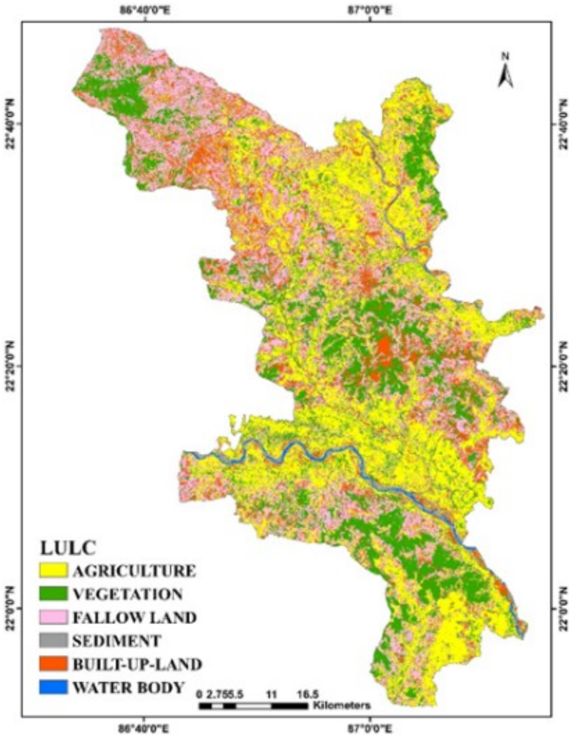
86°40'0"E
87°0'0"E
22°40'0"N
22°20'0"N
22°0'0"N
N
Geology
Alluvial Plain
Flood Plain
Highly Dissected Hills and Valleys
Pediment Pediplain Complex
Waterbody - River
0 6 12 18 24
Kilometers

[E]

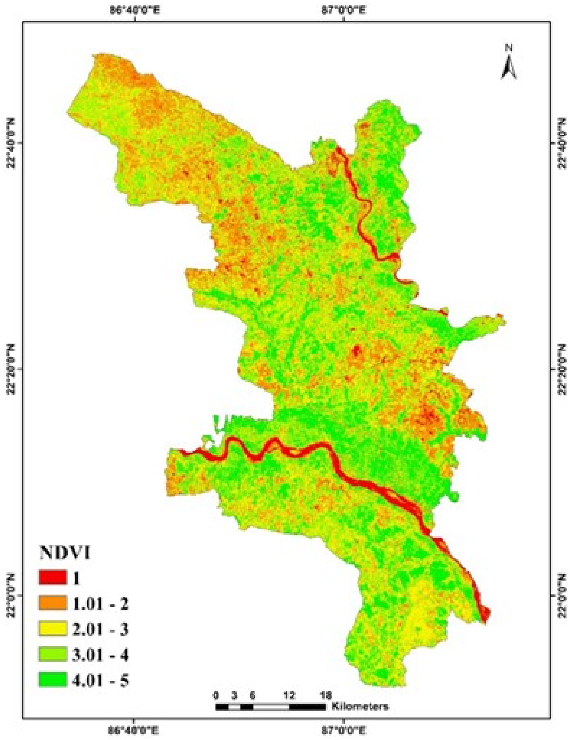


86°40'0"E
87°0'0"E
Soil Category
Fine Aeric Ochraqualfs
River
Rocky Outcrop
Miles
0 2 4 8 12 16

[F]



[G]



[H]

Figure 3. Agricultural Drought zone parameters: (A) Slope, (B) Drainage Density, (C) Lineament Density, (D) Annual Rainfall, (E) LULC, (F) Soil Category (G) Geology (H) Temperature (I) LULC (J) NDVI

The LULC map provides valuable insights for understanding the district's land use patterns, agricultural practices, and environmental conditions. It can be used for, identifying areas suitable for agriculture and other land uses. Assessing the extent of forest cover and its ecological importance. Monitoring urban expansion and its impact on land resources. Developing strategies for sustainable land management and conservation. Overall, the LULC map offers a valuable foundation for understanding the complex relationship between humans and the environment in Jhargram District.

4.8 NDVI and Zonation Analysis

The NDVI map reveals distinct patterns of vegetation cover across the district. Several key observations can be made. High NDVI Values (4.01-5) Areas with high NDVI values, represented by the darkest green, indicate dense and healthy vegetation cover. These regions likely consist of forests, dense plantations, or well-maintained agricultural fields. Moderate NDVI Values (3.01-4, 2.01-3, 1.01-2) Areas with moderate NDVI values, represented by shades of green, yellow, and orange, indicate varying levels of vegetation cover. This might include agricultural lands with varying crop conditions, open grasslands, or areas with a mix of vegetation and bare ground. Low NDVI Values (1): Areas with low NDVI values, represented by red, indicate sparse or degraded vegetation cover. These regions might be barren lands, rocky outcrops, built-up areas, or water bodies (See Figure 3). Overall, the NDVI map highlights the spatial variability in vegetation health and density across Jhargram District. This information is crucial for understanding the district's ecological status, agricultural productivity, and land use planning**.**

5.0 Agricultural Drought Zonation Mapping

The Agriculture Drought Prone Area map of Jhargram District provides valuable insights into the spatial distribution of drought vulnerability across the region.

- *High Drought Prone Areas* reveals significant portions (northern part of Binpur II, western part of Gopiballavpur I block) of the district classified as High Agriculture Drought Prone Areas (272.10 sq.km) (See Table. 5). These regions, characterized by the darkest shades of red and orange, respectively, are likely to experience frequent and severe droughts, posing substantial challenges to agricultural production.
- *Moderate Drought Prone Areas* (western Binpur I and southern part of Nayagram block), represented by yellow, are distributed across the district, indicating a moderate risk of drought (1727.15 sq.km) (See Table. 5). These areas may experience droughts periodically, affecting agricultural yields.
- *Low and Very Low Drought Prone Areas:* Areas (western part of Sankrail, eastern part of Gopiballavpur I and II, northern part of Nayagram) classified as Low and Very Low Agriculture Drought Prone Areas, depicted in green and blue, respectively, have a lower risk of drought (32.92 sq.km. & 1.26 sq.km. respectively) (See Table. 5). These regions generally have better access to water resources or possess soil and climatic conditions that mitigate drought impacts.

Table. 5 Agricultural Drought Zonation Estimation area with percentage value

Category	Area in sq.km.	Area in percentage
High	272.10	8.96
Moderate	1727.15	56.86
Low	1000.06	32.92
Very Low	38.33	1.26

Table: 6 Pairwise Comparison Matrix for Physical Indicators
Criteria at level 1 of decision hierarchy model

Criteria	1	2	3	4	5	6	7	8
Temperature	1	2	3	4	5	6	7	8
Rainfall	½	1	2	3	4	5	6	7
Geology	1/3	½	1	3	4	5	6	7
Soil	¼	1/3	1/3	1	5	6	7	8
Slope	1/5	¼	¼	1/5	1	5	6	7
Drainage Density	1/6	1/5	1/5	1/6	1/5	1	6	7
LULC	1/7	1/6	1/6	1/7	1/6	1/6	1	6
NDVI	1/8	1/7	1/7	1/8	1/7	1/7	1/7	1
CR: 0.08								

Table: 7 Pairwise Comparison Matrix for Physical Indicators
Criteria at level 2 of decision hierarchy model

Temperature (0C)	1	2	3	4	5
1. 32.3 – 32.4	1	3	5	7	9
2. 32.4 – 32.5	1/3	1	5	6	8
3. 32.5 – 32.6	1/5	1/5	1	3	5
4. 32.6 – 32.7	1/7	1/6	1/3	1	3
5. 32.7 – 32.8	1/9	1/8	1/5	1/3	1
CR: 0.08					

Rainfall (mm)	1	2	3	4	5
1.810 – 881	1	3	5	7	9
2. 882 - 954	1/3	1	5	6	8
3. 955 - 1030	1/5	1/5	1	3	5
4. 1040 - 1100	1/7	1/6	1/3	1	3
5. 1111 - 1170	1/9	1/8	1/5	1/3	1
CR: 0.08					

Slope (m)	1	2	3	4	5
1.<1.74	1	3	5	7	9
2. 1.75 – 3.48	1/3	1	5	6	8
3. 3.49 – 6.81	1/5	1/5	1	3	5
4. 6.82 – 13.10	1/7	1/6	1/3	1	3
5. 13.20 – 40.40	1/9	1/8	1/5	1/3	1
CR: 0.08					

Drainage Density (Sq. Kms)	1	2	3	4
1. 0.0869 – 0.918	1	2	4	5
2. 0.919 – 1.75	½	1	3	4
3. 1.76 – 2.58	¼	1/3	1	4
4. 2.59 – 3.41	1/5	1/4	1/4	1
CR: 0.07				

NDVI	1	2	3	4	5
1. 1.00	1	3	5	7	9
2. 1.01 – 2.00	1/3	1	5	6	8
3. 2.01 – 3.00	1/5	1/5	1	3	5
4. 3.01 – 4.00	1/7	1/6	1/3	1	3
5. 4.01 – 5.00	1/9	1/8	1/5	1/3	1
CR: 0.08					

Soil Category	1	2	3	4	5	6	7	8	9
Fine Vertic Ochraqualfs	1	2	3	4	5	6	7	8	9
Coarse Loamy Typic Ustifluvents	1/2	1	2	3	4	5	6	7	8
Coarse Loamy Typic Haplustalfs	1/3	1/2	1	2	3	4	5	6	7
Loamy Skeletal Lithic Ustochreprs	1/4	1/3	½	1	2	3	4	5	6
Fine Lomay Typic Ustifluvents	1/5	1/4	1/3	1/2	1	2	3	4	5
Fine Loamy Ulti Palestalfs	1/6	1/5	¼	1/3	1/2	1	2	3	4
Fine Loamy Aeric Ochraqualfs	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3
Fine Aeric Ochraqualfs	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2
Rocky Outcrop	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1
CR: 0.08									

LULC	1	2	3	4	5	6
Water Body	1	2	3	4	5	6
Vegetation	1/2	1	2	3	4	5
Agriulture	1/3	1/2	1	2	3	4
Sediment	1/4	1/3	½	1	2	3
Fallowland	1/5	1/4	1/3	1/2	1	2
Buildup Area	1/6	1/5	¼	1/3	1/2	1
CR: 0.02						

Geology	1	2	3	4	5
1. Alluvial Plain	1	3	5	7	9
2. Flood Plain	1/3	1	5	6	8
3. Highly Dissected Hills and Valleys	1/5	1/5	1	3	5
4. Pediment Pediplain Complex	1/7	1/6	1/3	1	3
5. Waterbody - River	1/9	1/8	1/5	1/3	1
CR: 0.08					

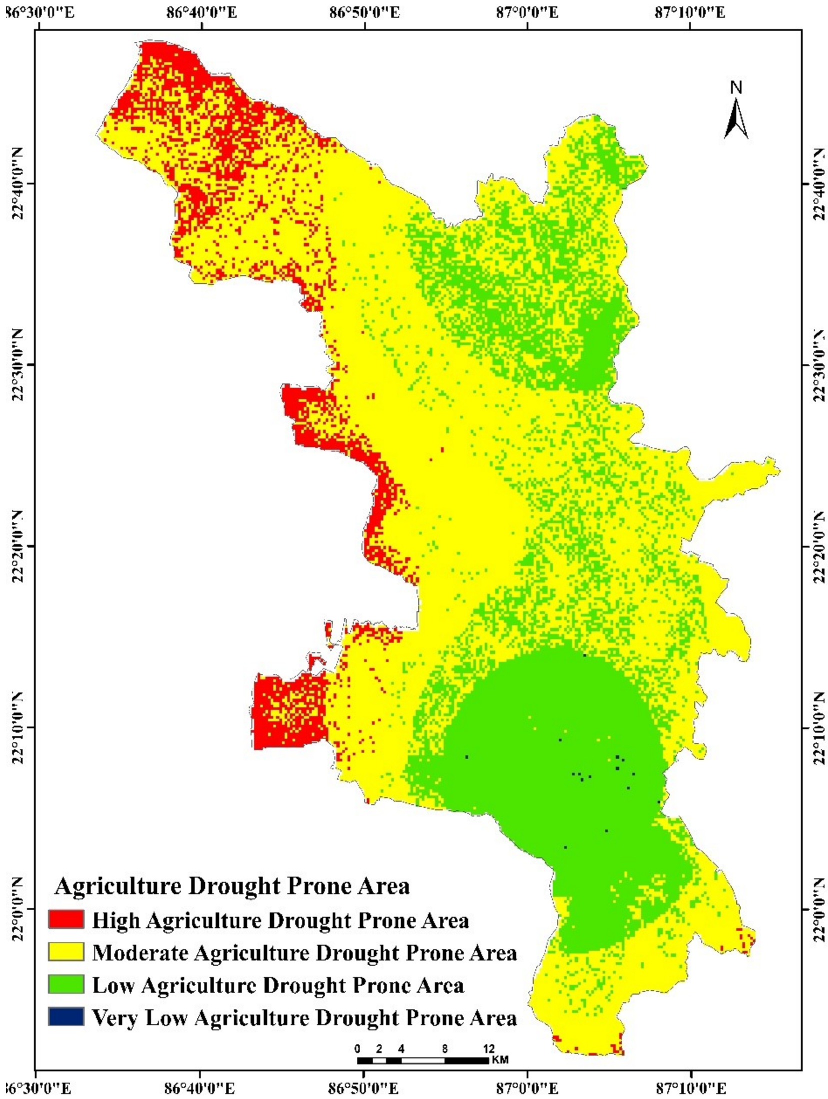


Figure 4. Map showing the spatial distribution of agricultural drought prone zones in Jhargram district.

6.0 Conclusion

The map highlights the varying degrees of drought vulnerability within Jhargram District. This information is crucial for developing targeted drought mitigation strategies and prioritizing interventions. Areas classified as Very High and High Drought Prone require urgent attention for implementing drought-resilient agricultural practices, improving water management, and providing early warning systems. Overall, the Agriculture Drought Prone Area map serves as a valuable tool for assessing the district's vulnerability to drought and guiding the development of sustainable agricultural practices.

Agricultural drought area analysis is crucial in undulating terrain areas like Jhargram District, West Bengal, where topography plays a significant role in determining the spatial distribution of drought. The district's undulating terrain, characterized by hills, valleys, and plateaus, creates a complex hydrological environment that exacerbates drought conditions.

Agricultural drought area analysis helps identify areas prone to drought, enabling policymakers and farmers to take proactive measures to mitigate its impacts. This analysis involves assessing various factors, including rainfall patterns, soil moisture, crop water stress, and land use/land cover changes.

References

[01] AghaKouchak, A., Farahmand, A., Melton, F.S., Teixeira, J., Anderson, M.C., Wardlow, B.D. and Hain, C.R., 2015. Remote sensing of drought: Progress, challenges and opportunities. *Reviews of Geophysics*, *53*(2), pp.452-480.

[02] Bodner, G., Nakhforoosh, A. and Kaul, H.P., 2015. Management of crop water under drought: a review. *Agronomy for Sustainable Development*, *35*, pp.401-442.

[03] Fekete, A., 2010. *Assessment of social vulnerability for river-floods in Germany* (Doctoral dissertation, Universitäts-und Landesbibliothek Bonn).

[04] Haile, G.G., Tang, Q., Li, W., Liu, X. and Zhang, X., 2020. Drought: Progress in broadening its understanding. *Wiley Interdisciplinary Reviews: Water*, *7*(2), p.e1407.

[05] Kalisa, W., Zhang, J., Igbawua, T., Ujoh, F., Ebohon, O.J., Namugize, J.N. and Yao, F., 2020. Spatio-temporal analysis of drought and return periods over the East African region using Standardized Precipitation Index from 1920 to 2016. *Agricultural Water Management*, *237*, p.106195.

[06] Dandapat, K., Chatterjee, U., Das, S., Patra, A., Manna, H., Ghosh, A., Pal, S.C., Towfiqul Islam, A.R.M., Costache, R., Alam, E. and Islam, M.K., 2024. Assessment of groundwater potential zones in data-scarce regions using GIS-based multicriteria decision making approach. *Geocarto International*, *39*(1), p.2311202.

[07] Kogan, F.N., 1995a. Application of vegetation index and brightness temperature for drought detection. *Advances in space research*, *15*(11), pp.91-100.

[08] Kogan, F.N., 1995b. Droughts of the late 1980s in the United States as derived from NOAA polar-orbiting satellite data. *Bulletin of the American Meteorological Society*, *76*(5), pp.655-668.

[09] Malczewski, J., 1999. *GIS and multicriteria decision analysis*. John wiley & sons., Inc., New York.

[10] Sumin Park, Jungho Im, Seohui Park, Yinghai Ke, Lindi J. Quackenbush (2017). A new drought monitoring approach: Vector Projection Analysis (VPA). Remote Sensing of Environment, Volume 252, https://doi.org/10.1016/j.rse.2020.112145.

[11] Park, E., Jo, H.W., Lee, W.K., Lee, S., Song, C., Lee, H., Park, S., Kim, W. and Kim, T.H., 2022. Development of earth observational diagnostic drought prediction model for regional error calibration: A case study on agricultural drought in Kyrgyzstan. *GIScience & Remote Sensing*, *59*(1), pp.36-53.

[12] Ramanathan, R., 2001. A note on the use of the analytic hierarchy process for environmental impact assessment. *Journal of environmental management*, *63*(1), pp.27-35. DOI:10.1006/ jema.2001.0455

[13] Saaty, T. L. (1977). The analytical hierarchy process, planning, priority. Pittsburgh: RWS publications. New York, NY: McGraw-Hill.

[14] Saaty T.L. 1980. The analytic hierarchy process. McGraw-Hill, New York, pp 20–25

[15] Yao, N., Li, Y., Li, N., Yang, D. and Ayantobo, O.O., 2018. Bias correction of precipitation data and its effects on aridity and drought assessment in China over 1961–2015. *Science of the Total Environment*, *639*, pp.1015-1027.

[16] Yoon, D. K., 2012. Assessment of social vulnerability to natural disasters: A comparative study. Natural Hazards, 63(2), 823-843.

[17] Zhang, A. & Jia, G., 2013. Monitoring meteorological drought in semiarid regions using multi-sensor microwave remote sensing data, Remote Sensing of Environment, 134, pp. 1-15. https://doi.org/10.1016/j.rse.2013.02.023.

[18] Zhou, K., Li, J., Zhang, T., & Kang, A. 2021. The use of combined soil moisture data to characterize agricultural drought conditions and the relationship among different drought types in China. Agricultural Water Management, 243, 106479.

Dr. Kishor Dandapat

Dr. Kishor Dandapat is an Assistant Professor of Department of Geography at Jogamaya Devi College, Kolkata, under University of Calcutta, West Bengal, India. He had a master's degree in Geography from Pt. Ravi Shankar Shukla University, Raipur and a Ph.D. from Utkal University, Bhubaneswar, under the guidance of Emeritus Professor Dr. Gopal Krishna Panda, Bhubaneswar and he qualified UGC-NET examination in the subject of Geography. His area of interest is in Geography, mostly focuses on human ecology, environmental issues, natural hazards and disaster management, and fluvial geomorphology. Dr. Dandapat published a book from international publishers '*Flood Hazards Management: A Community Approach*', Notion Press, Chennai, India. Currently a Major Research Project going on under Dr. Kishor Dandapat, entitled by "*Vulnerability of tribal communities towards food and nutrition insecurity: A study in Jhargram District of West Bengal*", sponsor by Indian Council of Social Science Research, ICSSR, New Delhi, India. He is a reviewer of several reputed national and international journals including those publihed from Springer Nature and Elsevier. He has reviewed various national and international journals, including *Sustainable Water Resources Management*, *Environmental Management*, *Disaster Risk Studies*, Scientific Reports, and *Arabian Journal of Geoscience*.

Prasanna Mahata
Prasanna Mahata is presently employed as Post Graduate Teaching Personnel in the Department of Geography at Sadhu Ramchand Murmu University of Jhargram, West Bengal. Earned a master's degree from Vidyasagar University and successfully qualified for the NTA UGC NET in the years 2019, 2021, 2023, and 2024. His research interests encompass Urban Planning, Social and Human Geography, Applied Geomorphology, Community Response, and Environmental Issues. Presently, he is involved as a research associate for an ICSSR project.

Biswajit Paramanik
Biswajit Paramanik completed his master's degree from Sadhu Ramchand Murmu University of Jhargram, West Bengal. His research interest area includes Geomorphology, Urban Planning, Social and Human Geography, Community Response and Environmental Issues, Remote sensing and GIS. He is currently engaged as a student of Sponsors Teachers Training College, Purulia, West Bengal.

Namgyal Tshewang Bhutia
Namgyal Tshewang Bhutia currently working as an Assistant Professor since 2015 in the Department of Geography, Jogamaya Devi college, Kolkata (university of Kolkata). He has also worked as Research Assistant in NATMO Kolkata, DST govt. Of India (2010-2015). He has completed his MA in geography from Visva-Bharati University with specialization in Remote sensing and Terrain evaluation

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 73-86

A Review on the Role of Soil Nematodes as Biological Indicator of Soil Health and Their Contribution to Sustainable Soil Management

Papia Das
Assistant Professor, Department of Zoology, Budge Budge College,
papia8@gmail.com

Abstract: Human induced impacts and their negative effects on terrestrial ecosystems triggered the attention towards the need for monitoring, assessing and managing ecological integrity to promote the long-term sustainability of these systems. The community structure and abundance of different soil nematodes can provide vital information on how organisms respond to these challenges and can provide a warning signal of anthropogenic impact. They have been most often used specifically as indicators of heavy metal, hydrocarbon pollution, microplastic pollution, organic enrichment and physical stresses due to climate change. Soil nematodes occupy key ecological niches in below ground food webs and are involved in nutrient mineralization and carbon sequestration and thereby can play crucial role in sustainable soil management. The aim of this review paper is to document the role of soil nematodes as bioindicator of soil health and their potential use for sustainable soil management.

Key words: soil nematodes, biological indicators, sustainable soil management

1. Introduction

Soil provides shelter and food to living organisms including humans. It is the main habitat of billions of microorganisms, fungi, plants and animals and provide us with food, fiber and fuel. But the advancement of technology, intensive agriculture, urbanization and climate change is causing damage to soil. So now there is a need to assess and monitor soil health and transform to sustainable use of soil which can help stabilize the climate naturally and ensure resilient supply chains, especially for food security. Soil health is "a living, dynamic system whose functions are mediated by a diversity of living organisms that require management and conservation" (Doran & Zeiss 2000) Bioindicators are therefore key when monitoring soil health. Bioindicators include microbes, protozoa and metazoan. Nematodes, the most abundant type of metazoan (Bongers & Bongers 1998), live in all varieties of soils. Nematodes vary in terms of their sensitivity to pollutants and environmental disturbances, and the communities of nematodes are widely accepted as simple indicators of soil health and soil quality (Griffiths *et.al.* 2016). Plant parasitic and free-living soil nematodes are correlated with the extent of nitrogen cycling and decomposition (Neher 2001). Free-living soil nematodes reflect soil health and the biodiversity of soil ecosystems (Urzelai *et al.* 2000). Many soil nematode indices such as the Shannon index, the maturity index (MI) for free-living nematodes and the plant-parasitic index (PPI) for parasitic nematodes are used to monitor changes in land use, environmental disturbance and the effects of management practices.

In recent studies soil nematodes have widely been used for soil health assessment, aided by developments in analytical and identification methods. Both morphological and molecular methods are currently used for soil nematode identification (Seesao *et.al*. 2017). The present paper aims to review the role soil nematodes as biological indicator for assessing soil health and their contribution to promote soil resilience and sustainable management of soil.

2. Role of soil nematodes as bioindicators

Primary indicators of land management sustainability are changes in soil quality or health over time that can be used for land managers to mitigate practices that reduce the long-term viability of their lands. To be a reliable indicator of soil health, an organism should be: 1) responsive to variations in land management, 2) correlated with soil functions, 3) useful for analysing environmental processes, 4) comprehensible and useful to land managers, and 5) easy and cheap to measure (Doran and Parkin, 1994). Many soil organisms including nematodes meet this criterion and thus can be useful indicators of sustainable and non-sustainable land management practices.

Soil nematodes are one of the most abundant group of metazoans which inhabit each and every corner of the Earth. They are found at all trophic levels of the soil food web in combination with plants, bacteria, microarthropods, and other nematodes (Ferris 2010). The use of soil nematodes as bioindicator for the assessment of soil health is increasing because of their high diversity and abundance and their essential roles in ecosystem function (Mulder *et al.* 2005).

Soil nematodes have been classified by feeding habit into bacterivores, fungivores, herbivores, omnivores and predators (Yeates *et.al.* 1993). Bacterivores and fungivores which feed on bacteria and fungi respectively play major roles in the decomposition of organism in soils, and thus changes in bacterivores and fungivores may reflect changes in decomposition pathways (Schratzberger *et.al.* 2019). Free-living nematodes are mostly beneficial nematodes which include bacterivores, fungivores, omnivores and predators. They engage in nutrient cycling and energy transfer within the soil food web thereby enhancing that web and soil ecology. Herbivores feed on plants. Omnivores and predators feed on bacteria, fungi, protist and nematodes and represent the smaller proportion of soil nematodes. They are sensitive to environmental disturbance.

Soil nematodes have also been categorized according to life strategy into colonizers (r-strategists) and persisters (K-strategists) (Bongers & Bongers 1998) and have been placed on a colonizer-persister (c-p) scale from 1 to 5. The c-p 1 group includes principally bacterial feeders which exhibit explosive population growth in microbe-rich soils and are tolerant to pollution-induced stress. The c-p 5 group is composed principally of omnivores, predators and plant feeders that are more sensitive to pollutants and other disturbances (Bongers & Bongers 1998). The diversity, community structures and functions of soil nematodes are important indices used for assessing soil health.

2.1 Soil nematode community and diversity indicators to access soil health

Species/community measures, diversity measures and maturity indices have been used to assess these communities. The species/community measures can be calculated by the number of taxa, absolute abundances and trophic structure based on relative abundances. Diversity measures include the Shannon index, the Simpson index and trophic diversity (Urzelai *et al.* 2000).

Numerous community indices have been used to monitor and assess soil conditions. These include Maturity Index (MI), enrichment index (EI), channel index (CI), structure index (SI), the fungivore/bacterivore (F/B) ratio, nematode channel ratio [NCR = B/(B + F)], ratio of obligate plant parasites to bacterivores and fungivores [Pp/(B + F)] and PPI (Urzelai *et al.* 2000, Tsiafouli *et al.* 2017). MI is the weighted mean c-p of all individuals in a representative soil sample which is inversely related to the extent of soil disturbance. Its value is less than two in nutrient enriched disturbed systems, but about four in undisturbed environments. EI reflects food availability and soil organic matter enrichment, in turn reflecting the sensitivities of functional nematode guilds (Matveeva & Sushchuk 2016). CI is calculated using the numbers of bacterivores and fungivores, revealing the predominant pathway of organic matter decomposition by bacteria and fungi (Matveeva & Sushchuk 2016). SI is calculated using an indicator weighting system based on the importance of the functional guilds along hypothesized trajectories of structure and provides location of the food web along the structure trajectory (Tsiafouli *et al.* 2017). PPI, i.e., MI equivalent for plant-feeding nematodes, is positively correlated with soil disturbance.

2.2. Methods of identification of soil nematode community and diversity

Both the morphological and molecular methods can effectively identify and analyse nematode community structure, and play critical role in evaluating soil health using the soil nematode community structure. Now the combined use of both the methods in assessing nematode community structure are gaining new insights.

2.3 Effect on nematode community due to climate change

2.3.1 Effect of Temperature

Wang *et al*. (2019) in his experiment found in his experiment that high temperature decreases nematode diversity and generic richness. Similarly, Liu *et al.* (2022) found in his studies that high temperature cause reduction in herbivores, with a short-term decrease in bacterivores and fungivores who recover over time, and relative tolerance of omnivores–predators.

2.3.2 Effect of Water stress

Franco *et.al.* (2020) found in his studies that long-term increase in mean annual precipitation increases the proportion of herbivores or plant parasitic nematodes in grass biomass.

Franco *et.al.* (2022) assessed the effects of precipitation on nematode genus diversity, community structure and metabolic footprint, across temporal and spatial scales, in arid, semiarid, and mesic grasslands in his studies and found that with increasing annual precipitation in all systems the free-living nematode diversity and evenness decreased over time.

Drought is the key limitation of soil nematode abundance even in short term events. Yang *et.al.* (2022) pointed out in his studies that drought condition induces reduction in total nematode abundance, and decrease in relative abundance of bacterivores, fungivores, and predators but relative abundance of herbivores remain unaffected. Homet *et.al.* (2023) found from his studies in Mediterranean forest that low precipitation lower bacterivore and fungivore abundance, cause marginal increase in omnivores and decrease in fungivores, show higher maturity and structure index, and lower prey: predator ratio. Gattoni *et al.* (2024) hypothesized that drought-driven increase in stress would impact nematode community diversity and composition indicating a potential threat to ecosystem stability.

2.4. Effect on nematode community due to anthropogenic activities

2.4.1. Effect of nutrient enrichment

Chen *et.al.* (2019) pointed out from their studies in semi-arid grassland that in long term nitrogen enriched condition, plant removal dwindled nematode taxon richness and abundance of bacterivores and herbivores and increases the abundance of fungivores and omnivores–predators. Shaw *et al.* (2019) showed in their studies conducted at subalpine forest ecosystem that nematode abundance increases in fertilized plots, while richness, diversity, and ecological maturity decreases. It was further pointed that enriched food web was mostly driven by bacterivores and herbivores, with persisting effects overtime. Liu *et.al.* (2020) showed in their studies that understory addition of nitrogen decreases most nematode trophic groups and community diversity compared to canopy addition of nitrogen. Xiao *et.al.* (2020) from their studies in grassland pointed out that soil acidification reduces the effect of short-term Nitrogen and Phosphorous enrichment on nematode community structure. Wan *et.al.* (2022) pointed out from their studies that long-term organic amendments and mineral fertilization show positive correlation with the abundance of most functional guilds of nematodes. Varga *et.al.* (2019) concluded from their studies that phosphorous input significantly increased nematode diversity and genera where bacterivores and herbivores were the most abundant trophic groups, and predators the least common. They found nematode biodiversity was unaffected by liming, and nematode diversity and maturity were reduced in the absence of liming.

2.4.2 Combined effect of multiple stressors on nematode community

Olatunji *et.al.* (2019) showed that plant type and water availability had a greater impact on nematode abundance and community composition, drought was detrimental to the total density of nematodes and functional guilds. They found bacterivores, herbivores, and omnivores were significantly more abundant in soils with legumes.

Caruso *et al.* (2019) studied the co-occurrence and distribution of three common and dominant nematode species (bacterivores *Plectus murrayi* and *Scottnema lindsayae*, and omnivore *Eudorylaimus antarcticus*) in the McMurdo Dry Valleys (Antarctica). They found spatial segregation between two competing bacterivore species, with contrasting responses to abiotic factors like, one is best adapted to lower temperatures, high salinity and low moisture environments, while the other thrives at higher soil moisture, higher temperatures and lower salinity.

Li *et.al.* (2020) inferred from their studies that climate, are more influential than historical factors in shaping nematode diversity patterns on a broader scale.

Neilson *et al.* (2020) pointed out in their paper that microbial community size is a potential predictor of nematode functional group in limed grassland.

Xiong *et.al.* (2020) inferred from their studies that increased aridity cause decline in total and relative nematode abundance of each functional guild. They further showed that taxonomic richness of total nematode community and functional guilds decreased under moisture scarcity. It was found from their studies, richness of bacterivores was higher at the dry end of the aridity gradient, while herbivores declined steadily and richness of fungivores and omnivores–predators remained stable up to a certain point, before dropping steeply.

Siebert *et al.* (2019) concluded from their study that drought favoured bacterivores and fungivores, and likely had detrimental effects on higher trophic levels while fertilization caused a prominent increase in bacterivores and an equally significant drop in fungivores.

Thakur *et.al.* (2019) inferred from their studies that nematode density increases at elevated level of nitrogen and CO_2.

Zhang *et.al.* (2020) found from their studies that artificial warming decreases nematode abundance especially of bacterivores and herbivores (with minor effects on fungivores) but the nematode community diversity and functions remained stable. It was also observed that reduced precipitation cause decrease in nematode abundance, especially of bacterivores and omnivores–predators, with fungivores and herbivores being relatively insensitive to water stress but with availability of water nematode abundance and community diversity increases.

From the studies of Nisa *et.al.* (2021) it was observed that nematode abundance and diversity reduces with increasing altitude, with bacterivores consistently being the dominant group. It was further observed that nematode diversity was mostly influenced by temperature and moisture and with increasing soil acidity nematode abundance decreases. From their study it was found that nematode diversity and richness were directly proportional to nutrient (N and P) levels.

2.4.3 Effect of land use on nematode population

Siebert *et.al.* (2020) hypothesized from their study that intensive land use increase bacterivores, fungivores, and herbivores. Renco *et al.* (2020) concluded from their study that lower C/N ratios in cultivated soils results in a reduction in nematode abundance and diversity while abundance of trophic groups, total abundance, and diversity of nematodes increases in soils with higher pH and C and N contents. Li *et.al.* (2020) hypothesized that land use conversion could cause negative impacts on soil taxa across a large spatial scale, but agronomic practices limit the climatic constraints on belowground biodiversity. Krashevska *et al*. (2019) studied the nematode community dynamics in rainforests and monocultures and found that in monocultures fungivores increase and bacterivores, herbivores, and omnivores–predators decrease but land use did not show any negative effect on nematode community. Gao *et al.* (2020) showed vegetation succession positively affect nematode abundance, diversity and complexity of community structure. Wang *et al*. (2020) found from their study that livestock grazing negatively affect bacterivores, herbivores, omnivores–predators' abundance and total nematode abundance but no detrimental effect was observed on fungivore abundance. Han *et al.* (2020) concluded from their study that land degradation lower nematode trophic diversity.

Zhang *et al.* (2020) observed from their study that plants with acquisitive strategies (i.e., those that produce fine roots and acquire resources more rapidly) promote nematode abundance contrary to species with conservative strategies (i.e., those that invest more in their root systems, slowing down resource uptake). Puissant *et al.* (2021) found from their studies that conventional practices decrease trophic structure, abundance and taxonomic richness of nematode communities while agroecological practices enhance the functional and taxonomic diversity of nematodes. They observed that crop rotation reduces herbivore abundance while crop cover increases omnivores–predators, bacterivores and fungivores increases in organic fertilization. It was further observed that pesticide application and monoculture cause reduction in nematode abundance and food-web structure while copiotrophic nematodes are favoured.

Zhao *et al.* (2023) pointed out from their study that addition of legume positively affect total nematode abundance, especially bacterivores improving metabolic activities of total nematodes, bacterivores, and omnivores–predators but positive effects of legume addition subsided after increased harvesting frequency. Trap *et al.* (2021) found from their study that the activity of beneficial nematodes increases with plant diversity. Further it was observed that nematodes show positive effects on plant growth and function associated with higher values in soil pH and cation contents.

2.4.4. Effect of heavy metal and plastic on soil nematodes

Huo *et al.* (2024) found from their study in urban brownfields that heavy metals specially chromium negatively affect nematode abundance of omnivores-predators whose population finally disappear with intensified heavy metal contamination. They found that soil nematode communities at high trophic levels are powerful indicators of response to Cr (VI) contamination and bacterivores show superior adaptations to heavy metal contamination. Findings of Chauvin *et al.* (2020) showed that fungal-feeding nematodes were relatively insensitive to metal contamination of soil and their abundance was higher in the very high contamination.

Korthals (1997) concluded from his studies that the nematode community structure was influenced by Cu, Ni or Zn pollution in the soil. Thus, nematode community can provide an early and sensitive signal of increased Cu, Ni or Zn pollution in the soil. Moreover, it was demonstrated that the nematode structure may also provide opportunities to identify specific types of disturbance, i.e., pollutants. Lu *et al.* (2020) concluded from their study that heavy metals namely cadmium and mercury had marked effects on the nematode abundance, life-history strategies and feeding type composition. Martinez *et al.* (2018) showed in their studies that certain genera of omnivores-predators nematodes, such as *Ironus* and *Eudorylaimus*, were found to be more abundant in sites with higher heavy metal concentrations. Some studies show r-strategist nematodes exhibit tolerance to heavy metal contamination, while k-strategist nematodes are more sensitive to contamination (Martín *et al*. 2014, Yang *et al*. 2022). Some studies show heavy metal contamination has a negative impact on the community of soil nematodes, which can be evaluated using ecological indices (Gutiérrez *et al*., 2016; Salamún *et al*., 2012). Kim *et al.* (2020) found from their studies that polyethylene terephthalate (PET) fragments and polyacrylonitrile (PAN) fibres show the highest toxicity, while high-density polyethylene (HDPE), polypropylene (PP), and polystyrene (PS) fragments induced relatively less adverse effects on nematodes.

3. Contribution of soil nematodes in sustainable soil management

3.1 Nematode contribution to soil health

A diverse community of beneficial soil nematodes act as key contributors to soil quality and can help with soil remediation and ecosystem functioning restoration, by enhancing soil organic C, increasing decomposition services, and keeping pests and pathogens under control. (Pires *et al.* 2023). Nematodes act as soil decomposer in the soil ecosystem. They feed on bacteria, fungi and other microorganisms releasing nutrients through their excretion and decomposition of organic matter. This nutrient mineralization process makes essential nutrients available to plants, supporting healthy plant growth and overall ecosystem productivity.

Soil nematodes breakdown organic matter by consuming microorganisms involved in decomposition and help to release carbon and nutrients back into the soil which finally improves soil structure and nutrient availability.

Nematodes burrow through the soil, create channels and pores that enhance soil aeration, water infiltration, and drainage. These activities improve soil structure, help in root penetration and allow water and air to move through the soil more effectively. These well-structured soils finally support healthier plant growth.

Nematodes, including predatory species, help to regulate the populations of microorganisms in the soil. They consume bacteria, fungi, and other microorganisms thereby prevent the overgrowth of potentially harmful species and finally contribute to a healthier soil ecosystem. Some nematodes are natural predators of plant pathogens and can control soilborne diseases by consuming the pathogens and reducing their populations. This natural disease suppression contributes to healthier plants and improved crop yields (Pandey *et al*., 2022).

3.2. Role of nematodes to promote soil resilience and restoration of soil food webs

Nematodes are highly adaptable animals and play diverse roles in ecosystem functioning, their physiological and life history traits make them less susceptible to environmental changes compared to larger fauna higher-up in the food web. So, these characteristics could prove useful for the resilience and resistance of soils to natural and anthropogenic changes. (Pires *et al.* 2023).

Chen *et al.* (2020) studied about the role of bacterivores to promote soil resistance and resilience under copper and heat stress. It was found two dominant bacterivore genera, *Acrobeloides* and *Protorhabditis,* responded differently to disturbance. They found *Protorhabditis* exhibited greater resistance and resilience to copper stress compared to *Acrobeloides,* while both genera displayed higher resilience only by the end of the experiment under heat stress. They also found from their experiment that increase in relative abundance of bacterivores did not significantly affect soil resistance in terms of microbiota but it improved soil resilience to copper stress.

Majdi *et al.* (2019) observed from their study that closely related species like *Plectus acuminatus* and *P. cf. velox* had very different thermal tolerance ranges between 25 and 30°C, and *A. nanus* exhibiting the broadest thermal tolerance range. Often severe anthropogenic impacts lead to simplified soil food webs, with limited top–down control by omnivores–predators, ultimately compromising ecosystem functioning and impairing their natural ability to mitigate the effects of climate change. To enhance soil resilience to climate change it is very crucial to restore the complexity of soil food webs. (Pires *et al.* 2023) Soil nematodes are one of the beneficial soil organisms which can play significant role to restore complexity of soil food webs to enhance soil resilience to climate change and other anthropogenic activities. Huang *et al.* (2023) concluded from their study that characteristics of nematode communities can effectively indicate the restoration of soil food webs and their possible driving forces under revegetation can be identified which have important implications for vegetation restoration in arid and semiarid regions.

4. Future insights

Structure of nematode community reflects soil condition. Thus, the changing diversity and structure of the soil nematode community can help evaluating soil quality. This potential role of nematodes as bioindicator are gaining popularity among ecologists, now a days. Free-living soil nematodes can be used as model organism to assess soil health which can address most of the agricultural and ecological questions. Many laboratories use free-living nematodes (principally *C. elegans*) for preliminary assessment of soil condition (Tejeda-Benitez 2016). Free- living soil nematodes play significant role in soil restoration and soil resilience to climate and anthropogenic changes. So, more study is needed to utilize these soil nematodes in sustainable soil management. Combined use of morphological and molecular identification of nematode is needed to study nematode community structure. But the number of nematode taxonomists is limited all through the world. To utilize these potential bioindicator organisms in present scenario of global crisis due to climate change more experts on nematode taxonomy is needed. So young researchers should be encouraged to work in this dynamic field to contribute to mitigate the present scenario of global crisis of climate change. It can be inferred from this review paper that community structure of soil nematodes can be used as potential bioindicator and provide insights on the overall soil health, and sustainable agroecological practices are a good way to promote their presence in degraded soils. A diverse community of nematode can help with soil remediation and ecosystem functioning restoration.

REFERENCES

[01] Bongers, T., Bongers, M., 1998. Functional diversity of nematodes. Applied Soil Ecology, 10(3): 239–251

[02] Caruso, T., Hogg, I.D., Nielsen, U.N., Bottos, E.M., Lee, C.K., Hopkins, D.W., Cary, S.C., Barrett, J.E., Green, T.G.A., Storey, B.C., 2019. Nematodes in a Polar Desert Reveal the Relative Role of Biotic Interactions in the Coexistence of Soil Animals. Communications Biology, 2, 63.

[03] Chauvin, C., Trambolho, M., Hedde˒, M., Makowski, D., Cérémonie, H., Jimenez, A., Villenave, C. 2020. Soil Nematodes as Indicators of Heavy Metal Pollution: A Meta-Analysis. Open Journal of Soil Science,10, 579-601.

[04] Chen, D., Xing, W., Lan, Z., Saleem, M., Wu, Y., Hu, S., Bai, Y., 2019. Direct and Indirect Effects of Nitrogen Enrichment on Soil Organisms and Carbon and Nitrogen Mineralization in a Semi-arid Grassland. Functional Ecology, 33, 175–187.

[05] Chen, X., Xue, W., Xue, J., Griffiths, B.S., Liu, M., 2020. Contribution of Bacterivorous Nematodes to Soil Resistance and Resilience under Copper or Heat Stress. Soil Ecology Letters, 2, 220–229.

[06] Doran, J.W. and T.B. Parkin. 1994. Defining and Assessing Soil Quality. In: Defining Soil Quality for a Sustainable Environment. Soil Science Society of America Special Publication no. 35. SSSA, Madison, Wisconsin.

[07] Doran J W, Zeiss M R., 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology, 15(1):3–11

[08] Ferris H., 2010. Contribution of nematodes to the structure and function of the soil food web. Journal of Nematology, 42(1): 63–67.

[09] Franco, A.L.C., Gherardi, L.A., de Tomasel, C.M., Andriuzzi, W.S., Ankrom, K.E., Bach, E.M., Guan, P., Sala, O.E., Wall, D.H., 2020. Root Herbivory Controls the Effects of Water Availability on the Partitioning between Above- and Below-ground Grass Biomass. Functional Ecology, 34, 2403–2410.

[10] Franco, A.L.C., Guan, P., Cui, S., Tomasel, C.M., Gherardi, L.A., Sala, O.E., Wall, D.H., 2022. Precipitation Effects on Nematode Diversity and Carbon Footprint across Grasslands. Global Change Biology, 28, 2124–2132.

[11] Gao, D., Wang, F., Li, J., Yu, S., Li, Z., Zhao, J., 2020**.** Soil Nematode Communities as Indicators of Soil Health in Different Land Use Types in Tropical Area. Nematology, 22, 595–610.

[12] Gattoni, K., Gendron, E.M.S., Powers, K., Powers, T.O., Harner, M.J and Porazinska, D.L., 2024. Effects of drought-induced stress on nematode communities in aquatic and terrestrial habitats of the Nebraska Sandhills. Frontiers in Ecology and Evolution, 12:1305930.

[13] Griffiths, B. S., Römbke, J., Schmelz, R. M., Scheffczy, A., Faber, J. H., Bloem, J., Pérès, G., Cluzeau, D., Chabbi, A., Suhadolc, M., Sousa, J. P., Martins da Silva, P., Carvalho, F., Mendes, S., Morais, P., Francisco, R., Pereira, C., Bonkowski, M., Geisen, S., Bardgett, R. D., de Vries, F. T., Bolger, T., Dirilgen, T., Schmidt, O., Winding, A., Hendriksen, N. B., Johansen, A., Philippot, L., Plassart, P., Bru, D., Thomson, B., Griffiths, R. I., Bailey, M. J., Keith, A., Rutgers, M., Mulder, C., Hannula, S. E., Creamer, R., Stone, D., 2016. Selecting cost effective and policy-relevant biological indicators for European monitoring of soil biodiversity and ecosystem function. Ecological Indicators, 69: 213–223

[14] Gutíerrez, C., Fernández, C, Escuer, M., Campos-Herrera, R., Rodríguez, M.E.B., Carbonell, G., et al., 2016. Effect of soil properties, heavy metals and emerging contaminants in the soil nematodes diversity. Environmental Pollution. 213, 184–194.

[15] Han, X., Li, Y., Du, X., Li, Y., Wang, Z., Jiang, S., Li, Q., 2020. Effect of Grassland Degradation on Soil Quality and Soil Biotic Community in a Semi-Arid Temperate Steppe. Ecological processe, 9, 63.

[16] Homet, P., Ourcival, J.-M., Gutiérrez, E., Domínguez-Begines, J., Matías, L., Godoy, O., Gómez-Aparicio, L., 2023. Short- and Long-Term Responses of Nematode Communities to Predicted Rainfall Reduction in Mediterranean Forests. Soil Biology and Biochemistry, 179, 108974.

[17] Huang, J., Huang, T., Chen, J., Li, G., Wang, Z., Huo, N., 2023. Nematode community characteristics indicate soil restoration under different revegetation approaches in the semiarid area of the Chinese loess plateau. Forest, 14(9), 1886.

[18] Huo, Z., Li, Z., Guan, P., Shi, F., Jiang, H., He, C., Wang, Z.,2024. Effect of heavy metal contamination on soil nematode communities in urban brownfields. Global Ecology and Conservation 49, e02787.

[19] Kim, S.W., Waldman, W.R., Kim, T.Y., Rillig, M.C. 2020. Effects of Different Microplastics on Nematodes in the Soil Environment: Tracking the Extractable Additives Using an Ecotoxicological Approach. Environmental science & technology, 3;54(21):13868-13878.

[20] Korthals, G.W., 1997. Pollutant-induced changes in terrestrial nematode communities. Thesis, Wageningen Agricultural University, Netherland.

[21] Krashevska, V., Kudrin, A.A., Widyastuti, R., Scheu, S., 2019. Changes in Nematode Communities and Functional Diversity with the Conversion of Rainforest into Rubber and Oil Palm Plantations. Frontiers in Ecology and Evolution, 7.

[22] Li, J., Zhao, J., Liao, X., Yi, Q., Zhang, W., Lin, H., Liu, K., Peng, P., Wang, K., 2023. Long-Term Returning Agricultural Residues Increases Soil Microbe-Nematode Network Complexity and Ecosystem Multifunctionality. Geoderma, 430, 116340.

[23] Li, X., Chen, X., Zhu, H., Ren, Z., Jiao, J., Hu, F., Liu, M.,2020. Effects of Historical Legacies on Soil Nematode Communities Are Mediated by Contemporary Environmental Conditions. Ecology and Evolution, 10, 6732–6740.

[24] Li, X., Zhu, H., Geisen, S., Bellard, C., Hu, F., Li, H., Chen, X., Liu, M., 2020. Agriculture Erases Climate Constraints on Soil Nematode Communities across Large Spatial Scales. Global Change Biology, 26, 919–930.

[25] Liu, T., Mao, P., Shi, L., Eisenhauer, N., Liu, S., Wang, X., He, X., Wang, Z., Zhang, W., Liu, Z., et al., 2020. Forest Canopy Maintains the Soil Community Composition under Elevated Nitrogen Deposition. Soil Biology and Biochemistry, 143, 107733.

[26] Liu, Y., Wang, W., Liu, P., Zhou, H., Chen, Z., Suonan, J., 2022. Plant-Soil Mediated Effects of Long-Term Warming on Soil Nematodes of Alpine Meadows on the Qinghai–Tibetan Plateau. Biology, 11, 1596.

[27] Lü, Y., Chen, X., Xue, W.F., Zhang, W.D. 2020. Short-term Effects of Cadmium and Mercury on Soil Nematode Communities in a Pot Experiment. Helminthologia, 23; 57 (2): 145–153.

[28] Majdi, N., Traunspurger, W., Fueser, H., Gansfort, B., Laffaille, P., Maire, A., 2019. Effects of a Broad Range of Experimental Temperatures on the Population Growth and Body-Size of Five Species of Free-Living Nematodes. Journal of Thermal Biology 80, 21–36.

[29] Martín, J.A.R., Guti´errez, C., Escuer, M., García-Gonz´ alez, M.T., Campos-Herrera, R., Aguila, ´ N., 2014. Effect of mine tailing on the spatial variability of soil nematodes from lead pollution in La Union (Spain). Science of the total environment 473, 518–529.

[30] Martinez, J.G., Torres, M.A., dos Santos, G., Moens, T., 2018. Influence of heavy metals on nematode community structure in deteriorated soil by gold mining activities in Sibutad, southern Philippines. Ecological Indicators 91, 712–721.

[31] Matveeva, E. M., Sushchuk, A. A., 2016. Features of soil nematode communities in various types of natural biocenoses: effectiveness of assessment parameters. Biological Bulletin, 43(5): 474–482

[32] Mulder, C., Schouten, A. J., Hund-Rinke, K., Breure, A. M., 2005. The use of nematodes in ecological soil classification and assessment concepts. Ecotoxicology and Environmental Safety, 62(2): 278–289.

[33] Neher, D.A., 2001. Role of nematodes in soil health and their use as indicators. *Journal of nematology*, *33*(4), p.161.

[34] Neilson, R., Caul, S., Fraser, F.C., King, D., Mitchell, S.M., Roberts, D.M., Giles, M.E., 2020. Microbial Community Size Is a Potential Predictor of Nematode Functional Group in Limed Grasslands. Applied Soil Ecology, 156, 103702.

[35] Nisa, R.U., Tantray, A.Y., Kouser, N., Allie, K.A., Wani, S.M., Alamri, S.A., Alyemeni, M.N., Wijaya, L., Shah, A.A., 2021. Influence of Ecological and Edaphic Factors on Biodiversity of Soil Nematodes. Saudi Journal of Biological Sciences, 28, 3049–3059.

[36] Olatunji, O.A., Gong, S., Tariq, A., Pan, K., Sun, X., Chen, W., Zhang, L., Dakhil, M.A., Huang, D., Tan, X., 2019. The Effect of Phosphorus Addition, Soil Moisture, and Plant Type on Soil Nematode Abundance and Community Composition. Journal of Soils and Sediments, 19, 1139–1150.

[37] Pandey, M., Maurya, A.K. and John, V. (2022 a). Fusarium wilt of chick pea and its management: present and future. Emerging Sustainability Trends in Agricultural, Rural

& Environmental Development. *Society of Biological Sciences and Rural Development*. 229-237. ISBN: 978-81-923535-8-6.

[38] Pires, D., Orlando, V., Collett, R.L., Moreira, D., Costa, S.R., Inácio, M.L. 2023. Linking Nematode Communities and Soil Health under Climate Change. Sustainability, 15, 11747.

[39] Puissant, J., Villenave, C., Chauvin, C., Plassard, C., Blanchart, E., Trap, J., 2021. Quantification of the Global Impact of Agricultural Practices on Soil Nematodes: A Meta-Analysis. Soil Biology and Biochemistry, 161, 108383.

[40] Rencˇo, M., Gömöryová, E., Cˇ erevková, A., 2020. The Effect of Soil Type and Ecosystems on the Soil Nematode and Microbial Communities. Helminthologia, 57, 129–144.

[41] Salamún, P., Renˇco, M., Kucanova, E., Brazov ´ a, T., Papajova, I., Miklisova, D., *et al*., 2012. Nematodes as bioindicators of soil degradation due to heavy metals. Ecotoxicology 21, 2319–2330.

[42] Schratzberger, M., Holterman, M., van Oevelen, D., Helder, J., 2019. A worm's world: ecological flexibility pays off for free-living nematodes in sediments and soils. Bioscience, 69(11): 867–876

[43] Seesao, Y., Gay, M., Merlin, S., Viscogliosi, E., Aliouat-Denis, C. M., Audebert, C., 2017. A review of methods for nematode identification. Journal of Microbiological Methods, 138: 37–49

[44] Shaw, E.A., Boot, C.M., Moore, J.C., Wall, D.H., Baron, J.S., 2019. Long-Term Nitrogen Addition Shifts the Soil Nematode Community to Bacterivore-Dominated and Reduces Its Ecological Maturity in a Subalpine Forest. Soil Biology and Biochemistry, 130, 177–184.

[45] Siebert, J., Sünnemann, M., Auge, H., Berger, S., Cesarz, S., Ciobanu, M., Guerrero-Ramírez, N.R., Eisenhauer, N., 2019. The Effects of Drought and Nutrient Addition on Soil Organisms Vary across Taxonomic Groups, but Are Constant across Seasons. Scientific Reports, 9,

[46] Siebert, J., Ciobanu, M., Schädler, M., Eisenhauer, N., 2020. Climate Change and Land Use Induce Functional Shifts in Soil Nematode Communities. Oecologia, 192, 281–294.

[47] Tejeda-Benitez L, Olivero-Verbel J., 2016. Caenorhabditis elegans, a biological model for research in toxicology. Reviews of Environmental Contamination and Toxicology, 237: 1–35

[48] Thakur, M.P., Del Real, I.M., Cesarz, S., Steinauer, K., Reich, P.B., Hobbie, S., Ciobanu, M., Rich, R., Worm, K., Eisenhauer, N., 2019. Soil Microbial, Nematode, and Enzymatic Responses to Elevated CO2, N Fertilization, Warming, and Reduced Precipitation. Soil Biology and Biochemistry, 135, 184–193.

[49] Trap, J., Ranoarisoa, M.P., Raharijaona, S., Rabeharisoa, L., Plassard, C., Mayad, E.H., Bernard, L., Becquer, T., Blanchart, E., 2021. Agricultural Practices Modulate the Beneficial Activity of Bacterial-Feeding Nematodes for Plant Growth and Nutrition: Evidence from an Original Intact Soil Core Technique. Sustainability, 13, 7181.

[50] Tsiafouli, M. A., Bhusal, D. R., Sgardelis, S. P., 2017. Nematode community indices for microhabitat type and largescale landscape properties. Ecological Indicators, 73: 472–479

[51] Urzelai, A., Hernández, A. J., Pastor, J., 2000. Biotic indices based on soil nematode communities for assessing soil quality in terrestrial ecosystems. Science of the Total Environment, 247(2–3): 253–261

[52] Varga, I., Benković-Lačić, T., Lončarić, Z., Popović, B. and Brmež, M., 2019. Liming, phosphorus and zinc influence on soil nematode community structure at hot pepper. *Horticultural science*, *46*(2).

[53] Vazquez, C., Goede, R.G.M., Korthals, G.W., Rutgers, M., Schouten, A.J., Creamer, R., 2019. The Effects of Increasing Land Use Intensity on Soil Nematodes: A Turn towards Specialism. Functional Ecology, 33, 2003–2016.

[54] Wan, B., Hu, Z., Liu, T., Yang, Q., Li, D., Zhang, C., Chen, X., Hu, F., Kardol, P., Griffiths, B.S., et al. 2022. Organic Amendments Increase the Flow Uniformity of Energy across Nematode Food Webs. Soil Biology and Biochemistry, 170, 108695.

[55] Wang, B., Wu, L., Chen, D., Wu, Y., Hu, S., Li, L., Bai, Y., 2020. Grazing Simplifies Soil Micro-Food Webs and Decouples Their Relationships with Ecosystem Functions in Grasslands. Global Change Biology, 26, 960–970.

[56] Wang, J., Li, M., Zhang, X., Liu, X., Li, L., Shi, X., Hu, H., Pan, G., 2019. Changes in Soil Nematode Abundance and Composition under Elevated [CO2] and Canopy Warming in a Rice Paddy Field. Plant and Soil, 445, 425–437.

[57] Xiao, H., Wang, B., Lu, S., Chen, D., Wu, Y., Zhu, Y., Hu, S., Bai, Y., 2020. Soil Acidification Reduces the Effects of Short-term Nutrient Enrichment on Plant and Soil Biota and Their Interactions in Grasslands. Global Change Biology, 26, 4626–4637.

[58] Xiong, D., Wei, C., Wubs, E.R.J., Veen, G.F., Liang, W., Wang, X., Li, Q., Putten, W.H., Han, X. 2020. Nonlinear Responses of Soil Nematode Community Composition to Increasing Aridity. Global Ecology and Biogeography, 29, 117–126.

[59] Yang, Q., Veen, G.F., Wagenaar, R., Manrubia, M., ten Hooven, F.C., van der Putten, W.H., 2022. Temporal Dynamics of Range Expander and Congeneric Native Plant Responses during and after Extreme Drought Events. Ecological Monographs, 92, e1529.

[60] Yang, X., Cheng, B., Wang, Z., Wang, S., Liu, L., Gao, Y., Zhang, H., 2022. Characteristics and pollution risks of potentially toxic elements and nematode community structure on farm soil near coal mines. Environmental Geochemistry and Health 1–18.

[61] Yeates, G. W., Bongers, T., De Goede, R. G. M., Freckman, D. W., Georgieva, S. S., 1993. Feeding habits in soil nematode families and general outline for soil ecologists. Journal of Nematology, 25(3): 315–331

[62] Zhang, C., Wang, J., Ren, Z., Hu, Z., Tian, S., Fan, W., Chen, X., Griffiths, B.S., Hu, F., Liu, M., 2020. Root Traits Mediate Functional Guilds of Soil Nematodes in an Ex-Arable Field. Soil Biology and Biochemistry, 151, 108038.

[63] Zhang, G., Sui, X., Li, Y., Jia, M., Wang, Z., Han, G., Wang, L.,2020. The Response of Soil Nematode Fauna to Climate Drying and Warming in Stipa Breviflora Desert Steppe in Inner Mongolia, China. Journal of Soils and Sediments, 20, 2166–2180.

[64] Zhao, J., Zhang, W., Liu, X., Yang, R., Xiao, D., He, X., Wang, K., 2023. Grass Harvesting Eliminates the Beneficial Effects of Legume Addition on Soil Nematode Communities in a Tall Grass Pasture. Agriculture, Ecosystems & Environment, 349, 108468.

Dr. Papia Das
Dr. Papia Das is an accomplished zoologist and educator, currently serving as an Assistant Professor of Zoology at Budge Budge College. She holds an M.Sc. and a Ph.D. in Zoology from the prestigious University of Calcutta. Her areas of interest include taxonomy, ecology, and biodiversity conservation. She actively engages in academic collaborations and research projects that enhance understanding in her field.

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 87-103

Exploring the Water Crisis in Purulia, West Bengal: A Brief Review

Poulami Chakraborty[1] and Dr. Indrani Chakraborty[*2]
Department of Zoology, Jogamaya Devi College, Kolkata
[1]poulamichakraborty1999@gmail.com, [2]indrani.nrs@gmail.com

Abstract: One of the most important resources is water, which is crucial for all forms of development. Water resource management is currently very difficult in semi-arid hard rock regions alike Purulia due to issues like restricted water supplies, water demand, regional inequities, and climate change. Residents of this region still struggle to satisfy basic necessities for daily life, like drinking water and food, even after 78th years of independence. In terms of human and economic development, Purulia is among the most underdeveloped districts in West Bengal. It is also home to the second-largest number of scheduled tribe people. The residents of Purulia district regularly face the problem of water scarcity, which has a detrimental effect on this district's growth. Therefore, the Purulia people must be released from the scourge of water scarcity. In order to identify the underlying causes of Purulia's water scarcity, the current study has been made. However, without looking at the actual causes of the water shortage for the district's future water resource management planning, it is hard to lessen the current state of Purulia's water scarcity.

Keywords: Water scarcity, Purulia, evapotranspiration, drought, groundwater depletion

1. Introduction

All life on Earth depends on water, making it the most significant natural resource. The availability of water is essential to our society's growth and well-being. This valuable resource is unevenly distributed, both in area and time and might be sparse or abundant at different periods (Reddy 2011). In general, the main causes of water scarcity are climate change accompanied by high temperature, low precipitation, and loss of vegetation cover. However, there should be certain inherent factors associated with each geographic area's setup, origin, structure, and position. In West Bengal, Purulia is one of the most backward districts and is highly dependent on the rural economy. It is a rural western subtropical region in West Bengal, India, where 87.26% of the population residing in rural areas and this district have the second-highest percentage (18.45%) of scheduled tribes, mostly living in forested areas (District Profile, Purulia District 2024). Its substantial forest cover, 29.69% of the total land area, emphasizes its socio-economic complexities and ecological importance (District Profile, Purulia District, 2024).

Purulia is experiencing a severe water crisis because of land fragmentation and climate change. For the last three decades, the situation has worsened due to an increase in temperature, little precipitation, and significant evaporation driven by substantial changes in

[*] Corresponding author

climate. Even though there are several rivers in the area, the region's undulating landscape accounts for about 50% of water runoff. As a result, the annual rainfall is a pitiful 1,100 mm, much less than the 1,500 mm normal for the state of West Bengal. Here, summers are hot with temperatures over 50ºC, while winters are cold with lows of 3.8ºC (Forbes India, 2024). Water development and poverty alleviation are strongly related, particularly in low-income nations that rely heavily on the rural economy (UN-WATER 2006). Since water is crucial to both human and economic development, it is imperative to determine the reasons behind the district's water scarcity. The current study is merely a helpful attempt to pinpoint the underlying reasons behind the Purulia district's water shortage.

2. Study area

Purulia is significant to all of India due to its tropical position and funnel-like shape. Purulia is located between longitudes 85°45' and 86°39' E and latitudes 22°36' and 23°30' N. The district has a total size of 6259 km². Elevations in the Purulia district range from 63 to 712 meters above sea level, making it a steep terrain. It is situated on the Chota Nagpur Plateau's eastern slope. The district is distinguished by its low-lying valleys, steep hills, and undulating topography. The Ajodhya Hills lie to the district's west, the Dalma Hills lie to its south, and the Panchet Hills lie to its northeast. In the western region of West Bengal, the highest peak is the Gorgaburu peak (677 m) of the Ajodhya highlands.

The area's topography is defined by the slopes, which primarily face east and southeast. Figure 1 shows the block boundaries and rain gauge stations surrounding the Purulia district which were generated using ArcView GIS software collected from the Survey of India (SOI) (Bhaya & Chakrabarty 2016).

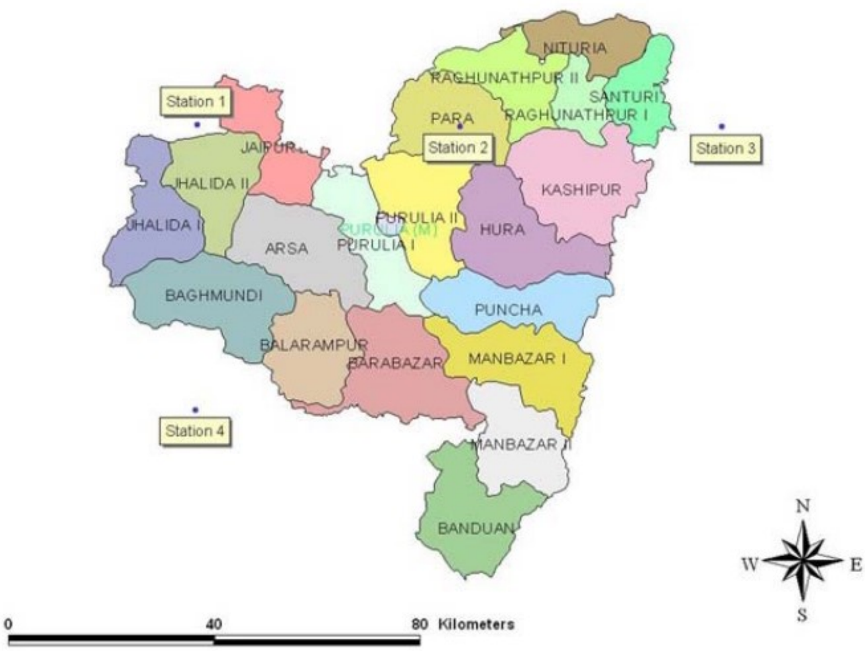


Figure 1. Map displaying the Purulia district of West Bengal's block boundaries and rain gauge stations (Bhaya & Chakrabarty 2016).

The district's notable rivers are the Damodar, Subarnarekha, Kumari, and Kangsabati. Most of the district's rivers flow east or northeast due to the district's general land slope. Since the rivers come from a plateau, they typically experience a shortage of water in the summer and winter, but during the monsoon season, the volume of water significantly increases. Purulia has a semi-arid climate. During the summer, Purulia experiences high temperatures of 50°C and lowest temperatures of 26°C.

The lowest temperature during the winter months is 3.8°C, while the highest temperature is 28°C. Rainfall in the district averages between 1050 and 1420 mm per year. This area has coarse, abrasive soils, including gravelly loams and sandy skeletal soils. In addition, red laterite soil that is rich in iron can be found in some areas. The high levels of calcium and potash render the soil unusable for farming. Farmers rely on monsoon rainfall for their agricultural operations because the district is prone to drought. With its unique soil, geography, drainage, forest, and entire range of physical environmental setup, Purulia's land shape is quite unusual and falls inside the West Bengal Rarh tract. There are currently 7 towns, 2687 villages, 2683 Mouzas, 170 Gram Panchayats and 20 Community Development (CD) blocks in the district. In most cases, the land surface is between 150 and 300 meters. Water scarcity has historically existed in Purulia, as evidenced by folklore and several folk songs, including Tusu, Vadu, and Jhumur (Ghosh & Mahato 2021). In terms of both economic and human development, Purulia is among the most underdeveloped districts in West Bengal. According to the 2011 Census, the district has the second-highest concentration of Schedule Tribes (ST) in West Bengal, and its economy is mainly on agriculture. Purulia is extremely wealthy and rich in its cultural past.

3. Causes of water scarcity in Purulia

Water scarcity has long existed in Purulia. Women in Purulia village start carrying earthen pots and pitchers down the village alleys each summer in search of water. Purulia's water scarcity is mostly caused by several issues. Due to the population's recent rapid development, the gap between the availability and demand for water is growing daily. Purulia has both a physical and an economic water shortage. Insufficient water resources to satisfy national or regional demands, particularly those for ecosystems to function properly, constitute physical water shortage (UNDP 2006). There is sometimes a physical scarcity of water in arid locations. Lack of investment in technology or infrastructure results in economic water scarcity.

3.1 Impact of Hydrometeorological Factor

The hydrometeorological conditions have a significant impact on the potentiality and availability of both surface and groundwater in any given area. This is also true in West Bengal's Purulia district. Water shortage in Purulia is mostly influenced by the primary hydrometeorological elements of runoff, air temperature, evapotranspiration, precipitation, and soil moisture.

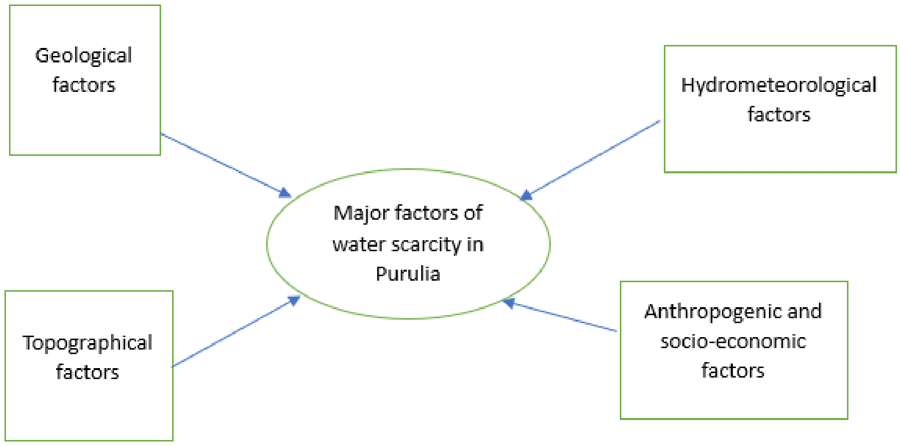


Figure 2. Common factors for water scarcity of Purulia.

The greatest quantity of precipitation, which is the primary source of water input, travels from the district boundary to the neighbouring areas as surface runoff due to the undulating topography, which eventually results in water scarcity. Another significant factor contributing to Purulia's water scarcity is the high rate of evapotranspiration. The sub-tropical climate of the district is typified by hot summers with high levels of transpiration and evaporation, which eventually results in a high rate of evapotranspiration (Bhaya & Chakrabarty 2016, Haldar & Saha 2015).

Water scarcity arises from evapotranspiration, which is a major cause of water loss. Purulia's water scarcity is also significantly influenced by temperature. There is dryness because of the extremely high summer temperatures and low winter temperatures, which range from 7°C to 52°C (Bhaya & Chakrabarty 2016, Haldar & Saha 2015).

A study analysing temperature from the year 1901 to 2000 found that Purulia exhibited an increasing trend in summer temperatures during this period. Purulia district has received Mean temperature $(29.508 \pm 3.324)^{0}$ C during the time period (Dey et al. 2018).

The temperature trend analysis was done by Dey et al. 2018 using a non-parametric statistical method for time series analysis, named, Mann-Kendall trend statistics.

$$S = \sum_{k=1}^{n-1} \sum_{j=k+n}^{n} sgn(X_j - X_k)$$

S: Mann-Kendall statistics, n: number of data points, $X_{j,}$ X_k: values at the time period of *j* and *k*.

Mann-Kendall τ (tau) =ATS / MPT, ATS = Actual Total Scores and MPT = Maximum Possible Total,

$$MPT = n(n - 1) / 2$$

$$Z = \frac{\tau}{\sqrt{2(2n+5)/9n(n+1)}}$$

Z: normal distribution. For N > 30, z value > 2.32 at 0.01 level of significance and > 1.64 at 0.05 level of significance for the sample to be statistically significant.

Table 1. Summer Temperature for the time period 1901 to 2000 of Purulia district.

Minimum	Maximum	Mean	SD	Mann-Kendall statistic (S)	Kendall's tau (τ)	Z value	Trend at 95% level of significance	Remarks
23.696	35.101	29.508	3.324	914	0.184	2.722	Increasing	Significant

(Dey et al. 2018)

Lack of precipitation and water scarcity in Purulia District – Severity of water scarcity or drought is measured by using the Standard Precipitation Index (SPI). The measure of drought vulnerability is the average condition of hydrological, agricultural, meteorological, and socio-economic drought (Baral et al. 2023) (Table 2). Various drought indices recommended by the India Meteorological Department are the Aridity Anomaly Index (AAI), SPI, Palmer Drought Severity Index (PDSI), etc. (Mishra & Bauri 2024, Raha & Deb 2023).

Based on the rainfall deficit, the drought index is called SPI.

$$AAI = (PE - AE/PE)*10$$

PE: water demand of a plant
AE: actual evapotranspiration (ET)
Classification: <25% mild, 26-50% moderate, >50% severe drought (Raha & Deb 2023)

Table 2. Types of droughts and their causes in Purulia, West Bengal. (Raha and Dey 2023)

Types of Droughts	Causes
Hydrological	Due to less average rainfall ground and surface water depletion
Agricultural	Groundwater depletion and loss of soil moisture causes less yield
Meteorological	Deficit of rainfall for an extended period, <25% mild
Socioeconomic	A shortfall in demand and supply, in an agro-based country with 1.4 billion, also impacts farm yield
Famine	Prolonged and severe hunger of the population resulting in community diseases, malnutrition, migration, sociopolitical instability
Desertification	Continuous drought, loss of topsoil, climate change, deforestation

Monthly precipitation data are used as input to SPI calculation and the same is used as input to the ArcView GIS to generate water scarcity severity maps. Based on a 12-month period, Figure 3 displays the area (as a percentage of the basin area) of the drought categories in September from 1971 to 2005. Additionally, it may be noted that for the years 1975, 1976, 1980, 1982, 1983, 1985, 1988, 1991, 1992, 1995, 1998, 2000, and 2001, scarcity affected over 50% of the study region (SPI < 0). This time series data indicates that scarcity episodes occurred in over 37% of the years during the 1971–2005 data period (Palchaudhuri & Biswas 2013).

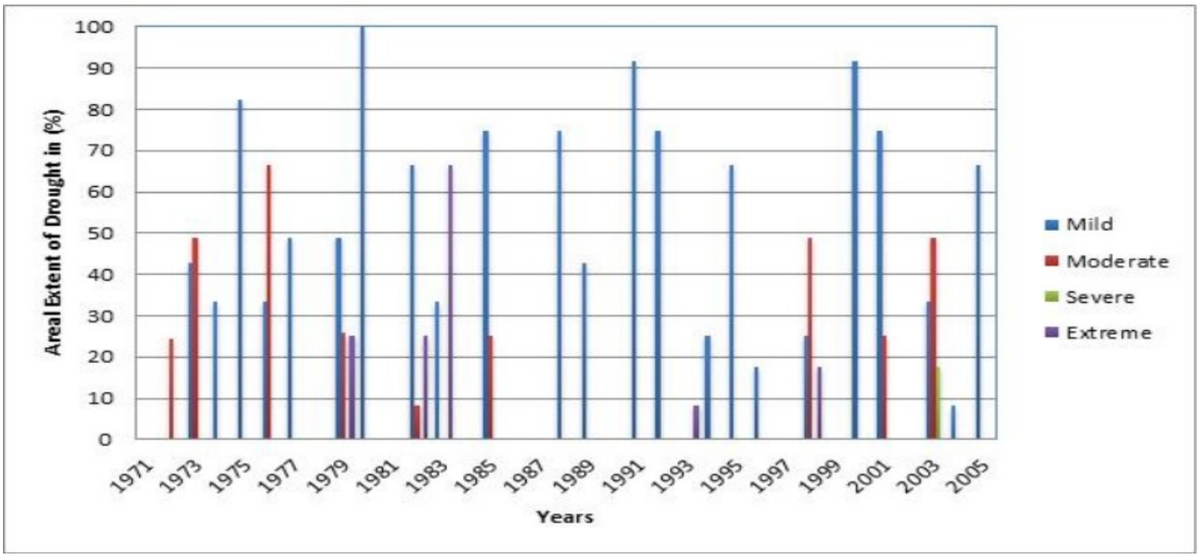


Figure 3. Areal extent of water scarcity severity in the Purulia district based on 12-month SPI for September (Palchaudhuri & Biswas 2013).

Table 3. Occurrence of water scarcity in the station of Purulia located at 23.5° N & 86.0° E

SPI Classes	Category of water scarcity	Water scarcity occurrence (%)		
		3 months	6 months	12 months
≤ −2	Extreme	0.00	5.714	5.882
(-1.99, -1.5)	Severe	8.57	2.857	2.941
(-1.49, -1)	Moderate	8.57	8.571	5.882
(-0.99, 0)	Mild	28.57	31.429	38.235

(Source: Palchaudhuri & Biswas 2013).

Table 3 shows percentage of water scarcity occurrence at multiple time scales and the categories of water scarcity in the station located in 23.5° N & 86.0° E of Purulia. In a study, SPI program developed by the National Drought Mitigation Centre, University of Nebraska-Lincoln is used to compute time series of SPI for each station in the basin and for each month of the year at different time scales (3, 6, and 12 months). It showed that the maximum SPI value (extreme water scarcity) occurs in station located in 23.5° N & 86.0° E in the year 1993. From the areal extent graph (Figure 3) it reveals that 1976, 1979, 1980, 1982, 1983, 1985, 2001 and 2003 are the worst years with nearly 100% of the total area under extreme water scarcity. Mild and moderate scarcity occur in the central portion of the Purulia district. The northeast part of the district is prone for severe water scarcity and extreme scarcity occurs in northwest and southwest part of the district. So, the entire district can be labelled as drought prone area (Figure 4) (Palchaudhuri & Biswas 2013).

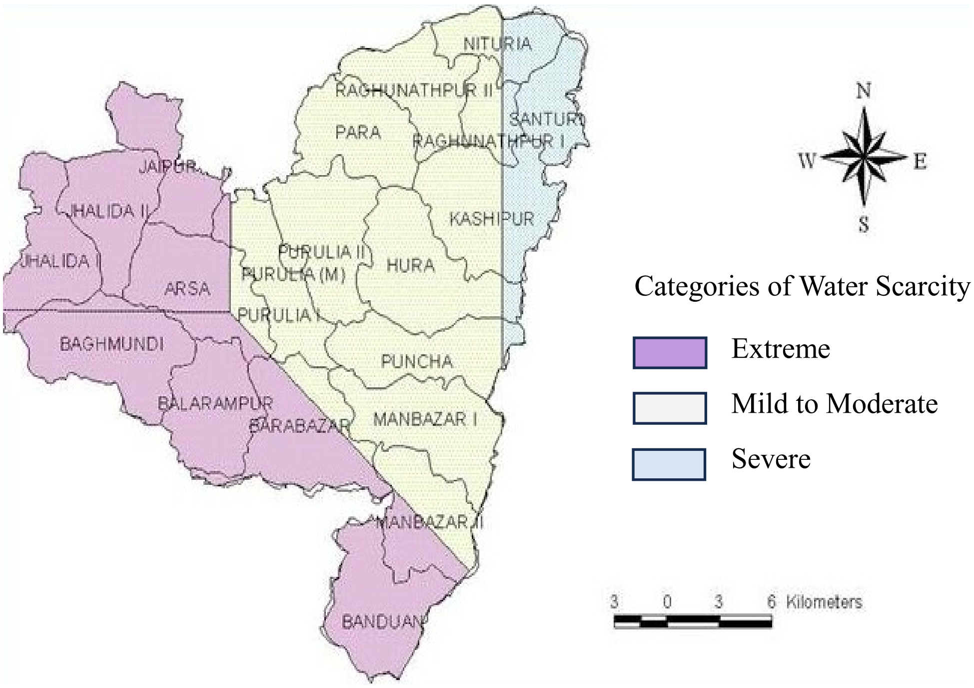


Figure 4. Categories of water scarcity in different blocks of Purulia district (Palchaudhuri & Biswas 2013).

3.2. Impact of Topological Factor

The district, which is a crucial section of the Chota Nagpur plateau, is largely covered in hills. The Panchakot hill is 2110 feet high, the Jaichandi hills are roughly 1045 feet high, and the Ajodhya hills in Purulia reach a height of 2200 feet. These western hills' slope progressively flattens out and merge with the east and south-eastern sides' level landscape. Thus, precipitation-induced surface runoff follows the slope from the western to the eastern side. As a result, there is comparatively little penetration in the western and northwestern districts.

3.3. Impact of Geological Factors

Any region's groundwater potentiality and availability are determined by its geologically regulated aquifer system. Granite gneiss rocks predominate in West Bengal's Purulia district. Geologically, Purulia is a hard rock terrain and, as a consequence of this, has low primary porosity and permeability.

The district primarily exhibits semi-arid climatic conditions, and the difference between the changes in diurnal temperature is remarkable here.

3.3.1 Groundwater depletion

Unregulated and excessive pumping of groundwater for irrigation, industrial use, and domestic purposes has led to declining water levels and well drying up in specific regions. Water scarcity is exacerbated by this overexploitation, especially when rainfall is insufficient. Only 1% of the area is irrigated by groundwater, which is limited by the rocky terrain and shallow wells frequently dry up. Although surface water, boreholes, and hand-dug wells are essential water resources, their daily use is mostly dependent on sufficient rainfall. Groundwater is crucial in the summer, but the problem is made worse by inadequate recharge rates that fall short of human demands (Haldar & Saha 2015).

The study conducted by the Central Ground Water Board in the Purulia district shows that groundwater occurs in Purulia within four distinct zones, i.e. (i) worn mantle, (ii) saprolitic zone, (iii) hard rock fracture zone, and (iv) unconsolidated sediment zone (Haldar & Saha 2015).

(i) The worn Mantle varies in depth and maximum thickness reaches up to 25 m. Groundwater occurs in water table conditions and is predominantly developed by open-dug wells. In some places, these wells become dry in the dry summer season. Water-yielding capacities are low and restricted within 2.75 lps. (Bera & Das 2021).

(ii) Weathered mantle and unweathered granitic rocks enclose the saprolitic zone. This zone's depth varies from 10 to 30 mbgl. The average thickness is 4m. The semi-confined conditions in which groundwater occurs can produce water at a pace of 2.5 lps. There is far less drawdown in the wells tapping this zone, and recovery is rather quick (Bera & Das 2021).

(iii) Saturated fractures located far below the surface of hard, crystalline rocks where groundwater is found. Typically, these fractures only occur between 50 and 110 mbgl. Shallower-depth fractures typically occur between 50 and 60 meters below the surface, and they are primarily accessed by hand-pumped borewells that produce water at a rate of less than 1 to 2.77 lps. At a depth of 100 to 110 meters, deeper fractures are discovered. In Manbazar, this zone has a yielding capability of 3 lps. Fractures are seen in Gondwana sediment zones at a depth of 103 meters. Their depth ranges from 24 to 36 mbgl, and they can produce water at 3.3 to 5.5 lps. (Bera & Das 2021).

(iv) The unconsolidated sediment zone between 5 and 13 mbgl. This tiny section is only 1 to 2 kilometers across the valley, and its thickness fluctuates. The alluvial tract's saturated thickness ranges from 1 to 5.5 meters. This zone has a medium capacity to yield water. For a long time, shallow tube wells and open-dug wells can produce 20 m^3 of water each hour (Bera & Das 2021).

Table 4. Summary of groundwater resources in Purulia District (Bera & Das 2021).

Block	Net groundwater availability (in ha m)	Existing Gross groundwater draft for all uses (in ha m)	Net groundwater availability for future irrigation (in ha m)	Stage of groundwater development (%)
Baghmundi	2172	597	1513	27.47
Barabazar	6275	483	5711	7.70
Arsha	3704	251	3382	6.79
Balarampur	2988	416	2518	13.93
Bandwan	2947	210	2691	7.11
Hura	3417	338	3007	9.90
Jhalda I	2144	996	1086	46.44
Jhalda II	2707	560	2081	20.68
Joypur	2090	972	1058	46.49

Kashipur	6073	1028	4953	16.93
Manbazar I	5258	371	4812	7.06
Manbazar II	3992	168	3775	4.20
Neturia	2942	277	2617	9.41
Puncha	4970	433	4476	8.71
Para	3178	401	2688	12.62
Purulia I	3602	785	2748	21.80
Purulia II	3781	604	3100	15.97
Raghunathpur I	2496	303	2147	12.12
Raghunathpur II	2267	246	1970	10.86
Santuri	3143	228	2875	7.24
Total	**70147**	**9666**	**59207**	**13.78**

Table 5. Availability of groundwater in the Blocks of Purulia (Kar et al. 2020, Bera & Das 2021).

Groundwater availability classes	Name of the Blocks
Very low (below 3000 ha m)	Baghmundi, Balarampur, Bandwan, Jhalda-I and II, Jaypur, Neturia, Raghunathpur- I and II
Low (3000-3999 ha m)	Arsha, Hura, Manbazar-II, Para, Puruliya – I and II, Santuri
Medium (4000-4999 ha m)	Puncha
High (5000 ha m and above)	Manbazar-I, Barabazar, Kashipur

Source: Roy 2014

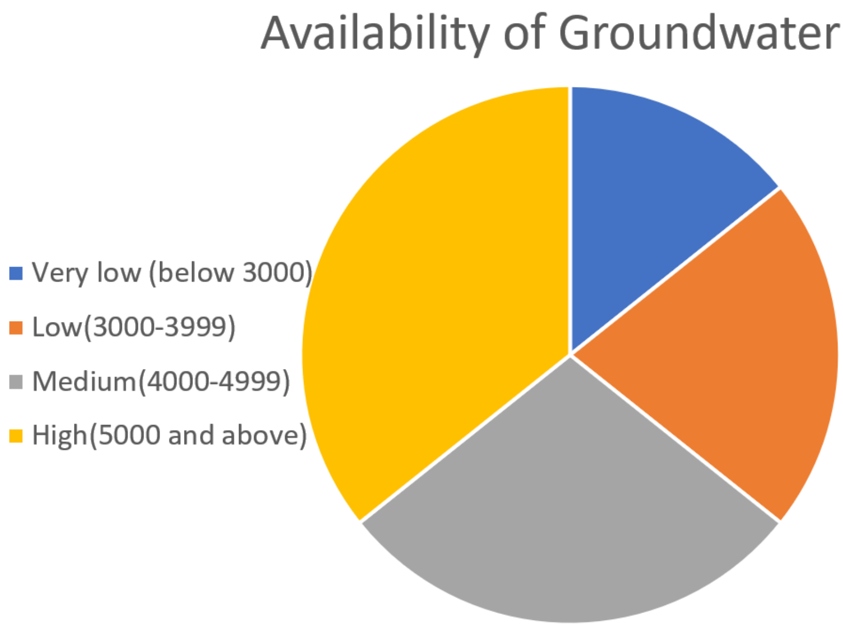


Figure 5. Chart representing the Table 5.

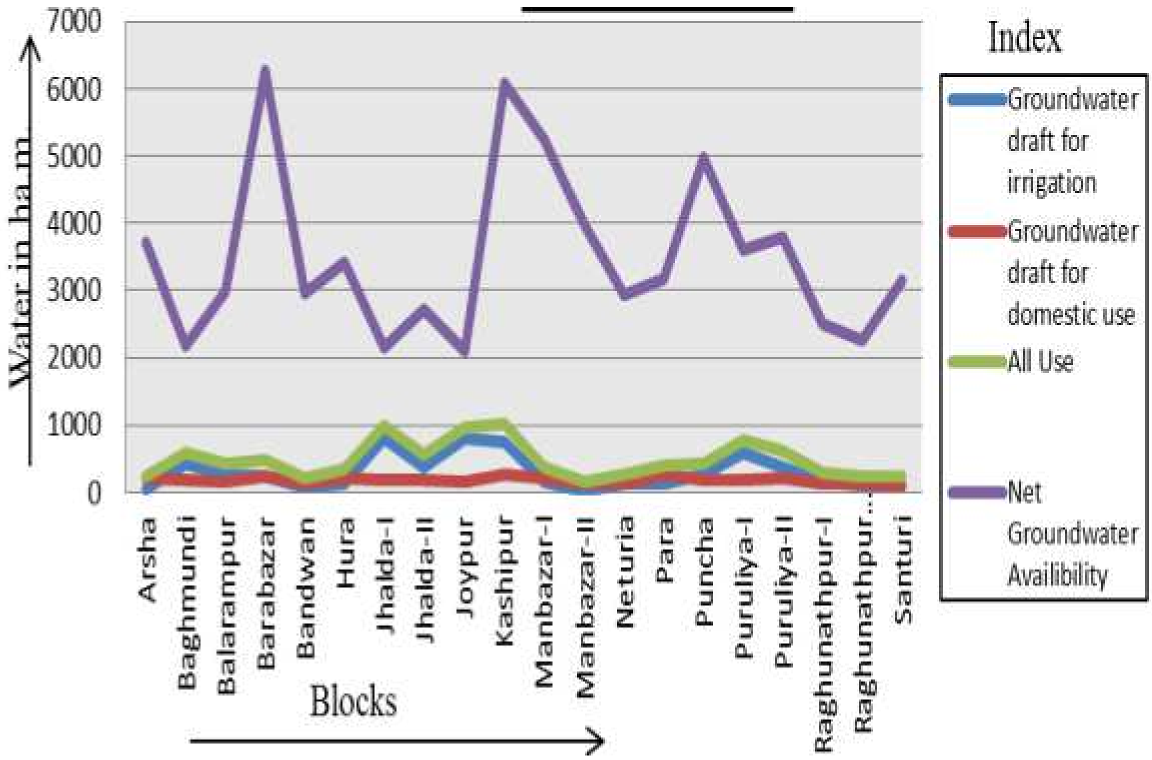


Figure 6. Groundwater scenario of Purulia district (Roy 2014).

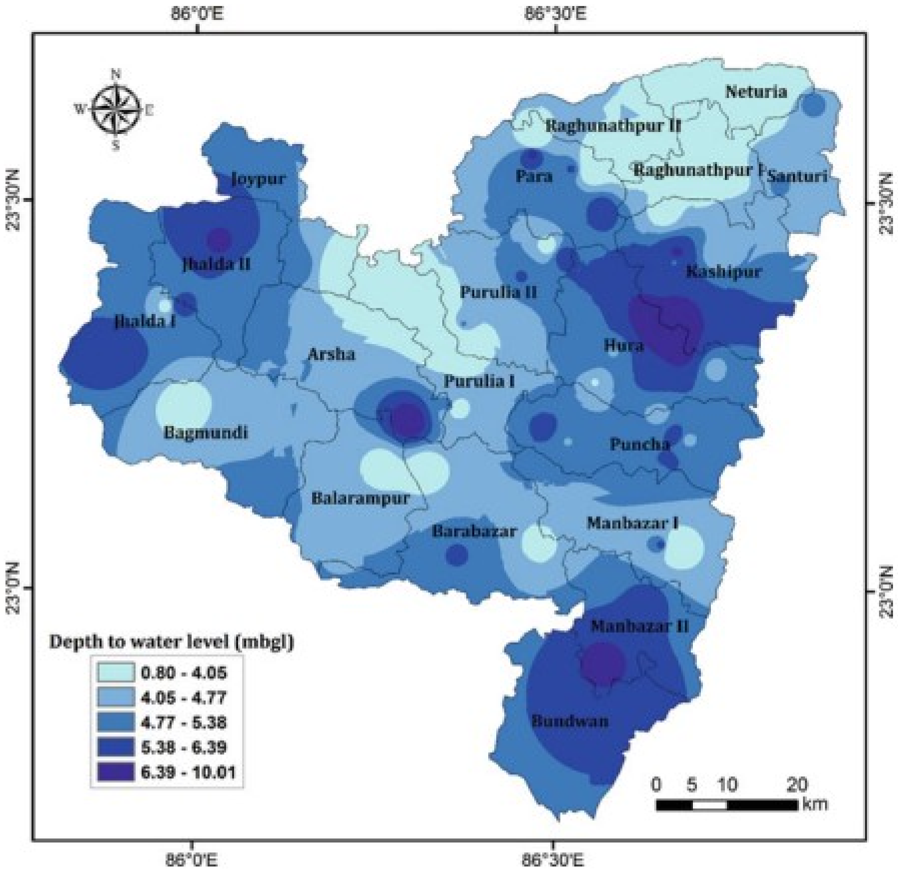


Figure 7. Distribution of groundwater depth in Purulia district during lean season in 2018.

Depth of groundwater level data, which is mainly of lean season of 2018, was collected from the Central Ground Water Board (CGWB). The groundwater development status and groundwater resource availability data were also taken from a published report booklet of CGWB on Purulia district. During the lean period, groundwater level varies from 0.80 mbgl to 10.1 mbgl. Higher groundwater depth ranging from 6.39 mbgl to 10.01 mbgl are observed in few blocks of Purulia, like Jhalda-I and Jhalda-II, Banduan, Manbazar-II, Kashipur, and Hura. On the other hand, shallow groundwater depth can be observed mainly in Neturia, Raghunathpur I and II, Purulia I, Baghmundi, and Manbazar I blocks as it is the source of drinking water, agricultural activities and due to the lack of precipitation and soil's water holding capacity. Groundwater equilibrium is getting hampered due to not following the basic rules of groundwater extraction, resulting in water crisis.

3.3.2 Water quality of Purulia

Climate change including increased temperature, and drought is directly affecting the water quality of Purulia, which affects pH, BOD, COD, total dissolved solutes, etc. In a study of a period of ten years (2012-22), by using Pearson correlation, it was found that there is a positive correlation between average annual temperature and COD (0.83), phosphate (0.71), and ammonia (0.71). BOD also has a strong correlation with ammonia (0.78) and phosphate (0.81). This result makes them sensitive water quality indicators to monitor the consequences of climate change (Mukherjee et al. 2024).

3.4 Impact of Socioeconomic and Anthropogenic Factors

Purulia's water scarcity is largely caused by several socio-economic and human factors, including poverty, population growth, ignorance of the water resource, unscientific water use, grazing, deforestation, agriculture, and antiquated groundwater withdrawal techniques (Pan 2021).

Another factor contributing to water scarcity is the overuse of ground and surface water for agriculture. With 3,48,500 hectares of net sown land, or around 55% of the total reported area, agriculture plays a crucial role in the Purulia district. This district's agriculture is primarily mono-cropped (Roy 2014). Paddy is the primary crop of the district. The crops are primarily cultivated with little fertilizer input and rainfed conditions. Compared to other West Bengal districts, productivity of this district is significantly lower. Thus, maximum amount of water is used for agriculture. One of the most noticeable effects of the growing population is deforestation. Therefore, the inhabitants of Purulia are forced to destroy the forest in order to increase the amount of agricultural land and settlement in order to meet the growing need for food and shelter. In addition, some people regularly destroy the natural vegetation in order to make a living (Mukherjee et al. 2024). High evaporation and soil erosion brought on by deforestation eventually result in water loss. Another significant contributing reason to water scarcity is grazing, which lowers the rate at which soil infiltration occurs (Raha & Deb 2023).

The poor backward class, who makes up a large portion of the district's population, lacks the contemporary technology and financial means necessary to build tube wells for themselves or the benefit of the entire village. Purulia is a district in West Bengal that is economically disadvantaged. Therefore, the residents must rely on dams or bodies of surface water to meet their water needs.

High evaporation and soil erosion brought on by deforestation eventually result in water loss. Another significant contributing reason to water scarcity is grazing, which lowers the rate at which soil infiltration occurs (Raha & Deb 2023).

Despite the area being dry 70% of the year, farmers struggle to get water from the dried-up Kasai River, which is essential for the area. Farmers spend about Rs 1,000 a day on diesel to run pumps and carry water by tanker to irrigate their far-flung areas, making farming financially viable (Bhaya & Chakrabarty 2016). Women in Purulia are responsible for bringing water, and walking many kilometers each day while toting heavy loads. This has an impact on childcare, their earnings prospects, and their health. Only two to three buckets of water per day are provided to each family by the government-installed solar taps in several Purulia villages, hardly enough to cover their daily needs (Bhaya & Chakrabarty 2016).

Table 6. Major factors of surface and groundwater scarcity of Purulia (Pan 2021).

Types	Factors	Government's Initiative
Economic Factors	Urbanization	Jal Dharo-Jal Bharo Scheme; Afforestation Programme; Rationing; MGNREGA
	Poverty	
	Population Growth	
	Deforestation	
	Primitive Technique in Agriculture	
	Lack of Budget	
	Proper Monitoring	
Social Factors	Unscientific water use	CSR, Community Development; Mati Utsav; Handicraft Fair
	Ignorance of people	
	Lack of Reservoir	
	Grazing	
	Inadequate Knowledge	
	Inadequate Institutions	
	Legal Authority	

3.4.1 Human Mobility in Purulia

A few multivariate research examined migration of people of Purulia brought on by climate change. Regular exposure to contaminated water increases the risk of infection for women, girls, and children. With dry riverbeds serving as the sole source of water for drinking, bathing, sanitation, and domestic chores, the entire district is facing a severe water crisis. For a steady income, many young people resort to illegal sand mining from the riverbed, which poses serious environmental risks such as habitat destruction, erosion, and flooding. Due to water scarcity, agricultural practices are unsustainable, which forces marginal laborers to relocate from Purulia to neighboring states in search of other sources of income (Forbes India, 2024). Higher percentages of migration are found in the blocks of Purulia with low SPI, and vice versa (Raha & Gayen 2021).

4. Mitigation approaches

4.1 Jalatirtha

The Jalatirtha scheme was launched in the year 2014-15 to conserve rain and surface water in the arid districts of West Bengal, including Purulia (Jalatirtha 2024). The scheme's objectives include:

- Constructing check dams, water collection systems, and small-scale surface flow irrigation projects (Jalatirtha 2024)
- Providing assured irrigation throughout the year (Jalatirtha 2024)

4.2 Jal Dharo-Jal Bharo

The Jal Dharo-Jal Bharo scheme aims to harvest rainwater from various water bodies, such as ponds, tanks, underground artificial recharge, canals, and reservoirs. It also aims to increase awareness of rainwater conservation and efficient use of water in irrigation (Jal Dharo-Jal Bharo 2024).

4.3 Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)

To enhance groundwater recharge, this program encourages scientific moisture conservation and runoff control techniques. It encourages community irrigation through registered user groups, farmer producers' organizations, and NGOs (PMKSY 2016).

4.4 Marble Lake Water Project

It is a piped Water Supply system from Marble Lake to the surrounding areas covering six villages and ten habitations benefiting 2995 people by drinking water (Marble Lake Water Project 2024).

4.5 'USHARMUKTI' Micro-Watershed Scheme

The goal of this system is explained by the name "USHARMUKTI." This plan aims to erase dryness and transform six more drought-prone West Bengal districts, in addition to Purulia, into verdant areas with abundant crop and vegetation development. The Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) is the project's central component. In addition, the program now includes organizations like the Bharat Rural Livelihoods Foundation (BRLF) and other voluntary service organizations. The primary purpose of this project is to develop the water divide.

4.6 Watershed Management

Managing drinking water and groundwater in dryland areas such as Purulia is the focus of watershed management. This model helps the farmers to maximize their return from agricultural production. This study carries out a sensitivity analysis by unsettling various technologies used in less water-intensive crop production, annual recharge of groundwater stock, and discount rate. This study states how upstream and downstream farmers can optimize net benefits from agriculture when there is water conflict between them. It also demonstrates how their water extraction patterns and benefits can change their social life (Ghosh & Gupta 2023).

A comprehensive strategy is needed to address the Purulia district's water shortage, one that incorporates effective irrigation methods, drought management strategies, climate-resilient water supply system promotion, sustainable and equitable management of water resources, and community engagement (National Hydrology Project 2023).

5. Conclusion

Addressing one of the most pressing issues, such as water scarcity, calls for a multidisciplinary approach to water resource management, particularly in areas like Purulia with numerous challenges like illiteracy, topographic and natural barriers, soil type and texture, a weak economy, poor community health, and climate change. In addition to preserving the natural balance of water resources, effective water management is unavoidably necessary for increased economic growth and better public health in a district like Purulia. The participation of local residents, businesses, institutions, and the government is essential. Ultimately, taking into account all of the information above regarding the value of water, the effects of water scarcity, and sustainable water use, it is imperative that people from all walks of life, as well as governmental and non-governmental organizations, collaborate in a comprehensive way to secure water for future generations and to safeguard the global natural ecosystem.

Achieving sustainable water resource management may need constant monitoring of the resulting needs and maintaining equilibrium between supply, demand, and water conservation due to climate change and rising water demand in several sectors, primarily irrigation like in Purulia. For survival, water is essential. Therefore, the water crisis is not merely another environmental crisis; rather, it is a source of instability and a threat to the entire civilization. Therefore, the freedom to utilize water responsibly and justifiably is one of every human being's fundamental rights.

ACKNOWLEDGMENT

I would like to thank the Research Committee of Jogamaya Devi College for making all the necessary arrangements for this publication and also to the Editorial Board of this volume for editorial handling of the article and efficiently coordinating all the works associated to it. I would like to thank Dr. Srabani Sarkar, Principal, Jogamaya Devi College for her constant inspiration.

References

[01] Baral, U., Saha, U.D., Mukhopadhyay, U. et al., 2023. Drought risk assessment on the eastern part of Indian peninsula—a study on Purulia district, West Bengal. Environ Monit Assess, 195, 1364. https://doi.org/10.1007/s10661-023-11920-4

[02] Bera, A., Das, S. 2021. Water Resource Management in Semi-arid Purulia District of West Bengal, in the Context of Sustainable Development Goals. In: Shit, P.K., Bhunia, G.S., Adhikary, P.P., Dash, C.J. (eds) Groundwater and Society. Springer, Cham. https://doi.org/10.1007/978-3-030-64136-8_23

[03] Bhaya, S., Chakrabarty, A., 2016. Application of Geoinformatics in Pattern Analysis of Seditious Activity in Purulia District of West Bengal in Relation to its Geographical and Socio-economic Background. International Journal of Scientific and Research Publications, 6(9).

[04] Dey, K.K., Dwivedi, V.K., Mishra, S., 2018. Analysis of Long-Period Seasonal Variation of Temperature for the District of Bankura and Purulia in a Time of Climate Change. International Journal of Current Research, 10(11), 75495-75497.

[05] District Profile, Purulia District, 2024, Government of West Bengal. National Informatics Centre, Ministry of Electronics & Information Technology, Government of India.

[06] Forbes India, 2024. Desperate Thirst: Climate change and recurrent water crisis plaguing West Bengal's Purulia district in India, Mar 28.

[07] Ghosh, S., Gupta, K., 2023. Dynamic Analysis of Watershed Management and Sustainable Agriculture in Dryland Regions: A Case Study of Purulia District, West Bengal. Review of Development and Change, 28(2), 207-244. https://doi.org/10.1177/09722661231221042

[08] Ghosh, S., Mahato, S., 2021. Moral Values in the Light of Purulia's Folk Culture. International Journal of Research Publication and Reviews, 2(11), 652-654.

[09] Haldar, S., Saha, P., 2015. Identifying the Causes of Water Scarcity in Purulia, West Bengal, India - A Geographical Perspective. IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT), 9(8).

[10] Jalatirtha, 2024. Water Resources Investigation and Development Department, Government of West Bengal.

[11] Jal Dharo-Jal Bharo, 2024. Water Resources Investigation and Development Department, Government of West Bengal.

[12] Kar, S., Sen, E., Mukherjee, S., 2020. A geospatial technique-based site suitability analysis for construction of water reservoirs in Arsha and Balarampur Blocks, Purulia. World Water Policy. 6. 10.1002/wwp2.12021.

[13] Marble Lake Water Project, 2024. Purulia, Government of West Bengal.

[14] Mishra, S., Bauri, B., 2024. Carving Drought Impact Over Purulia District, West Bengal, India. Advances in Research, 25, 186-205. https://doi.org/10.9734/air/2024/v25i31064.

[15] Mukherjee, P., Banerjee, G., Saha, N., Mazumdar, A., 2024. Water Quality Assessment of Purulia District, West Bengal, India Under Changed Climate Scenario. In: Mazumder, D. (eds) Sustainable Advanced Technologies for Environmental Management. SATEM-2023 2023. Springer Proceedings in Earth and Environmental Sciences. Springer, Cham. https://doi.org/10.1007/978-3-031-64006-3_8

[16] National Hydrology Project, 2023. Water Scarcity in Purulia, West Bengal Ground Water, July 12.

[17] Palchaudhuri, M., Biswas, S., 2013. Analysis of Meteorological Drought using Standardized Precipitation Index - A case study of Purulia District, West Bengal, India. International Journal of Environmental, Ecological, Geological and Geophysical Engineering, 7, 119-126.

[18] Pan, S., 2021. A Study on Present Scenario of Water Scarcity in Purulia District of West Bengal, India. Economy Polity Environment, 3(2).

[19] PMKSY (Pradhan Mantri Krishi Sinchayee Yojana), 2016. https://pmksy.gov.in/mis/Uploads/2016/20161205030245448-1.pdf.

[20] Raha, S., Deb, S., 2023. Evaluation of the Drought Trend Alongside of Change Point: A Study of the Purulia District in West Bengal, India. Curr World Environ., 18(2). https://doi.org/10.12944/CWE.18.2.10.

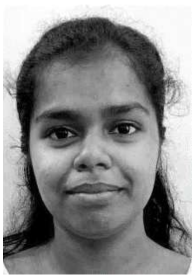
[21] Raha, S., Gayen, S.K., 2021. Drought-Induced Human Mobility in Purulia District of West Bengal. In: Rukhsana, Haldar, A., Alam, A., Satpati, L. (eds) Habitat, Ecology and Ekistics. Advances in Asian Human-Environmental Research. Springer, Cham. https://doi.org/10.1007/978-3-030-49115-4_15

[22] Reddy, P. Jaya Rami, 2011. A Textbook of Hydrology, Published by University Science Press, An Imprint of Laxmi Publications Pvt. Ltd., New Delhi, India.

[23] Roy, A., 2014. Availability, Scarcity and Potentiality of Ground Water Resources of Purulia District, West Bengal: An Appraisal. International Journal of Scientific Footprints, 2(1), 78-93.

[24] UNDP, 2006. Human Development Report, Beyond Scarcity: Power Poverty and the Global Water Crisis, Published by United Nations Development Programme, New York, USA.

[25] UN-WATER, 2006. Coping with water scarcity, A strategic issue and priority for system wide action. UN-WATER, www.unwater.org



Poulami Chakraborty

Poulami Chakraborty began her academic journey in the Department of Zoology at Jogamaya Devi College, Kolkata, as an undergraduate student and later transitioned into a teaching role after completing her M.Sc. from the University of Calcutta. She currently balances dual responsibilities, serving as a teacher cum instructor at Jogamaya Devi College in the morning while also working as a Research Assistant in the project *"Understanding the Role of Cholesterol Metabolism in Lung Cancer,"* conducted by the School of Medical Science and Technology, Indian Institute of Technology, Kharagpur (IIT-KGP).

Dr. Indrani Chakraborty

Dr. Indrani Chakraborty is an Assistant Professor in the Department of Zoology at Jogamaya Devi College, Kolkata. She earned her Ph.D. from the Department of Life Science and Biotechnology, Jadavpur University, in 2010. Her doctoral research focused on *"Oxidative Stress-Mediated Cellular Damage and Altered Erythrocytic Glucose Metabolism in Beta Thalassemia Major and Hemoglobin E Beta Thalassemia."* With a strong research background, her interests span Medical Biotechnology, High Dilution Research, Biophysics, Environmental Science, and related fields. She has contributed extensively to these areas through numerous original research publications in esteemed national and international peer-reviewed journals.

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 104-129

The Path to Recovery: Land Restoration as a Key to Combating Desertification and Drought Effects

Samuel Biswas[1] and Subhra Prakash Nayek
Assistant Professor, Department of BBA, Haldia Institute of Management
[1]samuelbiswas777@gmail.com

Abstract: Desertification and drought are global severe challenges worsened by climate change and unmaintainable land management practices. This research article analyses the role of land restoration in reducing the effects of these phenomena. Also highlighting its importance for ecological balance, agricultural yield, and community resilience. The paper synthesizes literature, case studies, and experiential data to understand restoration approaches fully. It emphasizes the interconnection of desertification, drought, and climate change. It also demonstrating how these problems produce a vicious cycle that endangers food security and socio-economic stability. The findings show that reestablishing degraded lands can improve soil fertility, enhance water retention abilities, and increase biodiversity. Moreover, creating more robust ecosystems capable of surviving climatic extremes. Furthermore, the research discusses the socio-economic consequences of land restoration efforts. It highlights the necessity for integrated approaches that contain local communities and policymakers. Engaging communities confirms that restoration measures are culturally suitable and tailored to meet the exact needs of those most harmed by land degradation. This research addresses the fundamental factors of land degradation through creative techniques like agroforestry, reforestation, and sustainable land management. It aims to contribute to sustainable development goals and enhance global resilience against climate-related challenges. Furthermore, it emphasizes the value of supportive policy frameworks focusing on human rights and community engagement in land management efforts. This research promotes collaboration among stakeholders at all levels. It supports an integrated approach to land restoration that restores ecosystems and protects the livelihoods of vulnerable populations. Finally, this study aims to inform future approaches for combating desertification and drought. It also encourages sustainable development on a global scale. As a result of these efforts, we can work towards a more sustainable future where ecosystems and communities unite.

Keywords: Sustainable agriculture, ecosystem rehabilitation, soil erosion prevention, water conservation, climate resilience, biodiversity enhancement, deforestation control, carbon sequestration, rural development.

1. Introduction

Desertification is the destruction of land in arid, semi-arid, and dry sub-humid parts resulting from many factors, comprising climatic variations and human activities (UNCCD 2017). Drought is a lengthy dry period that can contribute to significant water shortages, badly affecting agriculture, ecosystems, and human livelihoods (WMO 2020). The amalgamation of these two phenomena creates substantial threats to food security, biodiversity, and socio-economic stability worldwide.

The United Nations estimates that about 1.5 billion people live in regions influenced by desertification (UNCCD 2019). As climate change deepens these challenges, exploring successful land restoration strategies becomes progressively essential. This paper argues that restoring degraded lands is vital for fighting desertification and drought and nurturing sustainable development.

1.1 The Global Context of Desertification and Drought

Desertification impacts almost 2 billion hectares of land globally, which compares to about 1/4 of the Earth's land surface (FAO 2018). This phenomenon is mainly dominant in sub-Saharan Africa, parts of Asia, and the Mediterranean basin. These parts are characterized by unstable and weak ecosystems highly vulnerable to degradation due to climatic situations and human pressures. The outcomes of desertification go beyond ecological deterioration; they also include economic fatalities and social upheaval. For example, agricultural productivity drops meaningfully in degraded lands, resulting in food shortages and heightened poverty rates among affected populations.

Droughts worsen these problems by creating circumstances of extreme water shortage. According to the World Meteorological Organization (WMO), droughts have become more common and severe due to climate change, affecting up to 55 million people yearly (WMO 2020). The interplay between desertification and drought produces a vicious cycle: as land is damaged, its capability to hold moisture reduces, making it more vulnerable to drought. This cycle not only endangers agricultural output but also weakens the livelihoods of communities that depend on agricultural and natural resources.

1.2 Socio-Economic Implications

The socio-economic consequences of desertification and drought are severe. In various developing countries, agriculture is the critical source of income for rural populations. Farmers face decreased yields and enlarged vulnerability to food insecurity when land undergoes degradation or drought. This condition can lead to malnutrition and health problems within affected populations, mainly children and the elderly. Additionally, as agricultural productivity falls, families may be forced to move in search of better opportunities, resulting in urban overpopulation and an increased burden on city resources.

The economic costs connected with desertification are astonishing. The United Nations Convention to Combat Desertification (UNCCD) valuations that desertification costs countries about $42 billion annually in lost agricultural yield alone (UNCCD 2019). These losses can delay national development efforts and aggravate existing disparities within societies. Vulnerable groups—like women, native peoples, and smallholder farmers—are often disproportionately impacted by these challenges due to restricted access to resources and decision-making power.

1.3 The Role of Climate Change

Climate change plays a crucial role in intensifying both desertification and drought conditions. Increasing temperatures lead to higher evaporation rates from soils and water bodies while changing precipitation patterns worldwide (IPCC 2014). These changes can result in prolonged dry spells scattered with heavy rainfall events that lead to soil erosion and further damage to land quality. Therefore, climate change not only threatens current ecosystems but also makes it difficult to restore damaged lands.

Furthermore, climate change influences are inconsistent; they differ significantly across various regions. For example, while some parts may experience increased rainfall, causing flooding, others may face extended droughts with overwhelming costs for agriculture. This inconsistency poses substantial challenges for policymakers looking to implement successful land management techniques that consider local situations.

1.4 Importance of Land Restoration

Given the interconnection of these problems, desertification, drought, and climate change, it becomes progressively clear that land restoration should be prioritized in any comprehensive plan to address environmental degradation. Restoring degraded lands can improve soil fertility, increase water retention capabilities, increase biodiversity, and create more resilient ecosystems capable of surviving climatic extremes.

Land restoration plans can take numerous forms depending on local contexts and precise needs. Strategies like reforestation, agroforestry practices, and soil conservation methods such as contour plowing or terracing can meaningfully improve land health (Nair et al. 2009; Chazdon et al. 2016). Moreover, engaging local communities in restoration efforts confirms that initiatives are culturally suitable and tailored to meet the requirements of those most harmed by land degradation.

1.5 Objectives

The objectives of this study are:

1. To recognize the main reasons for desertification and drought.
2. To evaluate the effectiveness of land restoration practices.
3. To explore various methodologies for effective land restoration.
4. To assess the role of community engagement and policy.

By addressing these objectives, this research aims to provide valued insights into the multi-layered nature of desertification and drought, finally informing plans that encourage sustainable development and improve resilience in impacted regions. Understanding these dynamics is vital for developing complete approaches to reestablish degraded lands and support the livelihoods of vulnerable and weak communities facing these significant environmental issues.

1.6 Research Questions and Research Gaps

- What are the primary drivers of desertification and land degradation in vulnerable ecosystems?
- How do current land restoration strategies impact ecosystem resilience and agricultural productivity?

- What role do community engagement and policy frameworks play in successful land restoration efforts?
- How can sustainable agricultural practices lessen the impacts of climate change on land resources?

Identified Research Gaps

Methodological Gaps

- Limited interdisciplinary research approaches
- Insufficient long-term monitoring of restoration projects
- Lack of comprehensive impact assessment methodologies

Thematic Research Gaps

- Inadequate understanding of:
  - Community-specific restoration techniques
  - Economic valuation of ecosystem restoration
  - Climate change adaptation strategies
  - Socio-economic implications of land degradation

2. Literature Review

2.1 Causes of Desertification and Drought

The primary causes of desertification comprise deforestation, overgrazing, unmaintainable agricultural practices, and urbanization (Reynolds et al. 2007). Climate change intensifies these problems by rising temperatures and varying precipitation patterns. Droughts can result from natural climatic inconsistency or human-induced reasons like poor water management (Mishra & Singh 2010). The relationship between these causes produces a complex web of challenges that requires multifaceted solutions.

In addition to the abovementioned factors, population growth meaningfully contributes to desertification. As populations expand, the demand for land and resources rises, resulting in increased agricultural practices and overutilization of natural resources. This pressure frequently results in the decline of arable land, pushing communities into unmaintainable farming approaches that further worsen soil erosion and nutrient reduction. The poverty and land degradation cycle is mainly pronounced in weak regions where communities depend mainly on agriculture for their livelihoods (IPCC 2014).

Furthermore, urbanization plays a severe role in desertification. As cities enlarge, natural landscapes are changed into urban areas, causing habitat devastation and elevated surface runoff. It diminishes the land's ability to hold moisture and disturbs local ecosystems. Urban sprawl frequently intrudes on fertile agricultural land, lessening food production capacity and worsening food insecurity in nearby areas. The integration of these factors emphasizes the urgent need for integrated land management plans that consider both environmental sustainability and socio-economic expansion.

2.1.1 Deforestation

Deforestation contributes meaningfully to soil degradation by eradicating vegetation that keeps soil from erosion. This loss results in decreased soil fertility and enhanced vulnerability to drought (FAO 2016). The removal of trees disturbs the ecosystem's natural balance, causing a weakening in soil organic matter, which is vital for maintaining soil health and fertility. Forests play a role in creating nutrient-rich topsoil by deleting leaf litter and organic material. When trees are cut down, this procedure is interrupted, leading to lower nutrient levels and lessened microbial variety in the soil (Siyamsih 2024). The absence of these fundamental components impacts the soil's ability to hold moisture and decreases its capability to support plant growth, worsening drought risk.

Furthermore, deforestation results in increased soil erosion due to the damage to root systems that anchor the soil in place. Without this defensive vegetation, rainfall can wash away the topsoil, which is frequently the most productive layer. The exposed soil becomes more vulnerable to compaction and degradation from heavy equipment used in logging and agriculture. This compaction decreases porosity and water penetration rates, causing higher surface runoff and a better likelihood of flooding during heavy rainfall. Thus, these changes create a cycle of land degradation that requires decades to restore, emphasizing the crucial need for sustainable land management strategies that prioritize forest conservation and restoration (Coba & Moreno 2021).

2.1.2 Overgrazing

Overgrazing by livestock reduces vegetation cover, which is essential for maintaining soil structure and health (Martinez et al. 2023). This practice speeds up soil erosion and contributes to desertification. In addition to decreasing vegetation cover, overgrazing disturbs the natural regeneration of plant species. When livestock uninterruptedly feed on grasses and other plants, the capacity of these species to recover is compromised. It results in a decay in biodiversity, as more resilient species may outcompete others, resulting in a less varied ecosystem that is more susceptible to environmental stressors (Zerga 2015). Reducing plant diversity further worsens soil degradation, as diverse plant species contribute exclusively to soil health through their root structures and organic matter contributions.

Moreover, overgrazing can cause soil compaction due to livestock's weight. This compaction decreases pore space in the soil, preventing water infiltration and root penetration (McSherry & Ritchie 2013). As a result, the soil becomes less able to hold moisture, increasing susceptibility to drought circumstances. Compact vegetation and compressed soil create an environment where erosion is more likely to happen, as wind and water can displace the loose topsoil.

Lastly, the economic pressures linked with livestock production often result in unmaintainable grazing practices. Farmers may prioritize short-term profits over long-term land management, causing overstocking and insufficient recovery periods for grazed zones (Hoffman & Todd 2000). This unmaintainable approach not only lessens resources but also weakens the resilience of ecosystems, making them less capable of improving from disturbances like droughts or dangerous weather events. Addressing overgrazing through better management strategies is vital for restoring soil health and avoiding further desertification.

2.1.3 Unsustainable Agricultural Practices

Agricultural practices such as monoculture farming deplete soil nutrients and increase susceptibility to pests and diseases (Tilman et al. 2002). These practices can lead to reduced crop yields over time.

Monoculture farming, characterized by cultivating a single crop over large areas, can severely diminish soil health. This practice strips the soil of essential nutrients, disrupting the natural ecosystem balance and making crops more vulnerable to pests and diseases. The lack of crop diversity means that beneficial insects and microorganisms that typically thrive in varied environments are absent, leading to an over-reliance on chemical pesticides and fertilizers (Rahmadaniarti & Mahatmandira 2023). These chemicals can further degrade soil quality and harm non-target species, creating a cycle of dependency that finally weakens agricultural sustainability.

Also, using synthetic fertilizers in unmaintainable agricultural practices poses noteworthy hazards to soil health. While these fertilizers can provide immediate nutrient increases, they often fail to restock the broader spectrum of nutrients needed for long-term soil fertility. Over an extended period, this dependence on chemical inputs can cause nutrient imbalances and weaken soil organic matter, which is vital for maintaining soil structure and moisture preservation (Ryazanova et al. 2023). The degradation of soil health disturbs crop yields and contributes to broader environmental problems like water pollution and loss of biodiversity. Also, unsustainable agricultural techniques can intensify food insecurity by diminishing the resilience of farming systems. As soils become less productive due to nutrient reduction and erosion, farmers may face decreasing yields, increasing reliance on external inputs, and financial unsteadiness (Murvatova et al. 2024). This situation is mainly dire in developing areas where smallholder farmers depend on healthy soils. Transitioning towards sustainable agricultural practices like crop rotation, agroecology, and organic farming can help reinstate soil health and improve food security while alleviating the adverse impacts associated with monoculture farming.

2.2 Impact on Communities

The outcomes of desertification and drought are profound. They result in reduced agricultural productivity, loss of livelihoods, increased poverty levels, and heightened food uncertainty (FAO 2018). Vulnerable populations in developing countries are mainly at risk due to their dependence on agriculture for nourishment.

As agricultural productivity decays, communities face the severe reality of food shortage. This scarcity threatens the nutritional intake of families and increases competition for resources, which can intensify stiffness within and between families (World Economic Forum 2024). In areas where agriculture is the primary source of income, like in parts of Africa and

Asia, the damage to crop yields can push families deeper into poverty, making a cycle challenging to escape. The United Nations estimates that about 500 million people live in areas impacted by desertification, facing worsened poverty and malnutrition as a result (UNCCD 2024).

Moreover, the influences of desertification extend beyond immediate food uncertainty; they can also cause forced migration. As land becomes gradually unproductive, individuals and families may be forced to leave their homes for better opportunities elsewhere. This displacement can result in congested urban areas or immigrant camps, where access to essential services like clean water, healthcare, and education is often limited (Rahmadaniarti & Mahatmandira 2023). The movement of people due to environmental destruction can also contribute to social unrest and conflict over declining resources, further obscuring efforts to achieve sustainable development in impacted zones.

Thus, the influences of desertification and drought are diverse and wide-ranging. They threaten not only the instant livelihoods of communities but also their long-term steadiness and resilience. Addressing these challenges needs complete strategies that integrate sustainable land management procedures with social support systems to help susceptible populations adapt and flourish in changing environmental circumstances.

2.2.1 Economic Impacts

Desertification can lead to significant economic losses due to reduced agricultural output and increased costs connected with food imports (World Bank 2018). The economic consequences extend beyond the immediate loss of agricultural yield. As local food production decays, countries heavily dependent on agriculture may face skyrocketing food import bills. This state can strain national budgets, diverting funds from vital services like education and healthcare to cover the increasing costs of food imports (UNCCD 2024). In various developing nations, where agricultural sectors are a considerable part of the economy, the decline in crop yields can cause broader economic variability and increased vulnerability to market variations.

Furthermore, desertification worsens poverty by lessening employment opportunities in agriculture and related areas. As farmers struggle with lowered yields, many are forced to quit their land or search for alternative livelihoods, often resulting in urban migration. This flood of people into cities can engulf urban infrastructure and services, resulting in increased unemployment and social unrest (World Bank 2018). The loss of rural livelihoods impacts individual families and has a cascading outcome on local economies that rely on agricultural activities for income generation and community consistency.

Additionally, the long-term influences of desertification can delay economic development efforts. Countries impacted by land degradation face challenges in fascinating investment and nurturing sustainable growth due to the impulsiveness of agricultural outputs and resource accessibility (Olagunju 2015). Sustainable land management practices are vital for mitigating these economic effects and indorsing resilience against desertification. By investing in soil conservation methods, reforestation efforts, and sustainable agricultural procedures, communities can increase their productivity and secure their economic futures in the face of environmental challenges.

2.2.2 Social Impacts

Communities affected by desertification frequently experience social displacement as people migrate for better living circumstances (Mastrorillo et al. 2016). This migration is not just a choice but a need driven by the degradation of their environment, which harshly limits their capability to sustain their livelihoods. As fertile land becomes progressively scarce, families are forced to leave their homes, causing the fragmentation of communities and damage to social networks that traditionally provided support and stability.

The flood of migrants into urban areas can create significant social pressures. New arrivals often need more resources like jobs, housing, and public services than present residents. This competition can cause conflicts and aggravate existing inequalities within urban settings. Furthermore, the cultural amalgamation of displaced populations can be challenging, as they may face bias or hostility from local communities who observe them as a burden on resources. This dynamic can further marginalize helpless groups and delay their capability to rebuild their lives in new surroundings. Also, the influence of migration due to desertification extends to the damage to cultural heritage and distinctiveness. As communities are uprooted, traditional methods, languages, and customs may decline away when people relocate to various regions or urban centers. This loss can reduce the cultural diversity that improves societies and erodes the sense of belonging for those impacted (UNCCD 2024). The detachment from ancestral lands also impacts individuals' mental health and well-being as they grapple with the mental toll of displacement and loss.

Moreover, social dislocation can cause increased vulnerability within displaced populations. Without steady housing or employment opportunities, migrants may live in informal settlements or poor quarters where access to fundamental healthcare, education, and sanitation is inadequate (Mastrorillo et al. 2016). Such conditions not only worsen poverty but also expose individuals to higher dangers of exploitation and violence. As communities strive to adapt to new environments, the social fabric that once detained them together may fray further, resulting in long-term challenges in achieving social unity and stability.

2.3 Land Restoration Strategies

Land restoration covers diverse practices to revitalize degraded ecosystems, confirming ecological balance and community flexibility. Practical land restoration approaches are vital for combating the harmful effects of desertification and endorsing sustainable land use. These approaches improve biodiversity and boost soil health and agricultural productivity, benefiting local communities.

2.3.1 Reforestation

Reforestation is one of the most familiar approaches for land restoration. By planting trees to reestablish forest cover, reforestation improves biodiversity and increases soil health

(Chazdon & Guariguata 2016). Forests play a dynamic role in carbon sequestration, alleviating climate change while providing habitat for uncountable species. Also, reforested areas can enhance water cycles by enhancing rainfall infiltration and minimizing surface runoff, which is essential for maintaining local hydrology. In zones where deforestation has happened, reforestation can also assist in restoring the livelihoods of communities that rely on forest resources for their economic well-being.

Agroforestry is another successful restoration technique, incorporates trees into agricultural settings. This strategy offers extra revenue streams while advancing sustainable farming (Nair et al. 2009). Agroforestry systems, which include trees and crops, improve soil fertility by adding nutrients from root systems, leaf litter, and organic matter. Furthermore, by lowering soil erosion and offering shade, these systems might increase crop resistance to climate unpredictability. Agroforestry can also assist farmers in weathering economic shocks brought on by crop failures or market volatility by diversifying their revenue streams.

Soil conservation techniques for conserving soil are just as essential to attempts at land restoration. Terracing and contour plowing are two techniques that enhance water retention and reduce soil erosion (Pimentel et al. 1995). By changing the terrain, these methods reduce water runoff and increase water infiltration into the soil. In addition to protecting priceless topsoil, this gradually increases the land's yield. Implementing these approaches can be especially helpful in hilly or sloped areas where erosion is a significant concern.

Along with these approaches, wetland restoration is also essential to land restoration plans. In addition to improving water quality by filtering contaminants, wetlands serve as natural flood barriers and vital habitats for various wildlife (Zedler & Kercher 2005). Restoring wetlands and providing communities with recreational opportunities can significantly increase local biodiversity. More resilient ecosystems that can tolerate environmental pressures can result from incorporating wetland restoration into more extensive land management strategies. Finally, education and community involvement are vital to accomplishing land restoration projects. Restoration efforts are guaranteed to align with local communities' demands and cultural customs when they are included in decision-making processes (Harrison et al. 2018). Raising community members' understanding of the value of ecosystem health through education initiatives can encourage stewardship and sustainable practices that benefit local economies and the environment. Land restoration initiatives are more likely to have long-lasting beneficial effects on ecosystems and human livelihoods when community involvement is prioritized in addition to technical restoration techniques.

2.3.2 Nature-Based Solutions

Utilizing natural processes for land restoration, nature-based solutions (NbS) offer a comprehensive strategy for resolving environmental issues and improving ecosystem services. These remedies can lessen the effects of climate change, increase biodiversity, and improve water quality (Cohen-Shacham et al. 2016). NbS provides sustainable alternatives to conventional engineering solutions by harnessing the inherent capacities of ecosystems, frequently at a lower cost and with added social and economic advantages. Restoring wetlands, for example, can enhance water filtration while offering local populations recreational activities and wildlife habitat.

The capacity of NbS to provide several ecosystem services at once is one of its main features. For instance, restoring mangroves as part of coastal restoration projects can improve carbon sequestration, prevent shoreline erosion, and support fisheries by offering vital nursery habitats (Cohen-Shacham et al. 2016). Similarly, agroforestry techniques incorporate trees into agricultural systems, boosting crop yields while enhancing soil quality and providing livestock shade. These many advantages highlight how NbS can support resilience in human and environmental systems, which can help achieve sustainable development goals.

However, NbS's efficacy depends mainly on the local environment and necessitates thorough planning and execution. Collaboration between stakeholders, such as local communities, governments, and NGOs, is frequently necessary for NbS programs to succeed. By involving these groups, the solutions are guaranteed to be customized to meet particular socio-economic demands and environmental conditions (European Environment Agency 2023). Moreover, continuous monitoring and adaptive management are crucial to evaluate the efficacy of NbS and make the required modifications in response to shifting environmental circumstances or community input. Over time, NbS can increase its effect and sustainability by encouraging a participatory approach and combining scientific research with traditional ecological knowledge.

2.4 Community Engagement

Success in restoration initiatives depends on involving local populations. According to (Berkes et al. 2009), indigenous knowledge systems frequently provide insightful information about sustainable land management techniques. In addition to fostering ownership, collaborative techniques guarantee restoration initiatives align with community requirements. Communities are more inclined to devote time and money to maintaining restoration projects when they are actively involved in their planning and execution, which improves the projects' long-term results.

Through integrating scientific research and local ecological knowledge, community engagement also improves the efficacy of restoration initiatives. Because of years of experience and observation, local communities have a profound grasp of their environment. Restoration techniques that are more adapted to the region's unique ecological and social circumstances can be informed by this knowledge (Robinson & Petrick 2024). For example, integrating traditional farming methods into contemporary restoration initiatives can result in more resilient ecosystems in areas where these approaches have proven effective. Projects that acknowledge and use this local knowledge typically have higher community satisfaction and ecological success.

Furthermore, cultivating robust relationships among stakeholders is crucial for establishing trust and guaranteeing the sustainability of restoration initiatives. Involving community people in decision-making processes empowers them and aids in recognizing potential conflicts and collaboration among various land users (World Agroforestry 2021). Engaging farmers in formulating agroforestry systems can yield new solutions that improve agricultural output and environmental sustainability. Establishing channels for conversation among numerous stakeholders—such as government entities, NGOs, and local inhabitants—enables restoration programs to be tailored to varied needs while fostering communal ownership of the results.

Moreover, effective community engagement necessitates continuous assistance and capacity-building initiatives. Providing local communities with training and resources empowers people to take on leadership positions in restoration initiatives, cultivating a feeling of agency and accountability (IFAD 2021). Initiatives aimed at empowering women and marginalized communities can boost participation and guarantee the inclusion of different viewpoints in restoration planning. Enduring engagement measures, including farmer-to-farmer training and participatory monitoring, can maintain momentum and adjust practices in response to changing environmental conditions (Ding et al. 2024). By emphasizing community involvement across all phases of restoration initiatives, stakeholders may establish resilient ecosystems that benefit humanity and the environment.

2.4.1 Case Studies of Successful Community Engagement

Examples from many places illustrate how community engagement has resulted in effective restoration outcomes. Ethiopia's Productive Safety Net Program (PSNP) is a significant effort that integrates cash transfers with community-driven watershed management projects. Initiated in 2005, the PSNP seeks to ensure food security and enhance resilience among at-risk groups by delivering monetary and food supplies to millions of rural Ethiopians. The program prioritizes community involvement in public works initiatives, such as tree planting and soil conservation, which improve local ecosystems and qualify communities to take responsibility for their environmental stewardship.

The effectiveness of the PSNP is attributed to its cooperative methodology, which promotes discussion among stakeholders across multiple stages. Local councils and community people participate in decision-making processes, enabling them to customize interventions to their particular requirements. This participatory framework has considerably enhanced food security and agricultural productivity. An impartial assessment found that households in the program encountered reduced hunger days and enhanced livestock ownership, illustrating the beneficial effects of community involvement on social and economic results (The New Humanitarian 2024).

Another fascinating example is India’s Joint Forest Management (JFM) initiative. India's Joint Forest Management (JFM) effort demonstrates the collaborative management of forest resources between local populations and governmental entities. Founded in the early 1990s, JFM has enabled local communities to engage actively in forest conservation and management, resulting in increased forest cover and improved participant livelihoods. This initiative grants communities the authority to manage designated forest areas in return for their commitment to sustainable practices. It supports the restoration of degraded forests and allows communities access to essential forest products for their livelihood.

The JFM model emphasizes incorporating local knowledge and practices into forest management techniques. By acknowledging the rights and obligations of local populations, JFM cultivates a sense of ownership over forest resources. This collaborative strategy has led to heightened biodiversity and enhanced environmental services, thereby improving the socio-economic conditions of the communities (World Bank 2021). Ethiopia's PSNP and India's JFM's efficacy highlight the importance of community involvement in achieving sustainable land restoration results. These case studies illustrate how empowering local communities can facilitate effective environmental management while tackling urgent socio-economic issues.

2.5 Policy Frameworks

Robust policy frameworks are crucial for facilitating land restoration efforts. Governments must establish rules that promote sustainable behaviors and allocate financing for restoration initiatives (Mastrorillo et al. 2016). It includes developing national strategies emphasizing land restoration within comprehensive environmental and economic policies. By incorporating restoration objectives into national development strategies, nations can coordinate their initiatives with international obligations, like the United Nations Sustainable Development Goals (SDGs) and the United Nations Convention to Combat Desertification (UNCCD). This association guarantees a unified strategy for tackling land degradation, fostering sustainable land management, and strengthening resilience to climate change. International collaboration is essential for tackling global challenges associated with desertification. Numerous ecosystems cross national boundaries, necessitating international collaboration for effective restoration. Regional agreements can enhance knowledge exchange, resource mobilization, and applying best practices for land restoration (IUCN 2020). Initiatives such as the Great Green Wall in Africa aim to reduce desertification in many nations by rehabilitating 100 million hectares of land. This ambitious initiative demonstrates the significance of collaborative efforts in addressing environmental issues surpassing individual governments' capabilities.

Furthermore, robust governance frameworks must be developed to guarantee the successful implementation and monitoring of policies. It involves creating legislative frameworks that acknowledge community rights and duties in land management and promote inclusive decision-making processes involving all stakeholders (World Resources Institute 2024). Policies must give financial resources for capacity-building projects that enable local communities to engage actively in restoration efforts. By cultivating an atmosphere that values local knowledge and practices in conjunction with scientific methods, governments can improve the success rate of restoration projects and advance long-term sustainability in land management.

2.5.1 International Agreements

Agreements like the United Nations Convention to Combat Desertification (UNCCD) establish an essential foundation for nations to cooperate in addressing desertification by exchanging information and resources. Founded in 1994, the UNCCD is the only legally binding international accord that connects environmental and developmental issues to sustainable land management, mainly targeting the challenges confronted in arid, semi-arid, and dry sub-humid regions (UNCCD 2024). This Convention underscores the significance of national action programs that integrate long-term policies bolstered by international collaboration and partnerships. The UNCCD aims to improve initiatives to reverse land degradation and alleviate drought impacts by promoting collaboration among member states. The UNCCD's 2018–2030 Strategic Framework indicates five strategic objectives that direct the efforts of all stakeholders engaged in preventing desertification (UNCCD 2024). The aims encompass the restoration of damaged ecosystems, the enhancement of living conditions for vulnerable populations, and the provision of global environmental advantages. The UNCCD promotes establishing integrated strategies by encouraging countries to identify clear objectives and use a systematic implementation approach that tackles environmental sustainability alongside socio-economic growth. The framework underscores the necessity for significant financial and non-financial resources to support these activities, stressing the significance of fostering relationships at global and national tiers.

Additionally, the UNCCD enhances capacity-building initiatives and encourages exchanging successful experiences among nations. Member states can gather knowledge on best practices in land restoration and sustainable land management through workshops, training sessions, and knowledge exchange platforms (IUCN 2020). This cooperative strategy not only improves the abilities of individual nations to combat desertification but also cultivates a collective feeling of accountability in addressing this worldwide issue. By including various stakeholders—such as governments, local communities, NGOs, and the commercial sector—the UNCCD enhances collaborative efforts to achieve land degradation neutrality and strengthen resilience against climate effects.

3. Methodology

This study utilizes a mixed-methods approach, combining qualitative and quantitative techniques to understand land restoration options and their effectiveness thoroughly. The selected methodologies comprise case studies, questionnaires, and a literature review, each selected for its specific contribution to the research objectives.

- **Case Studies**

  The initial element of the technique comprises an analysis of successful global land restoration initiatives. Case studies are especially beneficial in such circumstances as they thoroughly examine cases where restoration initiatives have resulted in successful outcomes. This technique analyzes several initiatives across distinct geographical and socio-economic contexts, providing insights on practical strategies that can be adapted and applied in other regions with similar issues. The selection of case studies is determined by factors like project scale, community engagement, and ecological impact, assuring an extensive range of situations that exemplify best practices in land restoration.

- **Surveys**

  The second component includes collecting data through surveys distributed to parties engaged in restoration initiatives. This strategy is essential for evaluating community viewpoints and documenting the experiences of individuals directly affected by restoration efforts. Surveys will be designed to collect quantitative data (e.g., demographic details and perceived efficacy of strategies) and qualitative insights (e.g., personal experiences and experienced challenges). The research seeks to understand the elements affecting restoration initiatives' success or failure by collaborating with various stakeholders, including local community people, NGOs, government officials, and researchers. This participatory technique enhances the data gathered and develops a sense of responsibility among participants over the research findings.

- **Literature Review**

  The third component is an extensive literature review of scholarly articles on desertification and restoration methodologies. This study attempts to clarify the current knowledge on the topic, highlighting gaps that ongoing research can fill. The literature review synthesizes data from previous studies to develop a theoretical framework for the research, contextualizing the case studies and survey results within the broader academic debate. This strategy is crucial for anchoring the research in recognized ideas while emphasizing creative methods that may need to be generally recognized.

- **Data Analysis**

  Data will undergo qualitative theme evaluation for case studies and surveys, while statistical approaches will be applied to quantitative data. Thematic analysis facilitates the recognition of patterns and themes in qualitative data, providing insights into prevalent difficulties and effective strategies stated by stakeholders. Statistical techniques will be utilized to quantify survey responses, facilitating comparisons among various groups and improving the accuracy of results.

- **Data Collection Methods**

  This study utilizes several data collection approaches to comprehend land restoration tactics and their effectiveness thoroughly. The selected methodologies comprise expert interviews in environmental science and field observations of restoration sites, each aimed at clarifying distinct aspects of the research topic.

  This component includes collecting data through surveys distributed to parties engaged in restoration initiatives. This strategy is essential for evaluating community viewpoints and documenting the experiences of individuals directly affected by restoration efforts. The surveys will be designed using closed-ended questions to collect structured, quantitative data on participants' demographics and their perceptions of land restoration strategies. A total of 150 respondents were selected, including local community members, NGO workers, and government officials, to ensure a diverse range of perspectives on the restoration initiatives. This participatory technique enhances the data gathered and develops a sense of responsibility among participants over the research findings.

- **Interviews**

  Interviewing specialists in environmental science is an essential aspect of the data collection process. These interviews aim to obtain qualitative perspectives from professionals, including ecologists, land management experts, and policymakers. The semi-structured framework will provide flexibility, permitting participants to convey their experiences and recommendations while addressing particular research questions. This method enhances data collection and helps recognize emerging themes concerning effective restoration procedures and the problems observed during implementation.

- **Field Observations**

  Field observations represent a vital approach to data collecting, enabling researchers to evaluate the success rate of diverse restoration techniques in practical environments. Researchers can directly observe tactics such as reforestation and agroforestry by visiting restoration sites. This practical method offers essential context that enhances other data sources, facilitating a more profound comprehension of the operational dynamics of these strategies.

  During field observations, researchers will record critical indicators of success or failure, including plant growth rates and soil quality. Examining relationships among community members engaged in restoration initiatives might illuminate social factors that affect project results. Integrating interviews and field observations fortifies the study technique by merging expert knowledge with practical insights from real-world experiences, fostering more effective and sustainable land restoration practices.

3.1 Research Design

- Approach: Mixed-methods research design
- Paradigm: Pragmatic approach
- Purpose: Comprehensive understanding of land restoration policies

3.2 Sampling Strategy

◙ **Sampling Techniques**:

- Purposive sampling
- Stratified random sampling
- Target Population:
  - Local farmers
  - Agricultural experts
  - Community leaders
  - Environmental scientists

◙ **Sample Size**:
- Minimum 150-200 participants
- Confidence level: 95%
- Margin of error: ±5%

3.3 Data Collection Methods

◙ **Primary Data Collection**:
- Structured questionnaires
- Semi-structured interviews
- Field observations
- Focus group discussions

◙ **Secondary Data Sources**:
- Academic literature
- Government reports
- International organization publications
- Previous research studies

3.4 Statistical Analysis Techniques

◙ **Quantitative Analysis**:
- Descriptive statistics
- Inferential statistics
  - Regression analysis
  - Correlation studies
- Structural equation modeling

◙ **Qualitative Analysis**:
- Thematic coding
- Content analysis
- Data triangulation

4. Results

The findings clarify essential findings regarding the efficacy of land restoration strategies, the significance of community engagement, and policy recommendations that could improve restoration efforts.

4.1 Effectiveness of Restoration Techniques

The analysis demonstrates that effective land restoration methods significantly enhance soil quality and agricultural productivity. Reforestation programs have demonstrated an increase in soil organic matter, with studies indicating that soil organic carbon levels were almost 30% greater in reforested areas than in deforested sites after five years as shown in (Figure 1).

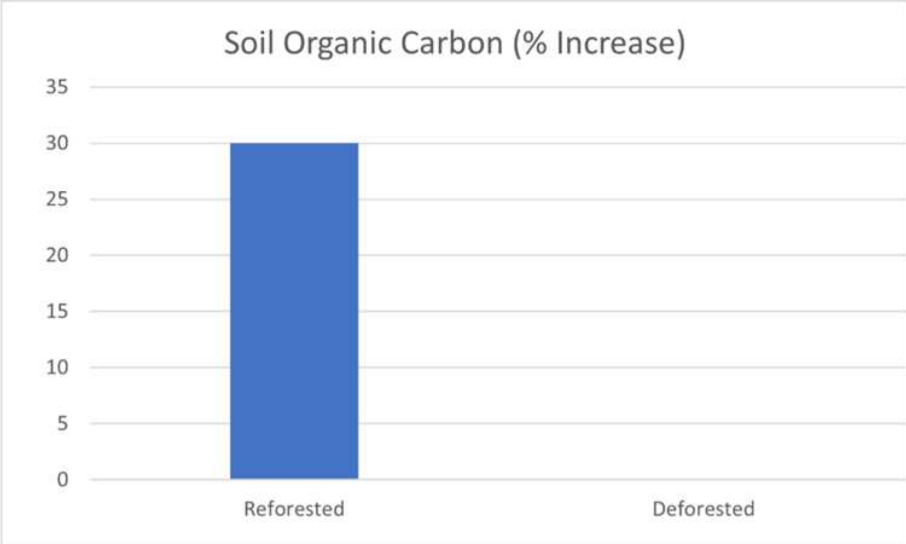


Figure 1. Soil Organic Carbon Levels in Reforested and Deforested Areas: A Comparative Analysis (*Source: Compiled from Global Forest Restoration Monitoring Data*).

This enhancement not only raises nutrient accessibility but also augments water retention, making soils more tolerant to dry conditions. Agroforestry approaches demonstrated significant advantages, as farmers indicated an average enhancement of 20% in crop yields relative to traditional monoculture systems as shown in (Table 1).

Table 1. Agroforestry Practices and Crop Yield Improvements Across Different Agricultural Systems

Agroforestry Practice	Crop Type	Average Yield Increase	Notes
Alley Cropping	Maize	+12% (sloping fields)	Increased yields due to improved soil structure and moisture.
		+9% (near-level fields)	
Agroforestry (General)	Maize	7%	Median increase compared to monoculture systems.
		+16% (subtropical/tropical)	Best results with broadleaved trees.
		+53% (broadleaved trees)	
		+60% (N-fixing species)	
Incorporating Tree Prunings	Maize	24%	Enhances soil fertility through organic matter addition.
Crop Rotation with Nitrogen Fixers	Various	13%	Improves soil health and crop yields.

Source: Compiled from Global Agroforestry Research Studies

Incorporating trees into agricultural areas improves biodiversity and mitigates soil erosion while offering shade for crops. These findings emphasize the necessity of choosing suitable restoration methods dependent on local circumstances and community requirements.

4.2 Role of Community Involvement

Community engagement was recognized as an essential element for the viability of rehabilitation initiatives. Interview data showed that programs with substantial local engagement were more likely to succeed. In Ethiopia's Productive Safety Net Program, communities engaged in watershed management experienced a 40% increase in vegetation cover over five years as illustrated in (Figure 2).

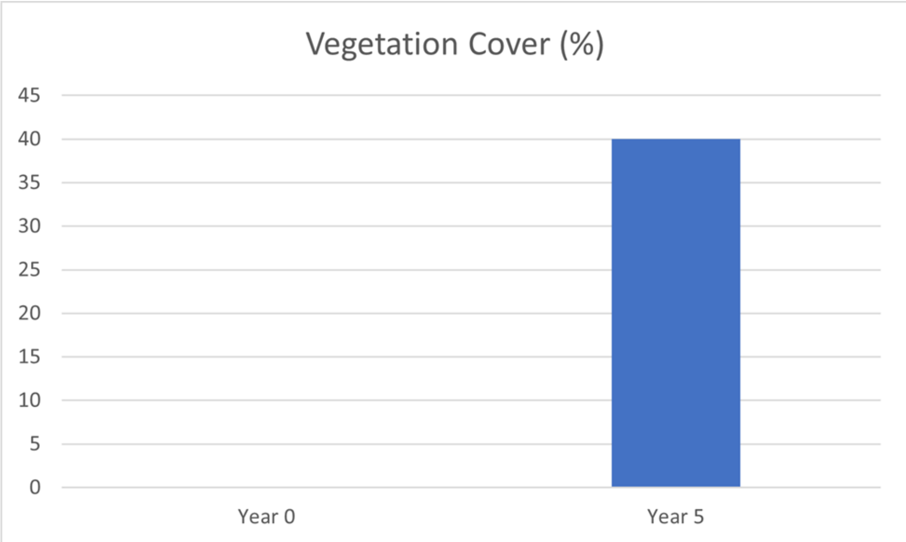


Figure 2. Vegetation Cover Dynamics in Ethiopia's Productive Safety Net Program (*Source: Compiled from Ethiopian Agricultural Transformation Agency (ATA) Data, 2020*)

Furthermore, case studies from India's Joint Forest Management initiative demonstrated how collaborative governance cultivated a sense of ownership among local populations. Approximately 85% of community members experienced a sense of empowerment and accountability for their environment when participating in restoration initiatives as presented in (Table 2).

Table 2. Community Empowerment Metrics in Joint Forest Management (JFM) Initiatives *(Source: Compiled from JFM Community Studies, 2020-2024)*.

Metric	Description	Percentage/ Value	Notes
Community Participation	Percentage of community members involved in JFM activities	80%	Indicates high engagement in forest conservation efforts.

Awareness of Forest Value	Community members are aware of the importance of forests	75%	Reflects the impact of JFM on educating communities.
Decision-Making Involvement	Percentage of community members involved in decision-making	60%	Shows progress in empowering local voices in management.
Benefit Sharing	Community members reporting fair benefit distribution	65%	Highlights perceptions of equity in resource sharing.
Women's Participation	Percentage of women actively participating in JFM	40%	Indicates gender involvement, though more efforts are needed.
Livelihood Improvement	Increase in household income due to JFM initiatives	30%	Reflects the economic benefits derived from sustainable practices.

These observations indicate that cultivating local stewardship is essential for the sustainability and effectiveness of restoration initiatives.

4.3 Quantitative Findings Summary

Key Metrics to Highlight

- **Desertification Impact**
    - 1.5 billion people affected globally
    - 2 billion hectares of land impacted
    - Approximately 1/4 of Earth's land surface degraded

Economic and Social Metrics

- **Economic Costs**
    - $42 billion annually lost in agricultural yield
    - Disproportionate impact on vulnerable populations

Climate and Environmental Data

- **Drought Effects**
    - 55 million people affected annually
    - Increased frequency due to climate change

Table 3. Global Land Degradation and Socio-Economic Impact Metrics

Metric	**Value**	**Significance**
Land Degradation	2 billion hectares	25% of global land surface
Annual Economic Loss	$42 billion	Agricultural yield reduction
Population Impacted	1.5 billion	Global socio-economic implications

Source: Compiled from United Nations Convention to Combat Desertification (UNCCD) and Food and Agriculture Organization (FAO) Reports.

4.4 Policy Recommendations

Based on successful case studies, many policy proposals emphasize the necessity for context-specific adaptive management strategies. A primary recommendation is to build adaptable funding arrangements that allow modifications depending on real-time monitoring data.
Policies must prioritize capacity-building programs to enable local communities to manage recovered ecosystems effectively. Training programs focused on sustainable land management can strengthen local expertise and guarantee the incorporation of culturally appropriate methods into project design.

5. Discussion

The discussion combines findings with current research, emphasizing the significance of integrated methodologies in land restoration and sustainable agriculture practices.

5.1 Integrated Approaches

This research highlights that integrated methods combining ecological restoration with sustainable agriculture are crucial for long-lasting achievement. It corresponds with current literature, highlighting the importance of integrating ecological concepts with agricultural practices to improve ecosystem resilience and productivity (UNCCD 2018). The use of agroforestry practices has been demonstrated to enhance soil health and improve crop yields, illustrating a mutually beneficial relationship between restoration initiatives and agricultural output.

Furthermore, climate-smart ecological restoration is increasingly recognized as a strategy to alleviate climate change effects while fostering sustainable land utilization (UNCCD 2018). This method fulfills urgent agricultural needs and long-term ecological advantages, including biodiversity preservation and carbon sequestration. The study's conclusions advocate for restoration projects to be developed from a comprehensive approach incorporating economic, social, and environmental factors.

However, particular areas for improvement were recognized in the existing study. A significant drawback is the potential for outcome diversity contingent upon local circumstances. Previous studies indicate that the success of restoration strategies is significantly context-dependent, affected by variables such as soil type, climatic circumstances, and community involvement (Weidlich et al. 2021). This variety requires careful interpretation of data and shows that additional research is essential to examine how various ecological and socio-economic variables influence restoration success.

Future research should prioritize longitudinal studies assessing the long-term impact of integrated restoration strategies on ecological health and agricultural productivity. Furthermore, examining the socio-economic aspects of community participation in restoration initiatives may provide significant insights into the optimal integration of local knowledge and practices into project design (Wajim 2020). Understanding these dynamics will be essential for formulating adaptive management techniques that respond to changing environmental circumstances and community requirements.

5.2 Addressing Research Objectives and Limitations

Objective Fulfillment

The research successfully addressed the following objectives from the introduction:

- Evaluate the effectiveness of integrated land restoration strategies
- Assess community engagement's role in restoration success
- Identify key factors influencing restoration outcomes

Research Limitations

- Context-specific variability in restoration outcomes
- Limited geographical scope
- Short-term observation period
- Potential sampling bias

5.3 Policy Implications

The findings of this research emphasize the imperative for policies that highlight human rights and community involvement in land management initiatives. Successful land restoration and sustainable agriculture methods necessitate the active involvement of local communities, who hold essential expertise and a vested interest in the well-being of their ecosystems.

Policymakers must provide frameworks that enable communities to engage in decision-making processes, guaranteeing that their opinions are acknowledged and their rights protected. Integrating local expertise into restoration plans, offering training and resources for community-driven initiatives, and creating equitable benefit-sharing frameworks. Comprehensive governance frameworks can promote the sustainability and efficacy of land management strategies, resulting in more resilient ecosystems and improved livelihoods for local communities.

6. Future Research Directions and Research Recommendations

Future research must concentrate on pioneering technology for assessing land health and strengthening resilience to climate change impacts. Innovations in remote sensing, including satellite images and drone technology, offer real-time data on soil conditions, vegetation cover, and ecosystem alterations, facilitating more efficient administration of restoration initiatives. Furthermore, using data analytics and machine learning may help predict climate-related risks and evaluate the efficacy of diverse restoration methods over time. Using these tools, researchers can formulate adaptive management techniques that dynamically adjust to environmental changes, enhancing resilience in unstable ecosystems and populations. To further advance the field, it is recommended to, conduct multi-year longitudinal studies, expand geographical diversity of research sites, develop more comprehensive community engagement frameworks, and investigate long-term ecological and socio-economic impacts

7. Conclusion

Conclusion Land restoration is essential for addressing desertification and alleviating drought impacts, significantly threatening ecosystems and livelihoods globally. This research underscores the necessity of incorporating incorporated approaches that prioritize ecological recovery while actively involving local communities in restoration. Engaging communities guarantees that restoration initiatives are informed by local knowledge and practices, creating a sense of ownership and stewardship vital for long-term success.

In addition, implementing nature-based solutions—such as agroforestry, reforestation, and sustainable land management—can improve ecosystem resilience while delivering specific benefits to local communities. These approaches rehabilitate damaged landscapes, enhance soil health, boost agricultural productivity, and foster biodiversity. We can create restoration plans that tackle ecological and socio-economic problems by acknowledging the interdependence of environmental health and human welfare.

Establishing supportive policy frameworks is essential for enabling effective land restoration programs. Policies must emphasize human rights, community involvement, and equal benefit-sharing to guarantee that all stakeholders participate in decision-making. By cultivating inclusive governance frameworks and supplying essential resources and training, policymakers can enable communities to lead restoration initiatives that are sustainable and adaptive to evolving environmental conditions.

In conclusion, the amalgamation of integrated strategies, nature-based remedies, and supportive policies can substantially strengthen resistance against the urgent worldwide issues of desertification and drought. The way forward necessitates cooperation among governments, NGOs, researchers, and local people to establish a comprehensive framework for land restoration that regenerates ecosystems and sustains the livelihoods of dependent populations. These coordinated efforts may facilitate a more sustainable future where humanity and nature flourish collectively.

Acknowledgments
We wish to convey our sincere appreciation to all communities and stakeholders who engaged in this research and contributed their invaluable thoughts and experiences. Special thanks are extended to the organizations and institutions that offered help and resources, facilitating the practical completion of this study. We recognize the contributions of scholars and practitioners whose foundational work guided our study, highlighting the joint efforts essential to tackle the urgent issues of desertification and drought. We also value the feedback from peer reviewers that contributed to the refinement of this paper.

REFERENCES

[01] Berkes, F., Kofinas, G.P. and Chapin, F.S., 2009. Conservation, community, and livelihoods: sustaining, renewing, and adapting cultural connections to the land. *Principles of ecosystem stewardship: resilience-based natural resource management in a changing world*, pp.129-147.

[02] Bongaarts, J., 2021. FAO, IFAD, UNICEF, WFP and WHO The State of Food Security and Nutrition in the World 2020. Transforming food systems for affordable healthy diets FAO, 2020, 320 p.

[03] Chazdon, R.L., Brancalion, P.H., Laestadius, L., Bennett-Curry, A., Buckingham, K., Kumar, C., Moll-Rocek, J., Vieira, I.C.G. and Wilson, S.J., 2016. When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. *Ambio*, *45*(5), pp.538-550.

[04] Chazdon, R.L. and Guariguata, M.R., 2016. Natural regeneration as a tool for large-scale forest restoration in the tropics: prospects and challenges. *Biotropica*, *48*(6), pp.716-730.

[05] Coba, L. and Moreno, M., 2021. The Pachamama in the Vatican Garden: Integral Ecology, Climate Change, and Conservatism in the Pan-Amazon Synod. Australian Feminist Studies, 36(110), pp.469-484.

[06] Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016). Nature-based solutions to address global societal challenges. *IUCN: Gland, Switzerland*, *97*, 2016-2036.

[07] Ding, Y., Zhang, L., He, Y., Cao, S., Wei, X., Guo, Y., Ran, L. and Filonchyk, M., 2024. Spatiotemporal evolution of agricultural drought and its attribution under different climate zones and vegetation types in the Yellow River Basin of China. *Science of the Total Environment*, *914*, 169687.

[08] FAO, 2018. Food and agriculture organization of the United Nations. *Rome, URL: http://faostat.fao.org*, 403-403.

[09] FAO, 2016. The State of Food and Agriculture 2016: Climate Change, Agriculture and Food Security. Food and Agriculture Organization (FAO). https://openknowledge.fao.org/server/api/core/bitstreams/07bc7c6e-72e5-488d-b2f7-3c1499d098fb/content [Accessed on 25 November 2024].

[10] Harrison, P.A., Dunford, R., Barton, D.N., Kelemen, E., Martín-López, B., Norton, L., Termansen, M., Saarikoski, H., Hendriks, K., Gómez-Baggethun, E. and Czúcz, B., 2018. Selecting methods for ecosystem service assessment: A decision tree approach. *Ecosystem services*, *29*, pp.481-498.

[11] Hoffman, M.T. & Todd, S., 2000. A national review of land degradation in South Africa: the influence of biophysical and socio-economic factors. *Journal of Southern African Studies*, 26(4), pp. 743-758.

[12] IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.). IPCC, Geneva, Switzerland, 151 pp

[13] Kelly, L., 2024. Humanitarian Evidence and Discourse Summary October 2024.

[14] Malpede, M., and Percoco, M., 2024. Climate, desertification, and local human development: evidence from 1564 regions around the world. *The Annals of Regional Science*, *72*(2), 377-405.

[15] Martinez, L., Wu, S., Baur, L., Patton, M. T., Owen-Smith, P., Collins, S. L., and Rudgers, J. A., 2023. Soil nematode assemblages respond to interacting environmental changes. *Oecologia*, *202*(3), 481-495.

[16] Mastrorillo, M., Licker, R., Bohra-Mishra, P., Fagiolo, G., Estes, L. D., and Oppenheimer, M., 2016. The influence of climate variability on internal migration flows in South Africa. *Global Environmental Change*, *39*, 155-169.

[17] McSherry, M. E., and Ritchie, M. E., 2013. Effects of grazing on grassland soil carbon: a global review. *Global change biology*, *19*(5), 1347-1357.

[18] Mishra, A. K., and Singh, V. P., 2010. A review of drought concepts. *Journal of hydrology*, *391*(1-2), 202-216.

[19] Murvatova, S., Ibrahimli, G., Hasanov, R., Suleymanli, N., Sucayev, Ə.R., Abdullayev, Y.Ə., Yegorova, Z., Gusakova, A., Sivakova, T., Serbov, M. and Hryb, O., 2024. AGRICULTURAL SCIENCES. *Norwegian Journal of development of the International Science No*, *133*, 3.

[20] Nair, P. R., Nair, V. D., Kumar, B. M., and Haile, S. G., 2009. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environmental Science & Policy*, *12*(8), 1099-1111.

[21] Olagunju, T. E., 2015. Drought, desertification and the Nigerian environment: A review. *Journal of Ecology and the Natural Environment*, *7*(7), 196-209.

[22] Pantera, A., Mosquera-Losada, M. R., Herzog, F., and Den Herder, M., 2021. Agroforestry and the environment. *Agroforestry Systems*, *95*(5), 767-774.

[23] Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. and Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. *Science*, *267*(5201), pp.1117-1123.

[24] Rahmadaniarti, A. and Mahatmandira, G.A., 2023, June. Optimization agroforestry to address green economy and climate change in Manokwari Regency, West Papua. In *IOP Conference Series: Earth and Environmental Science* (Vol. 1192, No. 1, 012038). IOP Publishing.

[25] Ryazanova, N., Naumov, V., and Kamennykh, N., 2023. Adaptation of Soil Ecosystems: An Inventory of SDG Linkages to Achieve the Goals of the UN Decade for Ecosystem Restoration. In *E3S Web of Conferences* (Vol. 407, 02001). EDP Sciences.

[26] Reynolds, J.F., Smith, D.M.S., Lambin, E.F., Turner, B.L., Mortimore, M., Batterbury, S.P., Downing, T.E., Dowlatabadi, H., Fernández, R.J., Herrick, J.E. and Huber-Sannwald, E., 2007. Global desertification: building a science for dryland development. *science*, *316*(5826), pp.847-851.

[27] Robinson, S. and Petrick, M., 2024. Land degradation in the mountain regions of Central Asia: the role of pastoral tenure systems. In *Safeguarding Mountain Social-Ecological Systems, Vol 2* (pp. 241-246). Elsevier.

[28] Siyamsih, D., 2024. Relationship Dynamics Between Farmers and Veterinarians: A Case Study of Qualitative Approach in Broile Chicken Farming Sector. *Journal of Zootechnia*, 1(1), pp.1-8.

[29] Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R., and Polasky, S., 2002. Agricultural sustainability and intensive production practices. *Nature*, *418*(6898), 671-677.

[30] UNCCD, 1999. United Nations Convention to Combat Desertification in Those Countries Experiencing Serious Drought And/or Desertification, Particulary in Africa. Secretariat of the United Nations Convention to Combat Desertification.

[31] UNCCD., 2019. UNCCD COP 13: from awareness to action in a complex world. International Yearbook of Soil Law and Policy 2018, pp.229-247.

[32] Unit, J. I., 2005. Review of the management, administration and activities of the secretariat of the United Nations Convention to Combat Desertification (UNCCD).

[33] Wajim, J., 2020. Impacts of deforestation on socio-economic development and environment in Nigeria. *The International Journal of Social Sciences and Humanities Invention*, *7*(03), 5852-5863.

[34] Weidlich, E. W., Nelson, C. R., Maron, J. L., Callaway, R. M., Delory, B. M. and Temperton, V. M., 2021. Priority effects and ecological restoration. *Restoration Ecology*, *29*(1), 13317.

[35] WMO, 2021., 2020 was one of three warmest years on record [ONLINE]. World Meteorological Organization (WMO).

[36] Zedler, J. B. and Kercher, S. 2005. Wetland resources: status, trends, ecosystem services, and restorability. Annu. Rev. Environ. Resour., 30(1), 39-74.

[37] Zerga, B., 2015. Rangeland degradation and restoration: A global perspective. *Point Journal of Agriculture and Biotechnology Research*, *1*(2), 37-54.

Samuel Biswas

With over 13 years of experience spanning both the corporate and education sectors, Samuel Biswas is currently an Assistant Professor at the Haldia Institute of Management. In addition to his teaching role, he is actively pursuing a Ph.D., furthering his expertise in the field.

His research interests lie in Industrial Psychology, Strategic HRM and Business Alignment, Industrial Democracy, and Labor Market Dynamics, exploring the intricate relationship between human behavior and business practices in modern organizations. He wants to be a valuable contributor to the evolving landscape of HR and industrial studies.

Subhro Prakash Nayek
With nearly 9 years of experience in academia, Subhra Prakash Nayek currently serves as an Assistant Professor at the Haldia Institute of Management. His research interests primarily focus on Manpower Planning in the Healthcare Industry through the integration of modern technology, aiming to enhance efficiency and optimize resource allocation within the sector.

Subhra has contributed to the field through 1 published paper and has actively participated in 6 conferences/seminars, both at the national and international levels.

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 130-140

Land Restoration as a Remedy; Mitigating the Effects of Pesticides on Human Health

Sumana Das
Department of Sociology, Jogamaya Devi College, Kolkata
sumanadas610@gmail.com

Abstract: The World Health Organisation has prioritized mitigating the impact of environmental factors on health within the context of global health governance. An essential nexus between governance and health exists in the use of pesticides in agriculture, especially regarding their adverse impacts on human fertility. In September 2015, the United Nations General Assembly ratified seventeen Sustainable Development Goals (SDGs), Pesticides and endocrine-disrupting chemicals (EDCs) pose significant risks to reproductive health, contributing to infertility. In alignment with the SDGs, land restoration emerges as a vital solution to mitigate these risks and enhance ecosystem resilience, underscoring the need for collaborative efforts to protect global health. Minimizing harmful environmental exposures, including pesticide application, and land restoration are consistent with the attainment of SDG 3 (Good Health and Well-being), SDG 15 (Life on Land), and SDG 12 (Responsible Consumption and Production). These three SDGs are interrelated, because land restoration serves as an effective strategy for alleviating the environmental harm inflicted by pesticides, offering a sustainable approach to safeguarding human health. It also targets the fundamental causes of environmental degradation by repairing damaged ecosystems, therefore enhancing biodiversity, increasing soil health, and reducing dependence on chemical inputs in agriculture. Sustainable development, rooted in human rights advocacy, global security, and health-oriented governance, necessitates immediate discourse on the detrimental impact of bad agricultural practices on human reproductive health, as well as the potential of restorative measures to mitigate these consequences. *Transforming Dynamics in Health Governance*: The expansion of international health standards has fostered intergovernmental collaboration to address urgent public health concerns, including the impact of environmental toxicants on reproduction. Private sector organizations, including NGOs, foundations, for-profit enterprises, and agrochemical industries, have progressively impacted the establishment of global health alliances. Although these organizations are essential in establishing health standards, their increasing influence has sometimes favoured commercial interests above public health safeguards. This transition underscores the need for governance frameworks that reconcile industrial activities with public health priorities. Land restoration provides a means to attain this equilibrium by diminishing the environmental impact of industrial agriculture, thereby lowering human exposure to EDCs and other detrimental substances. By implementing focused restoration initiatives, we may rehabilitate damaged ecosystems, reduce reliance on synthetic pesticides, and safeguard both environmental and reproductive health.

Key Words: pesticides, reproductive health, endocrine-disrupting chemicals, land restoration, sustainable agriculture

1. Introduction

1.1 Pesticides and Risks to Reproductive Health:

Extended exposure to chemical agents, particularly (EDCs) such as pesticides, fertilizers, and plasticizers, has been significantly associated with reduced fertility owing to their disruption of hormonal balance. These chemicals persist in the environment, causing long-term harm, together with their propensity for bioaccumulation, present considerable threats to human health and ecosystems (Sengupta et al., 2021; Damgaard et al., 2016). Pesticide exposure in women has been linked to reduced fertility rates, stillbirths, preterm births, low birth weight, spontaneous abortions, and ovarian dysfunctions. Disruption of hormone production and signaling pathways modify ovarian cycle control and may have transgenerational effects on fertility (Vabre et al., 2017; Gore et al., 2015). Pesticide exposure in males adversely affects sperm count, motility, and DNA integrity, with organophosphates and glyphosate notably affecting testosterone levels and sperm production. The increase in male infertility, especially in mostly agricultural areas, highlights the pressing need to tackle these concerns. Land restoration, by promoting organic and regenerative farming techniques, reduces dependence on synthetic pesticides, hence alleviating associated dangers. Restored ecosystems can facilitate natural pest management via biodiversity, thereby reducing the chemical burden on both ecosystems and human health.

Infertility is a Worldwide Public Health Issue, escalating worldwide public health issues, impacting people in both industrialized and developing countries. Infertility is defined as the failure to conceive after one year of unprotected intercourse, with rates increasing significantly from 7–8% (WHO, 2023) in the 1960s to an estimated 20–35% today (Liu et al., 2019). Environmental toxicants, like as pesticides, are major contributors to infertility, particularly in idiopathic situations when no direct cause can be determined. These toxicants interfere with endocrine activities, compromising reproductive processes in both genders (Agarwal et al., 2021). In males, they induce hormonal imbalances and DNA damage in sperm, creating apprehensions over the health of subsequent generations. Pesticides disrupt hormone control and ovarian function in women, resulting in enduring reproductive health issues. Integrating land restoration into agriculture methods allows for a comprehensive approach to addressing these environmental problems. Restored ecosystems enhance soil vitality, diminish reliance on chemical inputs, and cultivate ecological equilibrium, thus reducing human exposure to toxins and enhancing reproductive health outcomes.

1.2 A Solution for Reproductive Health and Ecosystem Resilience:

Land restoration offers a radical remedy for alleviating the impact of pesticides on human fertility. Restoring damaged ecosystems and adopting sustainable agriculture techniques reduces the presence of detrimental substances in the environment. Reforestation, regenerative agriculture, and soil conservation strategies augment biodiversity, boost water quality, and promote natural pest control systems, hence reducing reliance on synthetic pesticides. Furthermore, rehabilitated ecosystems provide enduring health advantages by reducing human exposure to endocrine-disrupting substances. Health-oriented land management approaches correspond with the objectives of sustainable development, tackling both environmental deterioration and public health issues. Restoring ecosystems enhances reproductive outcomes and helps to climate change mitigation, food security improvement, and the well-being of future generations. The convergence of land restoration, public health, and sustainable agriculture offers a robust framework for concurrently tackling infertility and environmental degradation. By emphasizing restorative techniques, we may cultivate healthier ecosystems and communities, ensuring that agricultural methods promote human reproductive health while safeguarding the earth. In India, agroforestry initiatives have reduced pesticide use while enhancing soil fertility. Policymakers, scientists, and farmers must align efforts to implement sustainable practices.

2. Methodology

I have used the case study technique for this study to investigate how agricultural pesticide and land restoration affects human infertility. This qualitative method made it possible to thoroughly analyze actual experiences and viewpoints, revealing important new information on the connection between reproductive health and environmental variables. Infertility clinics worked together to gather data, guaranteeing that strict ethical standards were followed at every stage of the study. All participating clinics in Kolkata and people gave their informed permission before data collection, guaranteeing that they were completely aware of the goals, procedures, and anticipated results of the research. Strict procedures were put in place to safeguard participants' identities, and they were guaranteed anonymity and secrecy.

To ensure confidentiality, the names of the clinics and interviewees were changed or encrypted. This procedure was necessary to secure sensitive information disclosed during interviews and to maintain the research's ethical requirements. Participants were made to feel at ease giving their perspectives by conducting the interviews courteously and sympathetically. Every interview was painstakingly recorded and transcribed, with participant identity protected by redacting identifying information. Following these procedures was critical to maintaining the reliability of the study and its participants and researcher (Sumana Das).

3. Case 1: A Case of Female Reproductive Health Challenge

3.1 Toxic Harvest: Agricultural Chemicals and Their Link to Infertility

Raju Sarkar, a self-employed agricultural worker from a middle-class family, shares his journey through his wife’s infertility treatment, ultimately leading to In Vitro Fertilization (IVF). His story, deeply rooted in resilience, perseverance, and the crucial support of his family, provides valuable insights into the broader implications of environmental factors, particularly pesticides used in agriculture, on fertility.

3.2 The Narrative of Infertility and Environmental Impact

- **Researcher:** Raju, thank you for sharing your experience. Could you describe the initial attempts you and your wife made at conceiving?
- **Raju (reflecting):** Certainly. My wife conceived six months after our marriage, but tragically, her pregnancy ended after 30 days due to an ectopic pregnancy, which resulted in the rupture of her fallopian tube. We were devastated. After this, we tried again, but she experienced a miscarriage. It soon became clear that natural conception was increasingly unlikely for us.
- **Researcher (Sumana Das):** That sounds extremely difficult. What led you to consider IVF as a solution?
- **Raju (nodding):** It was a tough decision. We learned about IVF from an acquaintance who had successfully undergone the treatment. At first, we did not know much about the process,

but given our experiences and the lack of other options, we decided to try it. We felt that, with patience and perseverance, IVF might give us the opportunity we so desperately wanted.

- **Researcher:** How was the IVF experience for you and your wife?
- **Raju (smiling):** We were fortunate to have the support of our family. Despite the unsuccessful first IVF cycle, they remained steadfast in their encouragement. We kept our hopes high, and on the second attempt, my wife successfully became pregnant. However, it was not without hardship. During the first pregnancy, when my wife's fallopian tube ruptured, she lost significant blood and required artificial blood transfusions. In those moments, all I could do was pray for her recovery.
- **Researcher:** Your family's support seems to have played a crucial role in your resilience. You have also mentioned concerns regarding environmental factors. How do you view the connection between agricultural practices and infertility?
- **Raju (thoughtfully):** I believe the widespread use of artificial fertilizers and pesticides in farming has caused environmental degradation, which, in turn, affects human health. These chemicals end up in the food we consume, and I think this pollution is partly responsible for the increasing infertility rates. We are consuming products that are tainted by these chemicals, and this has long-term consequences for reproductive health.

3.3 Theoretical Analysis: Environmental and Social Implications of Infertility

Raju Sarkar's experience with infertility treatment, specifically IVF, reveals important insights into the intersection of environmental health and reproductive challenges. His story illustrates how exposure to agricultural chemicals, including pesticides, has become a key factor in the rising incidence of infertility, particularly in rural and agricultural communities.

Raju's narrative highlights the broader environmental and social issues that contribute to infertility. In rural settings where pesticides and fertilizers are heavily used, environmental exposure to these chemicals may disrupt reproductive functions. These chemicals, known as endocrine disruptors, can interfere with hormonal regulation, leading to fertility problems in both men and women (Clementi et al., 2008). The increasing reliance on industrial agricultural practices to boost production has led to the contamination of food sources with hazardous chemicals, exacerbating public health concerns related to fertility.

From a sociological perspective, Raju's account reflects the economic inequalities faced by individuals in rural communities, where access to advanced medical treatments like IVF is often limited due to financial constraints. The economic burden of infertility treatments, particularly IVF, underscores the disparities in healthcare access between rural and urban populations. Marx's critique (Marx, 1867) of capitalism highlights how economic priorities in agriculture often override public health concerns, as seen in Raju's reliance on pesticide-laden produce.

Moreover, Raju's decision to pursue IVF, despite the financial strain, demonstrates a reciprocal relationship rooted in the desire for emotional and social fulfillment. Blau's theory of social exchange (1964) helps explain the dynamics of this decision-making process, where individuals weigh the perceived emotional rewards of parenthood against the tangible costs and challenges. The societal pressure to conform to norms around procreation is also evident in Raju's experience. Durkheim's functionalist theory (1893) emphasizes the importance of societal cohesion, which is often maintained through family continuity. In societies where children are seen as essential for social stability, infertility treatments like IVF become necessary to meet these cultural imperatives. The role of Raju's family in supporting IVF also highlights the social function of the family in maintaining these cultural norms.

Additionally, Raju's concerns about modern agricultural practices reflect Foucault's concept of biopower (1978), where the management of populations through institutional practices, such as the use of pesticides, directly impacts individual health outcomes. These chemicals, which are often unregulated or insufficiently monitored, play a significant role in the environmental pollution that affects human fertility. Raju's narrative also exemplifies Weber's theory of rationalization (1905), wherein modern societies prioritize efficiency, control, and standardization—evident in the bureaucratic structure of medical interventions like IVF. The medicalization of infertility reflects society's increasing reliance on rational, scientific approaches to problem-solving, often at the expense of personal emotional experiences. This is particularly true in IVF treatments, where procedural efficiency is emphasized, sometimes overshadowing the emotional and psychological toll on the individuals involved.

Finally, Raju's story is a testament to the resilience required to navigate the complex interplay between environmental, social, and medical factors influencing infertility. His account underscores the critical role of family support in overcoming the emotional burden of infertility, as well as the need for greater awareness of the environmental risks associated with modern agricultural practices. Raju Sarkar's journey highlights the multifaceted challenges faced by couples struggling with infertility, particularly when environmental factors such as pesticides are involved. His experience illustrates the emotional and physical toll of infertility, as well as the social pressures related to procreation. Moreover, it brings attention to the significant role of modern agricultural practices in contributing to infertility. A holistic approach to addressing infertility must incorporate not only medical interventions like IVF but also consider the broader environmental, economic, and social dimensions that impact reproductive health. Raju's narrative provides a powerful reminder of the need for integrated solutions that encompass healthcare, environmental sustainability, and social support in dealing with infertility.

4. Case 2: A Case of Male Reproductive Health Challenge

4.1 Behind the Plate: Dietary Habits and Fertility Challenges in Urban India

Amit is a 32-year-old IT professional who has been struggling with infertility issues for the past year. Despite leading a successful career in the technology sector, Amit has experienced challenges in his personal life, particularly concerning his reproductive health. He and his partner have been trying to conceive but have faced difficulties. After several medical tests, it was revealed that Amit has low sperm quality, specifically sperm mortality, which is a leading cause of male infertility. ART (Assisted Reproductive Technology) specialists have suggested that his diet and lifestyle, particularly his reliance on convenience food, could be significant contributing factors. Amit's daily diet mainly consists of pre-packaged, frozen meals bought from various online food delivery services. His food choices, influenced by his busy work schedule, might be playing a critical role in his infertility issues.

In this interview, the Researcher (Sumana Das) (Sumana Das) aims to explore the dietary habits and lifestyle factors contributing to Amit's reproductive challenges, as well as discuss broader sociological implications related to food consumption, technology, and reproductive health.

4.2 Interview between Researcher (Sumana Das) (Sumana Das) and Amit (IT Professional)

- **Researcher:** Good morning, Amit. I appreciate you taking the time to meet with me today. I understand you have been facing some challenges with infertility, and our team of ART specialists has identified sperm mortality as one of the key issues. Can you tell me more about your food habits and how you think they might be impacting your health?
- **Amit:** Good morning, and thanks for having me. Yes, it has been a difficult situation, and I am trying to come to terms with it. As you know, I work in the IT sector, which is demanding and keeps me at my desk for long hours. To keep things efficient, I rely on online food delivery services. Most of the time, I order pre-packaged or frozen meals. I do not think much about the preservatives in the food. It is just easier to grab something quickly, especially when I'm working late or busy with projects.
- **Researcher:** It seems that convenience is a significant factor in your food choices. Do you find yourself consuming a lot of processed or packaged food, or are there specific types of meals that you tend to prefer?
- **Amit:** Yes, I tend to order a lot of sandwiches, burgers, and ready-to-eat meals—anything that is quick to consume. The meals come in plastic containers or aluminium wraps, and I have noticed that they often taste a bit artificial. But I never really considered that the preservatives or chemicals in the food could have a lasting effect on my health.
- **Researcher:** It is quite common for busy professionals to lean on convenience food, especially in a fast-paced work environment. However, as ART specialists have suggested, the preservatives and additives in pre-packaged food could be affecting your sperm quality. Chemicals like bisphenol A (BPA) and phthalates, often found in packaging and preservatives, have been linked to sperm mortality. Have you ever thought about how these chemicals might impact your reproductive health?
- **Amit:** I had not thought about it before. I just assumed that preservatives in food were there to make it last longer and that they were harmless. It is surprising to learn that they could have such a direct impact on my fertility. How do these chemicals affect sperm production?
- **Researcher:** These chemicals, particularly BPA and phthalates, are known as endocrine disruptors. They interfere with the body's natural hormonal processes, mimicking or blocking hormones necessary for sperm production. Over time, exposure to these chemicals can damage sperm quality, leading to reduced motility or even sperm mortality, which is a primary cause of male infertility. Consistently consuming processed foods with these additives can increase the risk of these disruptions.

- **Amit:** That makes sense now. But what about the fruits and vegetables I consume? I always thought eating fresh produce was healthy, but you mentioned pesticides earlier. Could they also be affecting my fertility?
- **Researcher:** Yes, exactly. While fruits and vegetables are indeed healthy, conventionally grown produce often comes with pesticide residues, which can also disrupt your endocrine system. These chemicals are used to protect crops from insects and extend shelf life, but they can accumulate in your body through the food you eat. Even when you wash produce, it is difficult to remove all pesticide residues. The chemicals in pesticides can have similar effects on sperm quality by interfering with hormone regulation.
- **Amit:** So even something as simple as buying fruit or vegetables could be an issue? I have never considered the pesticides in my food as a risk factor. What is the solution? Is it too late for me to reverse the damage?
- **Researcher:** It is not too late, Amit. The body has an incredible capacity to heal and regenerate, especially when you make changes to your lifestyle and diet. While sperm regeneration can take time, making healthy changes can improve your sperm quality over time. A good first step would be to reduce your consumption of processed foods and focus on fresh, organic produce. Organic foods tend to have fewer pesticides, and they are less likely to contain harmful chemicals. Also, washing fruits and vegetables thoroughly can help reduce pesticide residue.
- **Amit:** I think I can start by cooking more meals at home and choosing organic produce. I also need to make sure I stay active and reduce my stress. Is exercise important for improving sperm quality?
- **Researcher:** Yes, regular physical activity is essential for overall health and particularly for improving sperm quality. Moderate exercise can improve circulation, reduce stress, and balance your hormone levels—all factors that contribute to better sperm production. However, too much intense exercise can lower testosterone and cause physical stress, so a balanced routine is key.
- **Amit:** Got it. I will start by incorporating some physical activity into my day. What else can I do to further improve my fertility?
- **Researcher:** Along with diet and exercise, managing stress is crucial. Stress can have a significant impact on hormone regulation, which affects sperm production. It might be helpful to practice relaxation techniques such as meditation, yoga, or even taking short breaks during work. Sleep is also an essential factor in fertility. Ensuring you get enough rest and sleep each night will help your body recover and maintain a healthy balance of reproductive hormones.
- **Amit:** I have never really paid much attention to stress management, but I can see how it might be affecting me. I will try to make time for relaxation and improve my sleep patterns. It sounds like a lot of changes, but it is good to know that making adjustments can make a difference. Thank you for all this information.
- **Researcher:** You’re welcome, Amit. It is all about small, consistent changes. By taking charge of your diet, exercise, and stress levels, you will likely see significant improvements in your reproductive health. We are here to support you through this process, and we can continue monitoring your progress along the way. Do you have any final questions or concerns?

- **Amit:** I think we have covered everything. I will start by changing my diet, reducing stress, and getting more exercise. Hopefully, that will make a difference. Thanks again for your help.
- **Researcher:** It was my pleasure, Amit. Remember, we are here to guide you. Take care, and I am confident you will see positive changes soon.

4.3 Theoretical Aspect:

Combining the insights of Bauman, Giddens, and Marx provides a nuanced understanding of Amit's fertility challenges and the broader societal factors influencing them.

1. **Zygmunt Bauman's Risk Society** the growing reliance on online food delivery services exemplifies the hidden risks of modern convenience, where preservatives and additives compromise health. This framework suggests that the hidden risks of modern food production, driven by technology and convenience, are often invisible to consumers, who remain unaware of the long-term consequences for their health, such as the impact of preservatives and pesticides on sperm quality.

2. **Anthony Giddens' theory of Modernity** highlights the role of disembedding in food consumption, where individuals like Amit are distanced from the processes that influence their diet and health. The increased reliance on technology, such as online food delivery services, and the globalized food system make it difficult for individuals to make informed choices about the risks they face.

3. **Karl Marx's critique of capitalism** underscores the economic forces behind the food industry, where corporate interests prioritize profit over the health and well-being of consumers. In this context, the production and distribution of processed foods, packed with preservatives and pesticides, are a reflection of a capitalist system that values efficiency and profit maximization, often at the cost of consumer health.

In summary, the conversation with Amit provides valuable insight into the health risks associated with modern food consumption, particularly the impact of processed foods and convenience-based diets. Amit's reliance on online food delivery services, which often involve packaged and preservative-laden meals, is directly linked to his fertility issues, including sperm mortality. His case highlights how daily food choices—driven by convenience rather than health consciousness—can have long-term, unforeseen consequences.

Amit's experience reveals how many individuals are unaware of the hidden risks in the food they consume, particularly the long-term effects of preservatives, pesticides, and additives in agricultural products. His struggle underscores the need for greater awareness and education about the potential dangers lurking in seemingly harmless convenience foods, which are increasingly prevalent in modern society.

Ultimately, Amit's story is a call to action for individuals to reflect on their dietary choices and the broader environmental and health consequences of those choices. By becoming more informed and proactive about food consumption, there is potential for positive change—not only in Amit's fertility journey but also in the health of many others who may unknowingly be facing similar risks. This conversation serves as a reminder of the importance of making conscious, informed decisions in our daily lives, especially when it comes to the food we eat.

5. Conclusion

Environmental deterioration, and pesticide usage in particular, have far-reaching consequences for human reproductive health, as this research shows. The analysis uncovers a disturbing but critical story, driven by sustainable development goals and indexed by terms like pesticides, EDCs, land restoration, reproductive health, and sustainable agriculture. Raju Sarkar and Amit's stories illustrate how environmental pollutants, together with socioeconomic status and contemporary lifestyle choices, contribute to infertility in a way that is specific to men and women.

Raju's story exemplifies the connection between larger social structures and capitalist goals and the reproductive repercussions experienced by rural farming communities due to heavy chemical inputs. The problems that Amit is facing are reflective of urban life in general, where chemically loaded diets and convenient foods are to blame for men's dwindling fertility. Both stories provide credence to the idea that environmental pollutants, whether consumed orally or via direct contact, are a major contributor to infertility in all populations.

As a comprehensive approach, land restoration promotes resilient ecosystems, lessens reliance on chemicals, and benefits human health, among other benefits. By supporting sustainable agriculture, preserving terrestrial ecosystems, and ensuring excellent health and well-being, this restorative strategy aligns with SDGs 3, 12, and 15. Sustainable development, public health consciousness, and social justice must all be part of the solution to infertility, which cannot be solved alone via medical treatments. This study lends credence to the idea that protecting the world and its inhabitants' reproductive health may be achieved in the future through responsible governance and ecological harmony.

Reference

[01] Agarwal, A., Baskaran, S., Parekh, N., Cho, C. L., Henkel, R., Vij, S., Arafa, M., Panner Selvam, M. K., & Shah, R., 2021. Male infertility. *The Lancet, 397*(10271), 319–333. https://doi.org/10.1016/S0140-6736(20)32667-2

[02] Babakhanzadeh, E., Nazari, M., Ghasemifar, S., & Khodadadian, A., 2020. Some of the factors involved in male infertility: A prospective review. *International Journal of General Medicine, 13*, 29–41. DOI: 10.2147/IJGM.S241099

[03] Bergman, Å., Heindel, J. J., Jobling, S., Kidd, K. A., & Zoeller, R. T., 2013. *State of the science of endocrine-disrupting chemicals 2012*. United Nations Environment Programme and the World Health Organization. Retrieved from https://apps.who.int

[04] Clementi, M., Tiboni, G. M., Causin, R., La Rocca, C., Maranghi, F., Raffagnato, F., & Tenconi, R., 2008. Pesticides and fertility: An epidemiological study in northeast Italy

and review of the literature. *Reproductive Toxicology, 26*(1), 13–18. DOI: 10.1016/j.reprotox.2008.05.062

[05] Damgaard, I. N., Jensen, T. K., Petersen, J. H., Grandjean, P., Skakkebaek, N. E., & Main, K. M., 2016. Pesticides and male reproductive health: A systematic review of the epidemiological evidence. *International Journal of Andrology, 34*(2), 123–134. DOI: 10.1111/j.1365-2605.2016.00777.x

[07] Foucault, M., 1978. *The history of sexuality, Volume 1: An introduction*. Pantheon Books.

[08] Gore, A. C., Chappell, V. A., Fenton, S. E., Flaws, J. A., Nadal, A., Prins, G. S., Toppari, J., & Zoeller, R. T., 2015. EDC-2: The Endocrine Society's second scientific statement on endocrine-disrupting chemicals. *Endocrine Reviews, 36*(6), E1–E150. DOI: 10.1210/er.2015-1010

[09] Leaver, R. B., 2016. Male infertility: An overview of causes and treatment options. *British Journal of Nursing, 25*(18), S35–S40. DOI: 10.12968/bjon.2016.25.18.S35

[10] Liu, J., Zhang, P., Zhao, Y., & Zhang, H., 2019. Low-dose carbendazim disrupts mouse spermatogenesis might be through estrogen receptor-related histone and DNA methylation. *Ecotoxicology and Environmental Safety, 176*, 242–249. DOI: 10.1016/j.ecoenv.2019.03.103

[11] Marx, K., 1867. *Das Kapital: A critique of political economy*. Penguin Classics.

[12] Weber, M., 1905. *The Protestant ethic and the spirit of capitalism*. Scribner.

[13] Murshidi, M. M., Choy, J. T., & Eisenberg, M. L., 2020. Male infertility and somatic health. *Urologic Clinics of North America, 47*(2), 211–217. DOI: 10.1016/j.ucl.2019.12.008

[14] Sengupta, P., Banerjee, R., Nath, S., & Dutta, S., 2021. Environmental and lifestyle factors in declining fertility: A global concern. *Reproductive Medicine and Biology, 20*(4), 459–478. DOI:10.1002/rmb2.12441

[15] Vabre, P., Gatimel, N., Moreau, J., Gayrard, V., Picard-Hagen, N., Parinaud, J., & Léandri, R., 2017. Environmental pollutants, a possible etiology for premature ovarian insufficiency: A narrative review of the literature. *Environmental Health, 16*(1), 37. DOI: 10.1186/s12940-017-0242-4

[16] Zegers-Hochschild, F., Adamson, G. D., de Mouzon, I., Ishihara, O., Mansour, R., Nygren, K., Sullivan, E., & Vanderpoel, S., 2009. International Committee for Monitoring Assisted Reproductive Technology (ICMART) and the World Health Organization (WHO) revised glossary of ART terminology, 2009. *Fertility and Sterility, 92*(5), 1520–1524. DOI: 10.1016/j.fertnstert.2009.09.009

[17] Zegers-Hochschild, F., Adamson, G. D., de Mouzon, I., Ishihara, O., Mansour, R., Nygren, K., Sullivan, E., & Vanderpoel, S., 2009. International Committee for Monitoring Assisted Reproductive Technology (ICMART) and the World Health Organization (WHO) revised glossary of ART terminology, 2009. *Fertility and Sterility, 92*(5), 1520–1524. DOI: 10.1016/j.fertnstert.2009.09.009

Dr. Sumana Das

Dr. Sumana Das is a State-Aided College Teacher in the Department of Sociology at Jogamaya Devi College, affiliated with the University of Calcutta. She holds an M.A. in Applied Sociology and an M.Phil., both with first-class distinctions, and earned her Ph.D. from the University of Burdwan.

Dr. Das specializes in Women's Studies, Medical Sociology, Gerontology, and Research Methodology. She has contributed to several major and minor ESRC-ICSSR research projects in the capacity of Project Assistant. A regular speaker at national and international seminars and webinars, she actively engages in academic discourse both within and beyond India.

In addition to her primary role, Dr. Das serves as a visiting faculty member at various medical and nursing colleges under the West Bengal University of Health Sciences. She is also involved in academic administration, fulfilling responsibilities as a moderator, Head Examiner, and in other key roles.

Her scholarly contributions include numerous book chapters, journal articles, and academic writings that reflect her areas of expertise.

⌘ Land Restoration, Desertification and Drought Resilience,
Jogamaya Devi College Interdisciplinary Volume 4 (2025), pp. 141-148

Restoring Land: Combating Desertification through Drought Resilience

Supatra Sen
Associate Professor (Botany), Asutosh College, Kolkata.
supatrasen@gmail.com

Abstract: Drought poses a global emergency driven by climate change and unsustainable land management, and claims more lives, causes more economic loss, and affects more sectors of society than any other environmental hazard. Desertification is a form of land degradation by which fertile land gradually transforms to a barren desert. Desertification often leads to food insecurity arising from low or poor food production, poverty, enhanced prevalence of zoonotic diseases, deficit of wood and timber resources, diminished supply of drinking water, affected livelihoods and others. True success in drought and desertification combat is about significant improvements in land-based natural capital viz. soil, forests, land under cultivation, minerals leading to restored ecosystem services and sustained livelihoods. Drought must be tackled proactively by the community as a whole acting together for effective resilience.

Keywords: land degradation, community-based conservation, water scarcity, sustainability, integrated water resource management

1. Introduction

Desertification**,** a global issue of serious concern, is the consequence of long-term interaction of various land degradation processes, which get enhanced under conditions of severe aridity. It is the process due to which there is drastic reduction of biological productivity of arid areas by natural or anthropogenic factors. Desertification has grave social, economic and ecological implications worldwide and is thus a driver of sustainable development.

Land degradation results from quantitative or qualitative change in soil properties, which leads to reduction of potential of production of the particular land. Hence there is change in the characteristics of the Earth leading to formation of more desert and desert-like conditions, due to weakening of biological energy.

A number of factors including extreme climate conditions particularly drought and anthropogenic activities cause deterioration of soil quality leading to poorer utility of land. Drought poses a global emergency driven by climate change and unsustainable land management and claims more lives, causes more economic loss, and affects more sectors of society than any other environmental hazard. Desertification therefore is a form of land degradation by which fertile land gradually transforms to a barren desert.

2. Causes and Effects of Desertification

Desertification is caused by a combination of factors which change over time and location. The direct factors are land use practices and patterns along with climate change while population explosion, socio-economic conditions and policies are the indirect factors.

In the 21st century, desertification is usually due to the cumulative effects of natural and anthropogenic activities *viz.* deforestation, urbanization, overexploitation of natural resources, improper agricultural practices and soil damage due to misuse, overgrazing and erosion. Desertification often leads to food insecurity arising from low or poor food production, poverty, enhanced prevalence of zoonotic diseases, deficit of wood and timber resources, diminished supply drinking water, affected livelihoods and others. Such adverse effects are bound to have a profound impact on human health – such as malnutrition and dehydration arising from drastic reduction in food and drinking water availability, rise in water and food-borne diseases due to unhygienic conditions, respiratory ailments as a result of dust particles and air pollutants produced by erosion, wind etc., rapid rise in infectious diseases due to migrating populations trying to combat desertification.

3. The full impact of Desertification

(a) **Economic impact**: Desertification threatens agricultural productivity. It drastically reduces soil health impacting rural livelihoods.

(b) **Climate change**: Desertification aggravates climate change events, which causes greater damage. Degraded land loses its capacity to absorb carbon-dioxide, the greenhouse gas that is the largest contributor in enhancing global warming.

(c) **Carbon sequestration:** It is intricately linked with desertification, as desertification significantly reduces the ability to sequester carbon due to the loss of vegetation cover in dry environments. Healthy vegetation serves as a key carbon sink, so with rising desertification, the capacity to store carbon is significantly diminished (Hooke & Sandercock 2017).

(d) **Water scarcity**: land deterioration has resulted in drastic reduction in the quantity and quality of both **surface and groundwater** resources.
The dry land population susceptible to water stress and drought effect is projected to reach 178 million with temperature rise of 1.5°C due to global warming by 2050.

(e) **Rights of indigenous people**: The worst affected are the indigenous communities, who are threatened by insecure land tenure lose their ability to fight climate change.

4. The Desertification Convention at Rio and thereafter

Desertification, climate change and biodiversity loss were earmarked as the major crises and hurdles to sustainable development during the 1992 2nd Earth Summit at Rio. The Rio Conventions are three environmental and development treaties accepted at the 2nd Earth Summit: United Nations Framework Convention on Climate Change (UNFCCC), Convention on Biological Diversity (CBD) and United Nations Convention to Combat Desertification

(UNCCD). These three conventions are linked as they target interconnected issues and work in sync for the well maintenance of land, climate and biodiversity. In 1994, UNCCD was established by the General Assembly which is the only legally binding international agreement connecting environment and development to sustainable management of land. 17th June was declared "World Day to Combat Desertification and Drought" by a resolution A/RES/49/115. 2010-2020 was declared the United Nations Decade for Deserts and the Fight against Desertification (UNDDD) by the UN General Assembly in 2007. The goals set for the decade were raising awareness of the causes and solutions to desertification, mobilizing funds and financial support and technical expertise, monitoring and reporting the progress made and promoting sustainable land management. Out of 197 under UNCCD, 169 affected countries work together for maintenance and restoration of soil and land and drought mitigation in dry arid areas possessing some of the most fragile ecosystems of the world. UNCCD supported nearly 70 drought-prone countries to form strategic action plans to mitigate drought mediated disasters.

The United Nations Decade for Deserts and the Fight against Desertification (UNDDD) spanned for a decade from 2010 to 2020. The UN General Assembly declared the decade in response to the increasing land degradation and arid lands globally. The decade aimed to raise awareness of the reasons and solutions to desertification, marshal financial and technical support, observe and report on progress and ultimately endorse sustainable land management. Some of the highlights of the decade included the pledge of the government and private sector to restore 1 billion hectares of degraded land by 2020, plan of 128 countries to determine targets for 2030 with 90 countries already in track. The positive outcomes of reversing land degradation include rising amount of healthy land, improved air and water quality, safe and quality food with improved ground cover.

In 2022, the UNFCCC, CBD, and UNCCD convened meetings of their respective Conferences of the Parties (COPs) addressing the "**triple planetary crisis**" of climate change, pollution and biodiversity loss.

5. Measures taken by India to curb desertification/land degradation

It has been realized that success is merely not just about hectares under restoration or trees planted. In fact, true success is about significant improvements in land-based natural capital viz. soil, forests, land under cultivation, minerals leading to restored ecosystem services and sustained livelihoods. Land to most people and cultures, is sacred globally. Hence its restoration must be based on traditional knowledge and belief systems of the indigenous (Sen 2019, 2024a). Thus, degraded land must certainly be restored with the full support, cooperation and consent with the people who live and work on it – the indigenous communities.

(a) Integrated Watershed Management Programme is a means to restore ecological balance by connecting, conserving and improving the degraded natural resources with the establishment of Rural Employment and livelihoods.

(b) Desert Development Programme was launched in 1995 to minimize the deleterious effect of drought and to revive the natural resource base of the identified desert areas. It was launched simultaneously for hot desert areas of the states of Rajasthan, Gujarat, Haryana and cold deserts of Jammu & Kashmir and Himachal Pradesh.
(c) India became a signatory to the UNCCD in 1994 and was sanctioned in 1996. India is striving to restore 26 million hectares of degraded land by the year 2030 and achieve its national commitment on Land Degradation Neutrality –LDN which is Sustainable Development Goal target 15.3. Land Degradation Neutrality is a status whereby the quantity and quality of land resources, essential to support ecosystem functions and services and progress food security, remains constant or rises within specific temporal and spatial scales and Ecosystems.
(d) National Afforestation Programme implemented by the Ministry of Environment, Forest and Climate Change since 2000 is targeted to the afforestation of degraded forest lands. National Action Programme to Combat Desertification was prepared in 2001 to address issues of rising desertification and to take suitable measures.
(e) National Mission on Green India was approved in 2014 with the aim of conserving, restoring and enhancing India's decreasing forest cover within a limited time span of 10 years.

Food systems need restructuring as that ultimately restores land. About 90 % of our food comes from soil and crop systems are the primary drivers of land degradation. Over-use of fertilizers must give way to Regenerative Agriculture. Direct agricultural subsidies must be given to sustainable farming which produces affordable and quality food. Agroforestry and permaculture i.e. sustainable agricultural ecosystems practices must be practiced and encouraged (Sen, 2024b). Such approaches are in tandem with restoration, ensuring healthy soil, water and biodiversity with increased food security (Sen 2018, Sinha et al. 2024)

6. Resilience Strategies for Drought

Droughts have far-reaching impact on agriculture, landscaping, recreation, infrastructure and public health. Communities must acclimatize to be more drought resilient by exercising strategies to conservation of water at the domestic level, agricultural and industrial processes, explore and access fresh sources of water, and efficient drought management on a watershed level. Drought resilience strategies are already being executed in drought-prone areas which can satisfactorily provide a number of economic, environmental and public health benefits and save long term financial loss.

6.1 Aquifer Recharge

Prolonged drought can reduce groundwater aquifers which most communities depend on for supply of drinking water and irrigation purposes. Through the National Drought Resilience Partnership (NDRP) there are consistent efforts to promote storm-water and rainwater capture or rainwater harvesting to provide additional water supplies and replenish aquifers. There are ongoing field studies to record the influences of innovative green infrastructure practices –

like dry wells and infiltration basins, on movement of water into aquifers besides assessing the quality of the replenished water.

6.2 Water Reuse

Water conservation practices promoting reuse of water, known as fit-for-purpose water for potable (drinking) and non-potable (not for drinking) water are becoming increasingly significant. Besides water reuse, the expansion of non-traditional water supplies like impaired, alternative or reclaimed water which were previously not considered for reuse is promoted, without compromising human and environmental health. Efforts for integrated water resource management and proactive drought response are on the rise (Sen 2011, 2013).

Approaches for control of waterborne contaminants, advancing water systems that cover the complete water cycle, developing approaches to appraise transformative water systems - systems that fulfil public health and environmental purposes while optimizing treatment and making best use of recovering water resource and system resilience, and assessment of rainwater harvesting systems for non-potable water supplies are all currently in vogue.

6.3 Desalination

Brackish and salt water if purified can add to water supplies in areas impacted by drought. Scientists are growing salt-tolerant algal species that remove salts from such water bodies, which could simultaneously reduce the energy footprint and cost of desalination. The algal species in use are - from Chlorophyta - *Chlorella, Chlorococcum, Desmodesmus, Scenedesmus, and Monoraphidium* and from Cyanobacteria - *Spirulina, Nostoc, Oscillatoria and Anabaena*. The algae could then be harvested and used as raw material for biofuel production making the entire process eco-friendly and energy efficient. Researchers are also identifying, designing and demonstrating cost-effective options that will enable the recovery and reuse of impure water from compromised sources.

6.4 Response, Recovery and Restoration

Pan India partnerships with provision of research grants, tools, support, and training go a long way to help communities become more drought resilient. Research also includes preparedness for drought, pre-drought planning and emergency response.

Climate Ready Utilities Program is functioning countrywide using the Climate Resilience Evaluation and Awareness Tool to help carry out climate change risk assessment in order to identify utility-level strategies that ultimately build preparedness and resilience.

EPA and the Indian Health Service are organizing federal and state partners to supervise information on infrastructure needs and funding, technical assistance, emergency drought relief, and conservation strategies for tribes.

6.5 Other Possible Measures of Drought Combat

There must be sustained community efforts to identify, and find solutions to drought related issues, drought resilience and watershed sustainability (Chouhan 2018). Watershed Management programme works with academia to provide products and services for communities to address watershed problems related to water shortage and drought. Other areas of concern are loss of soil, flash floods, loss of aquatic life and others. The private sector too must be involved and funding from their end encouraged.

Countries must cooperate and peacefully co-exist as connecting with each other across borders as the Great Green Wall which spans 22 African countries ascertaining fertile land, food security, economic opportunities and climate resilience.

Drought must be tackled proactively for effective resilience. Communities must take measures prior the strike of the hazard and not wait for it to cause huge losses. The economic returns of building drought resilience are more than ten times larger than the initial investment, and bring considerably significant social, environmental, sustainable developmental gains. The community as a whole acting together can build drought resilience faster and more efficiently (Sen 2024c).

7. Conclusion

17 June also known as "Desertification and Drought Day", is observed every year to promote public awareness of international efforts to combat desertification. For this year 2024, the theme of the Desertification and Drought Day is **"**United for Land- Our Legacy, Our Future**"** which spotlights the future of land stewardship and the need for collective action for our most precious resource to ensure stability and sustainability of billions globally.

The slogan for World Environment Day 2024 must indeed be realized –
"Our land. Our future. We are #GenerationRestoration." The words "Our Land, Our Future" highlights the idea of integrated action to restore land that will positively impact future generations. No individual, state or organization solitarily can ensure successful implementation of the environmental objectives. The phrase "We are #GenerationRestoration" is a call for action, targeted to mobilize individuals, communities and nations to participate actively in restoration efforts. It fosters a sense of empowerment coming with collective responsibility, encouraging particularly the younger generation, (the worst victims of climate change and hence crucial stakeholders), to contribute to global restoration efforts.

REFERENCES

[01] Chouhan, T.S., 2018. Combating desertification, land degradation, and climate change: Management of drylands. Scientific Publishers.

[02] Hooke, J., Sandercock, P., 2017. Combating Desertification and Land Degradation, Spatial Strategies Using Vegetation. Springer.

[03] Sen, S., 2024a. Sustainable agriculture for zero hunger: combating abiotic stress. Journal of Environment & Socio-biology, 21(1), 93 – 100.

[04] Sen, S. 2024b. Towards Zero Hunger: Abiotic Stress on Crop Plant Physiology and Productivity. In: Ed. Mukhopadhyay S., Das, A. (eds.), Critical Studies in Science Volume 1, Asutosh College Publication Cell, 3 – 8. ISBN 978-81-966693-7-9.

[05] Sen, S., 2024c. Mission 'Sustainable Agriculture': Mitigating abiotic stress with nano particles. Journal of Stress Physiology & Biochemistry, 20(3), 230 – 236

[06] Sen, S., 2019. Blueprint for sustainability: Reviewing the Indian scenario. Lambert Academic Publishing. ISBN 978-620-0-23781-1

[07] Sen, S., 2018. Many faces of resource management: Blueprint for sustainable conservation. 123 – 135. Available at: http://www.harvestjournal.net/wp-content/uploads/2018/02/Muses-Volume-1-2018.pdf. Accessed on: December 15, 2024.

[08] Sen, S., 2013. From Conflict to Cooperation: 'Water for Life'. Musings, An Academic Journal 4, 17 – 21. ISSN: 0975-8054.

[09] Sen, S., 2011. From Abundance to Scarcity: Education for Water Conservation. In: Sen, S., Emerging Trends in Contemporary Education: Implications for 21st Century. Uluberia College. 78 – 82. ISBN 978-81-922305-1-1

[10] Sinha, D., De, A., Maurya, A.K., Abdi, G., Sen, S., 2024. Oxidative responses, antioxidative system, and redox regulation during water stress. In: Srivastava, P. K. (ed.), Water Stress in Crop Plants and Its Management. CRC Press, Taylor & Francis Group, Boca Raton, Florida, U.S.A. 76 – 128.

Further Reading (Recommended for students and young researchers)

[A] World Meteorological Organization, 2022. Drought and Water Scarcity https://www.droughtmanagement.info/literature/1284_IDMP_Water_Scarcity_Report.pdf.

[B] United Nations Convention to Combat Desertification, 2022. Drought in Numbers. https://www.unccd.int/resources/publications/drought-numbers.

[C] United Nations Office for Disaster Risk Reduction, 2021. GAR Special Report on Drought. https://www.undrr.org/publication/gar-special-report-drought-2021.

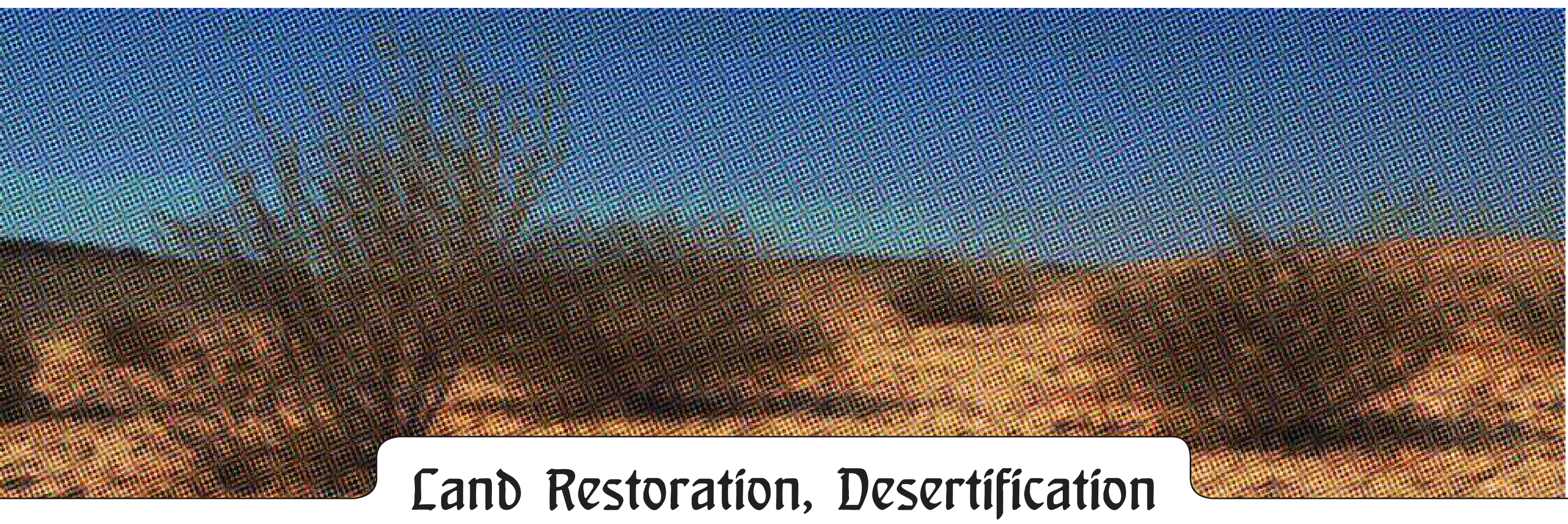
[D] Mirzabaev, A., J. Wu, J. Evans, F. García-Oliva, I.A.G. Hussein, M.H. Iqbal, J. Kimutai, T. Knowles, F. Meza, D. Nedjraoui, F. Tena, M. Türkeş, R.J. Vázquez, M. Weltz, 2019: Desertification. In: P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.). Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. DOI: https://doi.org/10.1017/9781009157988.005.

[E] United Nations Convention to Combat Desertification, 2019. Land Degradation Neutrality for biodiversity conservation: How healthy land safeguards nature.

https://www.unccd.int/resources/publications/land-degradation-neutrality-biodiversity-conservation-how-healthy-land.

Dr. Supatra Sen

Dr. Supatra Sen completed her B.Sc., M.Sc., M.Ed., M.Phil., Ph.D. from the University of Calcutta. An alumnus of Presidency College, she is currently Associate Professor (Botany) in Asutosh College, Kolkata and has published over one hundred twenty-five international books, papers and reviews. An academic career spanning three decades she has edited several UGC funded ISBN volumes, besides serving as resource person in different National and International seminars and webinars. She is actively engaged in writing and framing academic modules for different universities. Her research interests are Environmental Stress Physiology and Biochemical Ecology. She won the Environmentalist of the Year Award in 2014, the Best Faculty Award in 2017 and the World Ecological Restoration Award in 2018. Dr. Sen is the founder and Chief Editor of an ISSN peer-reviewed multi-disciplinary academic journal 'Harvest' since 2016 and also President of an academic body Social Environmental Biological Association (SEBA). Though her tryst with poetry is brief, she is an internationally published poet.



Land Restoration, Desertification and Drought Resilience