IntechOpen

IntechOpen Series
Environmental Sciences, Volume 36

Restoring Ecosystems and Assessing Drought Risk
Approaches and Practices

Edited by Humood Naser and Sener Akıncı

Restoring Ecosystems and Assessing Drought Risk - Approaches and Practices

Edited by Humood Naser and Sener Akıncı

Published in London, United Kingdom

Restoring Ecosystems and Assessing Drought Risk - Approaches and Practices
http://dx.doi.org/10.5772/intechopen.1006455
Edited by Humood Naser and Sener Akıncı

Contributors
Girma Nigussie, Mekbib Fekadu, Cara Steger, Bikila Warkineh and Sebsebe Demissew, Kiranmayi Raparthi, Michael Aide, Vanda Pires and Tânia Moura, Fhumulani I. Mathivha and Selelo Matimolane

First published in London, United Kingdom, 2025 by IntechOpen
IntechOpen is the global imprint of INTECHOPEN LIMITED, registered in England and Wales, registration number: 11086078, 167-169 Great Portland Street, London, W1W 5PF, United Kingdom

For EU product safety concerns: IN TECH d.o.o., Prolaz Marije Krucifikse Kozulić 3, 51000 Rijeka, Croatia, info@intechopen.com or visit our website at intechopen.com.

British Library Cataloguing-in-Publication Data
A catalogue record for this book is available from the British Library

Restoring Ecosystems and Assessing Drought Risk - Approaches and Practices
Edited by Humood Naser and Sener Akıncı
p. cm.

This title is part of the Environmental Sciences Book Series, Volume 36
Topic: Ecosystems and Biodiversity
Series Editor: J. Kevin Summers
Topic Editors: Salustiano Mato, Josefina Garrido and Francisco Ramil

Print ISBN 978-1-83634-902-0
Online ISBN 978-1-83634-901-3
eBook (PDF) ISBN 978-1-83634-903-7
ISSN 2754-6713

If disposing of this product, please recycle the paper responsibly.

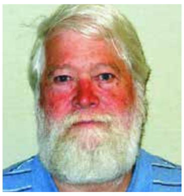
IntechOpen Book Series
Environmental Sciences
Volume 36

Aims and Scope of the Series

Scientists have long researched to understand the environment and man's place in it. The search for this knowledge grows in importance as rapid increases in population and economic development intensify humans' stresses on ecosystems. Fortunately, rapid increases in multiple scientific areas are advancing our understanding of environmental sciences. Breakthroughs in computing, molecular biology, ecology, and sustainability science are enhancing our ability to utilize environmental sciences to address real-world problems.

The four topics of this book series - Pollution; Environmental Resilience and Management; Ecosystems and Biodiversity; and Water Science - will address important areas of advancement in the environmental sciences. They will represent an excellent initial grouping of published works on these critical topics.

Meet the Series Editor



J. Kevin Summers is a Senior Research Ecologist at the Environmental Protection Agency's (EPA) Gulf Ecosystem Measurement and Modeling Division. He is currently working with colleagues in the Sustainable and Healthy Communities Program to develop an index of community resilience to natural hazards, an index of human well-being that can be linked to changes in the ecosystem, social and economic services, and a community sustainability tool for communities with populations under 40,000. He leads research efforts for indicator and indices development. Dr. Summers is a systems ecologist and began his career at the EPA in 1989 and has worked in various programs and capacities. This includes leading the National Coastal Assessment in collaboration with the Office of Water which culminated in the award-winning National Coastal Condition Report series (four volumes between 2001 and 2012), and which integrates water quality, sediment quality, habitat, and biological data to assess the ecosystem condition of the United States estuaries. He was acting National Program Director for Ecology for the EPA between 2004 and 2006. He has authored approximately 150 peer-reviewed journal articles, book chapters, and reports and has received many awards for technical accomplishments from the EPA and from outside of the agency. Dr. Summers holds a BA in Zoology and Psychology, an MA in Ecology, and Ph.D. in Systems Ecology/Biology.

Meet the Volume Editors

Dr. Humood Naser is an Associate Professor of Environmental Biology at the Department of Biology, College of Science, University of Bahrain. Dr. Naser holds a Ph.D. in environmental biology from Newcastle University and an M. Sc. in integrated environmental studies from the University of Southampton, UK. He is the author of several books, chapters, and articles published in reputed journals. His general research interests include environmental and ecological impact assessment, conservation biology, effects of environmental pollutants on species and ecosystems, environmental quality monitoring, and sustainable development.

Dr. Şener Akıncı received his Ph.D. degree in 1997 from Sheffield University, England. Since then, he has been studying Stress Physiology at the Department of Biology, Faculty of Science, Marmara University, Turkey, where he is Director of the "Native Plants and Water Products Applied Research Center". He has published over 25 original research articles, both nationally and internationally, and authored a book chapter in 2012, published by IntechOpen. Additionally, he edited a book in 2013. He is currently working as a Professor at the Botany section, Department of Biology, Faculty of Science, Marmara University, Turkey.

Contents

Preface

Ecological restoration, as the process of assisting the recovery of degraded, damaged or destroyed ecosystems, is currently emerging as an important discipline to mitigate the environmental challenges associated with rapid urbanization and climate change.

Ecosystem restoration provides a wide array of benefits ranging from restoring degraded habitats, enhancing biodiversity and ecosystem services to improving human well-being and promoting sustainable development. These benefits are the main mandate of the UN Decade (2021-2030) that calls for the protection and revival of ecosystems for the benefit of people and nature.

Numerous restoration initiatives at different scales are implemented around the globe. These include ecological restoration that focuses on ecological interactions of species and community dynamics, along with ecosystem services. Additionally, restoration includes broader physical and chemical remediations and actions related to geochemical monitoring and risk assessment for emerging soil contaminants.

Droughts are associated with climate change, leading to several ecological, agricultural, economic, and social impacts. Therefore, there is a need for integrated monitoring frameworks, resilient land management strategies, and adaptive policy interventions.

Increasing frequency and severity of droughts can pose challenges to the long-term success of restoration initiatives. Drought events can affect vegetation establishment, seedling survival, and ecosystem structure, leading to a reduction in biodiversity recovery. Conversely, effective restoration initiatives can contribute to climate adaptation and drought resilience by improving soil and water quality and supporting diverse and functional ecosystems.

This book, *Restoring Ecosystems and Assessing Drought Risk – Approaches and Practices*, responds to these dual global challenges. It highlights interdisciplinary research and case-based insights focused on ecosystem restoration and drought risk monitoring. The book is structured into three sections: 1. Ecological Restoration, 2. Environmental Restoration and 3. Drought Risk Assessment.

It presents five chapters that span diverse ecological regions and methodological approaches.

Chapter 1 examines the long-term ecological and social impacts of plantation forests in the Ethiopian highlands. It emphasizes the role of effective forest management in restoring degraded landscapes, which includes mixed-species plantations and local knowledge integration.

Chapter 2 focuses on peri-urban landscapes, emphasizing the importance of local engagement and spatial planning in enhancing agri-ecosystem services. It provides a participatory planning model aimed at integrating ecosystem services into urban development policies.

Chapter 3 provides an important case study on emerging soil contaminants and the need for baseline assessments and targeted restoration protocols in floodplain environments affected by industrial and geochemical dynamics.

Section three of the book provides two cases of drought risk assessment from Europe and Africa. Chapter 4 investigates historical drought trends using key meteorological indices. It demonstrates increasing drought frequency and severity, particularly in southern Portugal, and calls for improved planning and mitigation strategies. Chapter 5 evaluates multiple drought indices to identify the most effective tools for capturing complex drought dynamics in South Africa. It emphasizes the importance of a more comprehensive assessment of drought conditions and recommends enhanced monitoring for adaptive water resource management.

The book provides a comprehensive overview of contemporary research and approaches in ecosystem restoration and drought risk assessment. It offers valuable insights for researchers, practitioners, planners, and policy makers working across disciplines to address the twin challenges of ecosystem degradation and climate vulnerability.

We extend our sincere thanks to all authors who have contributed to this book. We are also grateful to the IntechOpen editorial team for their continuous support and cooperation.

Humood Naser
Department of Biology,
College of Science,
University of Bahrain,
Zallaq, Bahrain

Sener Akıncı
Faculty of Science,
Department of Biology,
Marmara University,
Istanbul, Turkey

Section 1

Ecological Restoration

Chapter 1

Impacts of Forestation on Human and Plant Communities in the Highland Regions: A Study of Guassa in Ethiopia

Girma Nigussie, Mekbib Fekadu, Cara Steger, Bikila Warkineh and Sebsebe Demissew

Abstract

The Ethiopian highlands are inhabited by 88 million people who live in a diverse landscape. The Afroalpine ecosystem extends above 3000 meters above sea level and is known for its abundant species diversity, rarity, and endemism. This chapter aims to examine the effects of plantation forests on the human and plant communities in the Afroalpine zone. We focused on the Guassa Community Conservation Area (Guassa), a community-based conservation area in the north central highlands where plantation forests have been started since the 1970s. The study site covers an area of approximately 78 square kilometers and varies in elevation from 2600 to 3700 meters above sea level. We interviewed 100 individuals residing in the four administrative areas nearest to Guassa and carried out vegetation sampling from 70 quadrats distributed along the study area. The native grassland and plantation forest exhibited a similar number of ecosystem services. Nevertheless, survey participants identified seven distinct ecosystem services provided by the native grassland, while only three unique ecosystem services were reported from the plantation forest. The perceived capacity to draw rain and offer a habitat for wildlife made both native grassland and plantation areas highly prized. Across the surveyed vegetation types, we documented 87 species from 63 genera and 31 plant families, as well as 19 endemic species.

Keywords: native grassland, plantation area, ecosystem service, local community, plant diversity, community conservation area

1. Introduction

Ethiopian highland regions are home to more than 88 million people (70% of the total population) living in a highly heterogeneous landscape, including the greatest extent of the iconic and rapidly disappearing Afroalpine ecosystem [1, 2]. Afroalpine ecosystem befalls over 3000 m a.s.l and is characterized by high levels of species diversity, rarity, and endemism [1]. The isolated "sky-islands" that make up afroalpine pocket habitats are divided from one another by vast savannas, semi-deserts, agricultural regions, and other social-ecological barriers that impede the movement of species [3–6]. Massive diurnal temperature variability, sometimes referred to as "summer every day and winter every night," affects afroalpine species [7–9]. Promising adaptations to this severe climate, afroalpine vegetation gives rise to tussock grasses, rosette plants, cushion plants, and sclerophyllous shrubs [8]. Millions of people rely on these landscapes for their subsistence, and they also support specialized markets that support local honey and wild-harvested coffee [10, 11].

Ethiopia's highlands are in danger due to changing land uses and the climate [12]. Global warming is occurring in mountains at a disproportionately high and rapid rate when compared to lowlands [13]. The distribution of precipitation in many Ethiopian highland areas appears to be changing from bimodal to unimodal [14–16], and the effects of the loss of early season rains on vegetation communities are still unknown. The remaining patches of native vegetation have been contaminated by uncontrolled wood gathering, livestock foraging, and other plant harvesting. In certain places, native vegetation has been nearly totally replaced by agriculture and plantation forests of non-native species [17, 18]. The most common issue in highland areas is thought to be soil erosion, which is especially noticeable when agricultural fields extend into marginal areas with thin soils, steep slopes, or cliffs [19–21].

Although plantation woods have long been utilized as a strategy for conserving water and soil, especially on steep hillsides, their political and social history in Ethiopia is complex [22]. During the socialist military Derg dictatorship of 1974–1991, about 7000 hectares of the study area (Guassa) were reforested, frequently against the wishes of the local populations and with little to no benefits to them [22]. During this time, the World Bank and the African Development Fund also launched extensive plantation development projects [23]. Many communities cleared these State-owned plantation woods when the Derg was overthrown, citing a variety of justifications including resentment of the previous administration, confusion about plantation ownership, and a desire for private gain [22]. Alternative afforestation strategies have been pursuing smaller, private quadrats for individual and community woodlots since the 1990s in an effort to decrease management disputes and improve local benefits from plantation forests [24, 25].

The merits and drawbacks of plantation forests, especially those that use non-native species like cypress and eucalyptus, are still hotly debated [26]. The benefits of site-appropriate tree plantation forests have been speculated to include increased soil organic matter [20, 27], stabilization of the soil [26], and restoration of ecosystems [28]. The local population has also benefited economically [25]. There is a belief, meanwhile, that planted woods take up otherwise valuable and scarce cropland in Ethiopia, and that some species, such as eucalyptus, drain the water and nutrients required for crops [24]. In comparison to other plantation species, exotic conifer species like *Cupressus lusitanica* have been linked to low species richness and diversity in the understory [29]. It has also been demonstrated that in certain situations, quickly expanding species such as *Eucalyptus* can outcompete local tree species [30]. Lastly, there are ongoing worries about how fairly planted forests and "Guassa" grass resources are used, since women and low-income households would not gain from initiatives at the same rates as wealthier households and men [31, 32]. Because wealthy households used work in addition to their manpower, something that impoverished people are unable to accomplish, and because women are unable to compete with men on equal terms when the preserved area is opened for limited days to exploit the resources.

This chapter's goal is to look into how plantations affect the Afroalpine zone's plant and people populations. We used a case study of a community-based conservation area in the north central highlands, known as the Guassa Community Conservation Area. In order to ascertain how vegetation change—including the establishment of plantation forests—has affected the subsistence and earnings of people in the study region, we first conducted surveys and group interviews with locals [33]. Next, in order to ascertain the differences between native Afroalpine grasslands and exotic plantation forests in terms of plant communities, we carried out vegetative sampling. We predicted that while plantation forests would benefit the local population more than natural vegetation, native vegetation would have a higher species variety.

2. Study area

Guassa Community Conservation Area ("*Guassa*") lies between 10° 15′–10°27′ N and 39° 45′–39° 49′ E, and is located 295 km north-east of Addis Ababa, Ethiopian capital city (**Figure 1A**).

Guassa is about 7800 hectares and ranges from 2600 to 3700 m a.s.l. Average annual precipitation is 1650 mm, falling mainly within the "*kirem*t" season from June to September [14], with sporadic showers occurring in the "belg" season from February to April. Guassa's monthly average temperature is 11.0°C (1.2°C SE) [14]. *Guassa* is a homeland for several endemic and endangered species, including the Ethiopian wolf (*Canis simensis*) and *gelada* monkey (*Theropithecus gelada*) [34]. The guassa grasses (Festuca macrophylla), which the natives appreciate for their use as

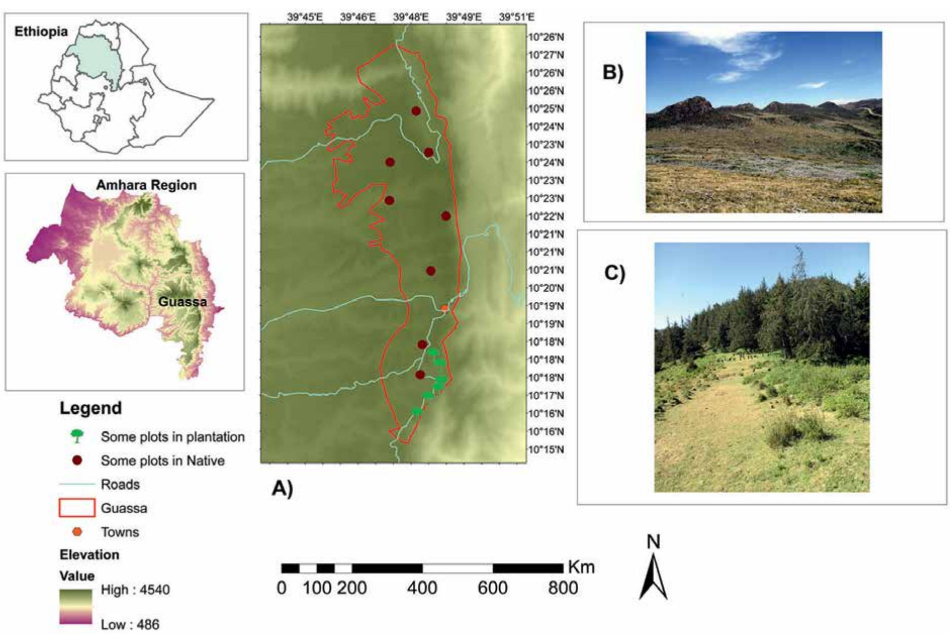


Figure 1.
Map of the Guassa Community Conservation Area and its environs. (A) purple points are used to indicate some quadrats in natural vegetation, while green tree shape points are used to indicate some quadrats in plantation forests. (B) shows a picture of some of Guassa's native vegetation kinds, and (C) shows a picture of Guassa's plantation forest.

forage, roofing, rope, and building material, are the source of the term Guassa [35]. Afroalpine only covers roughly 45 km2 of the protection area.

Over the course of its 400-year history, the Guassa management system has undergone significant changes in land management and politics. From around the 1600s until 1974, it was governed by the regional "Qero system" of communal management, which restricted access to the grasslands [34]. Then, things changed quickly. First, Emperor Haile Selassie took over in 1974. Next, there was a period of land restructuring under the military regime known as the "Derg" (1974–1991), followed by a period of mixed government and community management (1991–2003). After that, there was an increase in NGO leadership (2003–2012), and finally, there is the current co-management regime (2012–present) [33–36]. Since around 2000, the Guassa site has drawn more attention from travelers, the Ethiopian government, scientists, and international conservation organizations due to its importance as a water foundation and refuge for flora and fauna [37].

The extent of plantation woods in this region varies depending on whether they were created as individual woodlots or as public soil and water regulator initiatives [35]. A few tiny woodlots, both public and private, are scattered around the area outside the conservation area. The Derg regime developed a single, sizable plantation that is mostly confined within the conservation area. Our current comparison site is the sizable plantation inside the conservation area since it offers a rare chance to examine a long-term plantation site. In the 1990s, local populations burned many of the planted forests established by the Derg as a form of retaliation for previous atrocities committed by the State [22]. The two most common planted species are cypress (*Cupressus lusitanica*) and eucalyptus (*Eucalyptus globulus*).

2.1 Method for gathering and analyzing data

2.1.1 Social data collection method

A survey was created and distributed to 100 residents (25 per region) in the four administrative regions that are closest to the Guassa area. To enable them to consider changes to the plantation woods and protected area throughout the course of their lives, all respondents were older than 50. Respondents were randomly selected, and open-ended questions were utilized to explore their imagined timeline of historical events and how they influenced local communities. In order to identify the ecosystem services connected to both native vegetation and planted forests, we then conducted semi-structured group interviews [10]. We performed a group interview in each of the nine administrative divisions around Guassa to avoid a biased perspective from persons living closest to the Guassa area. Over the nine group interviews, we included 106 participants, whose ages ranged from 18 to 88 years, with an average age of 41. We were able to include a diverse spectrum of viewpoints and gain from insightful, lively discussions by combining the survey with group interviews [38].

We used descriptive statistics to analyze the surveys. We employed software package ANTHROPAC [39], to investigate the ecosystem service data, determining the comparative significance of each ecosystem function via the nine groups examined.

2.1.2 Vegetation data collection

In native grassland and plantation forest, we set up 70 sample quadrats along two transect lines with 35 quadrats in each area for natural vegetation and plantation forest. The distance between the two transect lines was 500 meters. Due to the plantation area having small area coverage in the Guassa area, quadrats were set up 100 meters apart from one another, while those in the native vegetation quadrats were set up 200 meters apart. For the purpose of gathering ecological data, each quadrat was measured as follows: 10 m × 10 m for trees, three sub-quadrats (4 m x 4 m) for shrubs, and five sub-quadrats (2 m x 2 m) for herbs [40].

For the ecological analysis, every type of plant in the quadrat was recorded, and any species that we were unable to identify in the field was gathered and preserved. All species' relative covers were noted and translated to values on a modified Braun Blanquet scale ranging from one to nine [41]. After pressing the plant specimens, we sent them to Addis Ababa University's National Herbarium, where we used databases of verified specimens and on-site specialists to identify the species.

To characterize the plant species diversity, we used the Shannon-Weiner diversity index, species richness, and evenness [6, 42–44] with the RStudio 2022.03 software and the community ecology package (vegan, version 2.6-4). Given that the the Shannon-Weiner diversity index considers both species richness and evenness and is independent of sample size and takes into account both species evenness and richness [45]. To determine whether there is a statistically significant difference in richness, diversity, and evenness between native grass and plantation forest, we employed a two-sample t-test.

3. Results

3.1 Plantation forests' effects on human communities

According to the majority of responders, plantation forests have benefited plant and human societies alike. A total of 15 ecosystem services, such as firewood, charcoal, honey, and lumber for building houses, were reported by respondents as being obtained from plantation trees (**Table 1**). The capacity of plantation forests to raise the area's groundwater table was also deemed valuable, but respondents clarified that this benefit only extended to cypress plantations and did not extend to eucalyptus plantations. According to one reply, "Our lives would have been extremely difficult if there had been no planted forest." Apart from its numerous advantages, it lessens the strain on natural grasslands.

It is challenging to draw direct parallels between the Guassa region in general and the "Guassa grass" (*Festuca macrophylla*) in particular because respondents cited ecological services for both. Six ecosystem benefits from the Guassa region as a whole and eight especially from the Guassa grass were reported by the respondents. When we combined these, we discovered that the number of ecosystem services varied slightly throughout vegetation kinds. The main reason native grasslands were valuable was because they provided the Guassa grass, which is the predominant roofing material in this area. This is why guassa grass had a high (1) Relative salience (S score) (**Table 1**). A high Relative salience (S score) indicates that all local people noticed the importance of identified resources. In addition, guassa grass is utilized to manufacture rope and other practical home products. Notably, firewood was supplied to the locals in the Guassa area until it was outlawed in 2010.

Only three distinct ecosystem services were offered by plantation forests, according to respondents, while seven unique ecosystem services were only present in native grasslands. Both vegetation types were prized for their purported ability to draw precipitation, serve as habitat for wildlife, and provide cash for nearby populations (**Table 1**).

Class	Ranked ecosystem services	Relative salience (S score)	Overlap
Guassa grass	Roof thatch	1.00	
	Rope construction	0.83	Unique
	Grass for construction	0.62	
	Income	0.44	
	Sleeping mat	0.26	Unique
	Foder	0.22	
	Floor covering	0.18	
	Local materials	0.02	Unique
Guassa native area	Harvest of *guassa* grass	1.00	Unique
	Source of water	0.71	
	Shelter for wild animals	0.47	
	To attract tourists	0.33	Unique
	To attract rain	0.05	Unique
	Harvest other plants	0.04	Unique
Guassa plantation forest	House construction	1.00	
	Firewood	0.85	
	Income	0.72	
	Soil protection	0.50	
	Household items	0.41	
	Shelter for animals	0.31	
	To attract rain	0.24	
	Climate regulation	0.11	
	Forage	0.11	
	Fence construction	0.08	Unique
	Shade	0.07	
	Source of honey	0.03	
	Charcoal	0.02	Unique
	Increase groundwater	0.01	
	Beauty	0.01	

Note: Relative salience index (S score) *is used to indicate how many people/participants mentioned the ecosystem service or purpose. The value of S score is from zero (Not mentioned by participants) to one (Mentioned by all participants). And it is calculated as follows: S- score = ecosystem service listed by participant/Total participant*100. Source: Adapted from the work of Nigussie et al. [46].*

Table 1.
Locally defined resource classes and their respective ecosystem services.

3.2 Plantation forests' effects on plant communities

We identified 88 species in total, representing 63 genera and 31 plant families among the two vegetation types surveyed (two outside the quadrat but still inside the study site), as well as 19 endemic species. From the natural grassland quadrat, we identified 78 species (**Table 1**). Of them, only 38 species (48.7%) were found in the original grassland region. Meanwhile, we recorded 48 species from the plantation area quadrat, eight of which (16.7%) existed merely on the plantation site. There were a total of 40 plant species that were shared by the original vegetation and the planting site. With 31 plant types, the Asteraceae family has the most, followed by the Poaceae (n = 9), Rosaceae (n = 4), Cyperaceae (n = 4), and Polygonaceae (n = 4). These five families represent 60% of all species found in the region.

The average plant species richness per quadrat (SD = 3.3) at the natural grassland site ranged from 6 to 18 species. With a range of 3–18 species (SD = 3.2), the plantation forest's mean species richness was nine species per quadrat. There was a statistically significant variation in the number of species per quadrat among the different plant types ($t(68) = 2.14$, $p = 0.04$). The natural grassland Shannon-Weiner diversity index value (beta diversity) was 2.98, but the plantation forest index was 2.20. There was a statistically significant difference in the diversity index and evenness per quadrat (alpha diversity) between the different vegetation types ($t(53) = 4.27$, $p < 0.001$) and ($t(42) = 4.62$, $p < 0.001$), respectively. In conclusion, **Table 2** shows that the evenness values for natural grassland and plantation forest were 0.7 and 0.6, respectively.

In the research region, we discovered 19 species (representing 22% of all plant kinds) that are native to Ethiopia and Eritrea, 11 of which are exclusive to the Afroalpine zone (**Table 2**). According to the study by Wodaj et al. [47], the preserved site has only nine indigenous species. The "Red List" of the International Union for Conservation of Nature has evaluated three of these species [48]. There were 12 endemic species in the plantation forest and 15 in the native grassland. Out of these eight species were common to both types of vegetation, leaving seven endemic species exclusive to native grasslands and four exclusives to plantation forests.

Comparing this chapter's findings to earlier vegetation assessments conducted in the region, endemic species were discovered in both native grasslands and plantation forests [47]. Using the Plants of the World webpage at Kew Royal Botanical Gardens, we verified the endemism of every species. We used the publications [7, 49] to determine if any species were exclusive to the Afroalpine zone. To find out if there has been an assessment of the risks to the sustainability of these species, we checked the website of the International Union for Conservation of Nature. In majority of them, it was impossible to find data regarding their threat status because the "Red list" assessment of Ethiopia was not comprehensive. About Ethiopia's endemic trees and shrubs, there is only red list information available [50] (**Table 3**).

Site	Richness	H'	H_{max}	Evenness
Native grassland	78	2.98	4.3	0.7
Plantation forest	48	2.20	3.8	0.6

Table 2.
Plant richness, diversity index (Ho), maximum possible diversity index (Hmax), and evenness for native grassland and plantation site (beta diversity).

Species name	Plantation forest	Native grassland	[47]	Endemic [49]	Afroalpine [7]	IUCN red list [50]
Alopecurus baptarrhenius S.M. Phillips	No	Yes	No	Yes	Yes	
Bidens pachyloma (Oliv. and Hiern) Cufod.	Yes	No	No	Yes	No	
Cineraria abyssinica Sch. Bip. ex A. Rich	Yes	No	Yes	Yes	Yes	
Cirsium dender Friis	No	Yes	No	Yes	No	
Cirsium schimperi (Vatke) C. Jeffrey ex Cufod.	No	Yes	No	Yes	No	
Conyza flabellata Mesfin	No	Yes	No	Yes	No	
Cynoglossum amplifolium Hochst. ex DC.	Yes	Yes	Yes	Yes	No	
Euryops pinifolius A. Rich.	Yes	Yes	Yes	Yes	Yes	Vulnerable
Festuca macrophylla Hochst. ex A. Rich.	Yes	Yes	Yes	Yes	Yes	
Festuca richardii E.B.Alexeev	Yes	Yes	No	Yes	Yes	
Inula confertiflora A. Rich.	Yes	Yes	No	Yes	No	Near threatened
Kniphofia foliosa Hochst.	Yes	Yes	Yes	Yes	Yes	
Lobelia rhynchopetalum Hemsl.	No	Yes	Yes	Yes	Yes	
Phagnalon abyssinicum Sch. Bip. ex Hochst.	Yes	No	No	Yes	Yes	
Plectocephalus varians (A. Rich) C. Jeffery ex Cufod.	Yes	Yes	Yes	Yes	Yes	
Senecio ochrocarpus Oliv. and Hiern	Yes	No	No	Yes	Yes	
Solanum marginatum L.f.	No	Yes	No	Yes	Yes	Least concern

Species name	Plantation forest	Native grassland	[47]	Endemic [49]	Afroalpine [7]	IUCN red list [50]
Thymus schimperi Ronniger	Yes	Yes	Yes	Yes	Yes	
Urtica simensis Hochst. ex A. Rich.	No	Yes	Yes	Yes	No	

Note: IUCN, International Union for Conservation of Nature.
Source: Adapted from the work of Nigussie et al. [46].

Table 3.
Comparison of endemic plants found in current and previous ecological studies.

4. Discussion

Our study used a case study of a community-protected area in Ethiopia's highlands to examine the effects of planted trees on the plant and human communities in the Afroalpine zone. When compared to planted forests, we discovered that native grasslands had a greater species variety. We also discovered that while plantation forests and native vegetation supplied about equal amounts of ecosystem services to humans, native vegetation provided a higher number of unique ecosystem benefits that could not be found elsewhere. Still, people and plants gain unique benefits from plantation forests, which underscores the complementing role these planned vegetation types play in a diversified ecosystem.

Worldwide, plantation forests are becoming more and more significant as the basis for harvests of both wood and non-timber forests [51, 52]. Although many people believe that wild forests provide more ecosystem services than plantation forests, a recent study suggests that this belief may be the result of insufficient monitoring conducted over too short a time [51]. Our case study's long-standing plantation forests demonstrate that planted forests can offer ecosystem services on par with those offered by naturally occurring plants.

The social, economic, religious, and ecological strain that is imposed on natural forests and other vegetation can actually be lessened by carefully designed and maintained plantations [51]. For example, plantation woods in Guassa provide a source for charcoal and firewood production, which are no longer available in the natural grasslands due to changes in management. For subsistence livelihoods, the provision of energy in the form of firewood and charcoal is an essential ecosystem function [53], and plantation forests can lessen the strain of deforestation on native forests or shrublands. Our findings show that, when seen as a component of a landscape-scale mosaic, plantation forests can sustain larger densities of endemic species in addition to providing ecosystem benefits. Interestingly, four indigenous species that were absent from the natural Afroalpine vegetation were discovered in the planted forest quadrat. We suspect this may be due to a combination of factors: the higher soil moisture in plantation forests, lower light levels, and increased rates of litter and decomposition within forests. Reforestation or plantation forests provide many ecological benefits, such as changing nutrient cycling, increasing stability of soil carbon, improving soil moisture, and enhancing water quality [54]. Therefore, while our results support previous work that finds lower species diversity and richness in plantation forests versus native vegetation [55, 56], we would argue that plantation forests can still contribute to increased plant richness at a landscape scale [57, 58].

A better solid result was obtained from the social history of plantation because this part was done by qualitative method. While the ecological part cannot be answered by interview and group discussion, the ecological differences between plantation and native grassland are explored through the quantitative method. To see the ecological differences between plantation and native grassland, we compared them to A t-test. Therefore, we were able to see the differences. For example, the native grassland is better in plant richness, diversity, and evenness than plantation areas. This implies that planting trees has an impact on native plant species [59]. Literature shows that Plantation Forests can have either a positive or negative impact on animal/fauna diversity [59]. It depends on management style or practice. If we plant sole exotic species, it could have negative impact, whereas, if we plant mixed tree species, it has positive role on fauna diversity [60]. However, we did not study the impact of plantation forest on animals/mammals, because it was not our objective.

5. Conclusions

This chapter adds to the ongoing discussions on how plantation forests affect human groups, especially in the diverse cultural landscapes found in the Ethiopian highlands. According to our findings, plantation forests provide a wide range of ecosystem services that are essential to local lives, such as financial revenue from specialized products like honey, lumber for building homes, and energy via the production of charcoal and firewood. Large-scale government plantings have been replaced with smaller-scale plantation forests with targeted management, and negative attitudes of plantation forests, which were historically common in this region, appear to have mostly diminished.

Our findings add to the ecological discussions concerning the effects of plantation forests on plant communities. At the landscape scale, the plantation forests in our example study offer an alternate habitat structure that supports greater plant diversity, even if they undoubtedly have less plant diversity than natural Afroalpine vegetation. The upkeep of long-term plantation forests may provide additional adaptive ability for the plant communities in the Ethiopian highlands as precipitation patterns continue to change.

6. Recommendations

Based on the findings of this study on plantation forests in the Guassa Community Conservation Area, the following recommendations are proposed to enhance both conservation outcomes and local livelihoods:

Promote mixed-species plantations: The study suggests that plantations of single exotic species, such as *Cupressus lusitanica* and *Eucalyptus globulus*, can reduce biodiversity and lead to negative ecological impacts, particularly on the native Afroalpine vegetation. Therefore, future plantation efforts should prioritize mixed-species plantations that include both native and non-native species. This strategy could mitigate negative impacts on plant diversity and enhance ecosystem services like soil stabilization, carbon sequestration, and water retention.

Incorporate local community involvement in plantation management: A key finding of this study is the socioeconomic benefits plantation forests provide to local communities, such as income from charcoal and honey production. However, negative experiences from previous government-led afforestation projects, particularly under the Derg regime, have led to distrust among communities. It is crucial to strengthen community-based forestry management by involving locals in decision-making and management processes. This approach will ensure that the needs and rights of marginalized groups, such as women and low-income households, are considered.

Adapt forest management to climate change: Given the changing precipitation patterns in Ethiopia's highlands, it is important to adapt forest management strategies to account for climate variability. This could involve selecting drought-resistant species and adjusting planting schedules to accommodate shifts in seasonal rainfall. Research and experimentation with native species that can withstand the increasingly dry conditions should also be prioritized.

By implementing these recommendations, plantation forests can serve both as a vital source of livelihood for local communities and as a tool for conserving biodiversity in the Ethiopian highlands.

Acknowledgements

We are grateful for financial support from the Rufford Small Grant Foundation, Addis Ababa University's Thematic Research third cycle grant, the Department of Plant Biology and Biodiversity Management at Addis Ababa University, and the Sekota Dry Land Agricultural Research Center. We also appreciate the field support provided by the Guassa lodge crew, which includes Agagaw, Laigefu, Abebe Gosim, and Mulugeta.

Author details

Girma Nigussie[1,2]*, Mekbib Fekadu[1,3], Cara Steger[4], Bikila Warkineh[1] and Sebsebe Demissew[1,5]

1 Department of Plant Biology and Biodiversity Management, College of Natural and Computational Sciences, Addis Ababa University, Addis Ababa, Ethiopia

2 Amhara Agricultural Research Institute at Sekota Dry Land Agricultural Research Center, Sekota, Ethiopia

3 Plant Ecology and Geobotany, Faculty of Biology, Philipps University of Marburg, Germany

4 Department of Natural Resources and the Environment, Cornell University, Fernow Hall, Ithaca, NY, USA

5 Gullele Botanic Garden, Addis Ababa, Ethiopia

*Address all correspondence to: girma.21@yahoo.com

References

[1] Enquist BJ, Feng X, Boyle B, Maitner B, Newman EA, Jørgensen PM, et al. The commonness of rarity: Global and future distribution of rarity across land plants. Science Advances. 2019;**5**(11):eaaz0414. DOI: 10.1126/sciadv.aaz0414

[2] UNDESA [United Nations Department of Economic and Social Affairs] [Population Division]. World Population Prospects 2022, Summary of Results. UN DESA/POP/2022/TR/NO. 3. New York, NY: United Nations; 2022. Available from: https://www.un.org/development/desa/pd/content/World-Population-Prospects-2022 [Accessed: August 15, 2023]

[3] Gizaw A, Kebede M, Nemomissa S, Ehrich D, Bekele B, Mirre V, et al. Phylogeography of the heathers *Erica arborea* and *E. Trimera* in the afro-alpine "sky islands" inferred from AFLPs and plastid DNA sequences. Flora. 2013;**208**(7):453-463. DOI: 10.1016/j.flora.2013.07.007

[4] Mairal M, Sanmartı'n I, Herrero A, Pokorn'y L, Vargas P, Aldasoro JJ, et al. Geographic barriers and Pleistocene climate change shaped patterns of genetic variation in the eastern Afromontane biodiversity hotspot. Scientific Reports. 2017;**7**:45749. DOI: 10.1038/srep45749

[5] Popp M, Gizaw A, Nemomissa S, Suda J, Brochmann C. Colonization and diversification in the African "sky islands" by *Eurasian Lychnis L.* (Caryophyllaceae). Journal of Biogeography. 2008;**35**(6):1016-1029. DOI: 10.1111/j.1365-2699.2008.01902.x

[6] Wondimu T, Gizaw A, Tusiime FM, Masao CA. Crossing barriers in an extremely fragmented system: Two case studies in the afro-alpine sky island flora. Plant Systematics and Evolution. 2014;**300**:415-430. DOI: 10.1007/s00606-013-0892-9

[7] Gehrke B, Linder HP. Species richness, endemism and species composition in the tropical Afroalpine flora. Alpine Botany. 2014;**124**:165-177. DOI: 10.1007/s00035-014-0132-0

[8] Hedberg O. Features of Afroalpine Plant Ecology. Acta Phytogeographica Suecica 49. Uppsala, Sweden: Almqvist and Wiksells; 1964

[9] Hunter ML Jr, editor. Maintaining Biodiversity in Forest Ecosystems. Cambridge, United Kingdom: Cambridge University Press; 1999. DOI: 10.1017/CBO9780511613029

[10] Senbeta F, Denich M. Effects of wild coffee management on species diversity in the Afromontane rainforests of Ethiopia. Forest Ecology and Management. 2006;**232**(1-3):68-74. DOI: 10.1016/j.foreco.2006.05.064

[11] Wakjira DT, Fischer A, Pinard MA. Governance change and institutional adaptation: A case study from Harenna Forest, Ethiopia. Environmental Management. 2013;**51**:912-925. DOI: 10.1007/s00267-013-0017-9

[12] Stevart T, Dauby G, Lowry PP II, Blach-Overgaard A, Droissart V, Harris DJ, et al. A third of the tropical African flora is potentially threatened with extinction. Science Advances. 2019;**5**(11):eaax9444. DOI: 10.1126/sciadv.aax9444

[13] Pepin N, Bradley RS, Diaz HF, Baraer M, Caceres EB, Forsythe N, et al. Elevation-dependent warming in

mountain regions of the world. Nature Climate Change. 2015;**5**:424-430. DOI: 10.1038/nclimate2563

[14] Fashing PJ, Nguyen N, Venkataraman VV, Kerby JT. Gelada feeding ecology in an intact ecosystem at Guassa, Ethiopia: Variability over time and implications for theropith and hominin dietary evolution. American Journal of Physical Anthropology. 2014;**155**(1):1-16. DOI: 10.1002/ajpa.22559

[15] Groth J, Ide T, Sakdapolrak P, Kassa E, Hermans K. Deciphering interwoven drivers of environment-related migration—A multisite case study from the Ethiopian highlands. Global Environmental Change. 2020;**63**:102094. DOI: 10.1016/j.gloenvcha.2020.102094

[16] Rosell S. Regional perspective on rainfall change and variability in the central highlands of Ethiopia, 1978-2007. Applied Geography. 2011;**31**(1):329-338. DOI: 10.1016/j.apgeog.2010.07.005

[17] Negash L. A Selection of Ethiopia's Indigenous Trees: Biology, Uses, and Propagation Techniques. Addis Ababa, Ethiopia: Addis Ababa University Press; 2010

[18] Wassie A, Teketay D, Powell N. Church forests in north Gonder administrative zone, northern Ethiopia. Forests, Trees and Livelihoods. 2005;**15**(4):349-373. DOI: 10.1080/14728028.2005.9752536

[19] Haregeweyn N, Tsunekawa A, Poesen J, Tsubo M, Meshesha DT, Fenta AA, et al. Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the upper Blue Nile River. Science of the Total Environment. 2017;**574**:95-108. DOI: 10.1016/j.scitotenv.2016.09.019

[20] Hurni H. Degradation and conservation of the resources in the Ethiopian highlands. Mountain Research and Development. 1988;**8**(2/3):123-130. DOI: 10.2307/3673438

[21] Nyssen J, Poesen J, Veyret-Picot M, Moeyersons J, Haile M, Deckers J, et al. Assessment of gully erosion rates through interviews and measurements: A case study from northern Ethiopia. Earth Surface Processes and Landforms. 2006;**31**(2):167-185. DOI: 10.1002/esp.1317

[22] Admassie Y. Twenty Years to Nowhere: Property Rights, Land Management and Conservation in Ethiopia. Trenton, NJ: Red Sea Press; 2000

[23] Pohjonen V, Pukkala T. Eucalyptus globulus in Ethiopian forestry. Forest Ecology and Management. 1990;**36**(1):19-31. DOI: 10.1016/0378-1127 (90)90061-F

[24] Jagger P, Pender J. The role of trees for sustainable management of lessfavored lands: The case of eucalyptus in Ethiopia. Forest Policy and Economics. 2003;**5**(1):83-95. DOI: 10.1016/S1389-9341(01)00078-8

[25] Meaza H, Tsegaye D, Nyssen J. Allocation of degraded hillsides to landless farmers and improved livelihoods in Tigray, Ethiopia. Norsk Geografisk Tidsskrift–Norwegian Journal of Geography. 2016;**70**(1):1-12. DOI: 10.1080/00291951.2015.1091033

[26] Moges DM, Taye AA. Determinants of farmers' perception to invest in soil and water conservation technologies in the North-Western highlands of Ethiopia. International Soil and Water Conservation Research. 2017;**5**(1):56-61. DOI: 10.1016/j.iswcr.2017.02.003

[27] Parrotta JA. The role of plantation forests in rehabilitating degraded tropical ecosystems. Agriculture, Ecosystems and Environment. 1992;**41**(2):115-133. DOI: 10.1016/0167-8809(92)90105-K

[28] Bishaw B. Deforestation and land degradation in the Ethiopian highlands: A strategy for physical recovery. Northeast African Studies. 2001;**8**(1):7-25. Available from: http://www.jstor.org/stable/41931353

[29] Lemenih M, Gidyelew T, Teketay D. Effects of canopy cover and understory environment of tree plantations on richness, density and size of colonizing woody species in southern Ethiopia. Forest Ecology and Management. 2004;**194**(1-3):1-10. DOI: 10.1016/j.foreco.2004.01.050

[30] Carnus M, Parrotta J, Brockerhoff E, Arbez M, Jactel H, Kremer A, et al. Planted forests and biodiversity. Journal of Forestry. 2006;**104**(2):65-77. DOI: 10.1093/jof/104.2.65

[31] Gobeze T, Bekele M, Lemenih M, Kassa H. Participatory forest management and its impacts on livelihoods and forest status: The case of Bonga forest in Ethiopia. International Forestry Review. 2009;**11**(3):346-358. DOI: 10.1505/ifor.11.3.346

[32] Nigussie Z, Tsunekawa A, Haregeweyn N, Adgo E, Tsubo M, Ayalew Z, et al. Economic and financial sustainability of an Acacia decurrens–based Taungya system for farmers in the upper Blue Nile Basin, Ethiopia. Land Use Policy. 2020;**90**:104331. DOI: 10.1016/j.landusepol.2019.104331

[33] Nigussie G, Fekadu M, Demissew S, Warkineh B. Impact of conservation management on land change: A case study in Guassa community conservation area for the last 31 years (1986-2015). Modeling Earth Systems and Environment. 2019;**5**(4):1495-1504. DOI: 10.1007/s40808-019-00650-7

[34] Ashenafi ZT, Leader-Williams N. Indigenous common property resource management in the central highlands of Ethiopia. Human Ecology. 2005;**33**:539-563. DOI: 10.1007/s10745-005-5159-9

[35] Steger C, Nigussie G, Alonzo M, Warkineh B, Van Den Hoek J, Fekadu M, et al. Knowledge coproduction improves understanding of environmental change in the Ethiopian highlands. Ecology and Society. 2020;**25**(2):2. DOI: 10.5751/ES-11325-250202

[36] Fischer A, Wakjira DT, Weldesemaet YT, Ashenafi ZT. On the interplay of actors in the co-management of natural resources—A dynamic perspective. World Development. 2014;**64**:158-168. DOI: 10.1016/j.worlddev.2014.05.026

[37] Welch C. Where the world's only grass-eating monkeys thrive. National Geographic. 2017. Available from: https://www.nationalgeographic.com/magazine/article/geladamonkeys-grass-eating-guassa-ethiopia-bleeding-heart [Accessed: August 15, 2023]

[38] Gibbs A. Focus groups and group interviews. In: Arthur J, Waring M, Coe R, Hedges LV, editors. Research Methods and Methodologies in Education. London, United Kingdom: Sage; 2012. pp. 186-192

[39] Borgatti SP. ANTHROPAC 4.0. Natick, MA: Analytic Technologies; 1996

[40] BLM [Bureau of Land Management]. Sampling Vegetation Attributes. Interagency Technical Reference. Washington, DC: BLM National Applied Resource Science Center; 1996

[41] van der Maarel E. Transformation of cover/abundance value in phytosociology and its effect on community similarity. Vegetation. 1979;**39**:97-114. DOI: 10.1007/BF00052021

[42] Erenso F, Maryo M, Abebe W. Floristic composition, diversity and vegetation structure of woody plant communities in Boda dry evergreen montane forest, West Showa, Ethiopia. International Journal of Biodiversity and Conservation. 2014;**6**:382-391. DOI: 10.5897/IJBC2014.0703

[43] Krebs CJ. Ecological Methodology. 2nd ed. (1st ed. 1991) ed. Menlo Park, CA: Addison Wesley Longman; 1999

[44] Magurran AE. Measuring Biological Diversity. Oxford, United Kingdom: Blackwell; 2004

[45] Kent M, Coker P. Vegetation Description and Analysis: A Practical Approach. Boca Raton, FL: CRC Press; 1992

[46] Nigussie G, Fekadu M, Demissew S, Warkineh B. Examining the impacts of plantation forests on human and plant communities in the Ethiopian highlands. Mountain Research and Development (MRD). 2023;**43**(4):1-8. DOI: 10.1659/mrd.2023.00010

[47] Wodaj H, Kelbessa E, Woldu Z. Floristic composition and herbaceous aboveground dry weight biomass of afroalpine vegetation in Guassa community conservation area, north Shewa, Ethiopia. International Research Journal of Biological Sciences. 2016;**5**(1):26-36

[48] IUCN [International Union for Conservation of Nature]. The IUCN Red List of Threatened Species. Version 2022-2. Gland, Switzerland: IUCN. Available from: https://www.iucnredlist.org; 2022 [Accessed: March 14, 2023]

[49] Dagne E. Natural Database for Africa (NDA) Software [CD-ROM]. 2nd edition (1st edition 2009) ed. Addis Ababa, Ethiopia: Addis Ababa University; 2011

[50] Vivero JL, Kelbessa E, Demissew S. The Red List of Endemic Trees and Shrubs of Ethiopia and Eritrea. Cambridge, United Kingdom: Fauna and Flora International; 2005

[51] Baral H, Guariguata MR, Keenan RJ. A proposed framework for assessing ecosystem goods and services from planted forests. In: Ecosystem Services 22:Bridge. United Kingdom: Cambridge University Press; 2016. DOI: 10.1017/CBO9780511613029

[52] Elsasser P, Altenbrunn K, Köthke M, Lorenz M, Meyerhoff J. Spatial distribution of forest ecosystem service benefits in Germany: A multiple benefit transfer model. Forests. 2021;**12**(2):169. DOI: 10.3390/f12020169

[53] Mead DJ. Forests for energy and the role of planted trees. Critical Reviews in Plant Sciences. 2005;**24**(5-6):407-421. DOI: 10.1080/07352680500316391

[54] Cunningham SC, Cavagnaro TR, Mac Nally R, Paul KI, Baker PJ, Beringer J, et al. Reforestation with native mixed-species plantings in a temperate continental climate effectively sequesters and stabilizes carbon within decades. Global Change Biology. 2015;**21**(4):1552-1566. DOI: 10.1111/gcb.12746

[55] Braun AC, Troeger D, Garcia R, Aguayo M, Barra R, Vogt J. Assessing the impact of plantation forestry on plant biodiversity: A comparison of sites in Central Chile and Chilean Patagonia. Global Ecology and Conservation. 2017;**10**:159-172

[56] Redei T, Csecserits A, Lhotsky B, Barabas S, Kröel-Dulay G, Onod'i G, et al. Plantation forests cannot support the richness of forest specialist plants in the forest-steppe zone. Forest Ecology and Management. 2020;**461**:117964. DOI: 10.1016/j.foreco.2020.117964

[57] Lemenih M. Expediting ecological restoration with the help of foster tree plantations in Ethiopia. Journal of the Drylands. 2006;**1**(1):72-84

[58] Pawson SM, Brin A, Brockerhoff EG, Lamb D, Payn TW, Paquette A, et al. Plantation forests, climate change and biodiversity. Biodiversity and Conservation. 2013;**22**:1203-1227. DOI: 10.1007/s10531-013-0458-8

[59] Wang C, Zhang W, Li X, Wu J. A global meta-analysis of the impacts of tree plantations on biodiversity. Global Ecology and Biogeography. 2022;**31**(3):576-587. DOI: 10.1111/geb.13440

[60] Hartley MJ. Rationale and methods for conserving biodiversity in plantation forests. Forest Ecology Management. 2002;**155**:81-95. DOI: 10.1016/S0378-1127(01)00549-7

Chapter 2

Participatory Planning Framework for Mainstreaming Ecosystem Services to Enhance Agricultural Resilience in Peri-Urban Areas

Kiranmayi Raparthi

Abstract

Ecosystem services are gaining prominence in urban and peri-urban sustainability discourses, especially in efforts to increase agricultural resilience. The parochial approach and understanding of peri-urban neighborhood dynamics, especially across the global south, has led to its limited recognition, amongst the global urban planning discourses, that are grounded around Eurocentric approaches and theories. This chapter deepens our understanding of peri-urban areas and ecosystem services by highlighting the relation between agri-ecosystem services and peri-urban areas and formulates a participatory planning framework for mainstreaming ecosystem services to enhance agricultural resilience in peri-urban areas thereby restore ecosystems. This chapter highlights that due to rapid urbanization, agricultural land in peri-urban areas is converted into built-up land to meet development needs, leading to reduced agricultural activities in peri-urban areas compared to urban areas. This chapter discusses the importance of peri-urban areas in restoring ecosystem services and enhancing agriculture resilience, emphasizing the need for capacity building in decision-making. The findings offer insightful information for urban planners and policymakers on the trade-offs between spatial design and ecosystem restoration to achieve agricultural resilience. This research has an implication necessary for restoring ecosystem services, thereby transforming peri-urban areas.

Keywords: peri-urban, ecosystem services, agriculture, resilience, participatory planning framework

1. Introduction

India has experienced a swift surge in urbanization rates, with future predictions indicating that this trend will continue. Rapid urbanization has led to many environmental impacts, especially with regard to physical changes in land use patterns, altering of natural hydrology, loss of biodiversity and destruction of ecosystem services [1, 2]. Rapid urbanization has led to urban sprawl, a typical phenomenon observed in the global south, that transforms rural agricultural land into fragmented leap-frog low-density built-up areas in the periphery of the city, leading to rural-urban interfaces and development of peri-urban regions [3–5]. The spatial transformation of these peri-urban areas has exacerbated various socio-economic, cultural and environmental biases, alleviating the area's ability to provide, regulate, maintain, and support ecosystem services for their sustainability and resilience. An in-depth assessment of peri-urban ecosystem services and livelihood dynamics can offer critical insights for enabling resilient futures. However, urban planning research fails to capture the diverse interactions, trade-offs and values these ecosystem services offer to peri-urban areas; thereby, it remains an under-explored area of research due to a lack of innovative methodological approaches that effectively assess the dynamics of peri-urban areas [6].

In India, peri-urban landscapes are transitional areas that lie at the interface of the urban and rural landscapes, providing various resources, including water and green open spaces used to meet urban requirements and also serve the essential environmental services of urban areas. Recent urban studies highlight that peri-urban areas of many Indian cities will experience a significant amount of urbanization in the future and will outgrow more quickly than the traditional urban centres, resulting in limited access to fresh water, increased waste and sanitation problems, lack of access to green spaces, and declining public health and other physical, socio-economic, and environmental consequences [7–10]. Due to rapid urbanization, agricultural land in peri-urban areas is converted into built-up land to meet the development needs. The parochial approach and understanding of peri-urban neighbourhood dynamics, especially across the global south, has led to its limited recognition amongst the global urban planning and design discourses that is mostly grounded around Eurocentric approaches and theories. Also, barriers and lack of frameworks lead to misdirection of planning with ecosystem services for sustainable peri-urban areas. One solution to this challenge is to reconceptualize peri-urban areas as hubs of peri-urban agriculture activities that offer an array of ecosystem services. However, the urban-rural divide is so ingrained that the current Indian planning system is insufficient to deal with problems and manage growth and development of peri-urban areas [11]. Moreover, lack of an efficient framework to organize and control the transformation of peri-urban areas makes the issue even more worse [12].

The institutional framework of peri-urban areas is often fragmented and overlapping as peri-urban areas are arranged at the interface of rural and urban administrative boundaries with institutions. Hence, defining the roles and responsibilities for peri-urban land use management within such an unclear governance and institutional setup often proves very challenging, leading to unresolved conflicts and increasing agricultural land insecurity and change. During agricultural land use management reforms, the importance and need of institutional context and local-level understanding of peri-urban issues for formulating institutional solutions are usually discovered and suggest the importance of considering them during problem-solving. However, this aspect has been often overlooked by institutions leading to often fragmented decision-making. As such, these peri-urban governance institutional framework challenges suggest the need for capacity building at both the urban and peri-urban levels [13].

The findings offer insightful information for urban planners and policymakers on spatial design and ecosystem restoration to achieve agricultural resilience. This chapter has an implication necessary for restoring ecosystem services, thereby transforming peri-urban areas. This chapter concentrates on the changes in the spatial patterns of agricultural land in the peri-urban areas of the western coastal plain of

India and highlights the effects of change in peri-urban agricultural land use change on agroecosystem services. This chapter puts forth an attempt to identify whether or not spatial planning as a tool can be used in managing and optimizing agricultural use and its associated agroecosystem services. This chapter concludes by discussing the role of peri-urban agriculture in ecosystem restoration and offers spatial planning guidelines to inform decision-making for future peri-urban land use change planning and maintaining of agroecosystem services.

2. Peri-urban land use change

Peri-urban areas are referred to as zones of transition characterized by a change from rural to urban with regard to changing demographics, land use change, economic activities, and institutions [14, 15]. In India, most of the peri-urban areas were historically agrarian-based settlements predominantly characterized by agricultural lands, forested hills, preserved woodlands, and wetlands, providing an array of ecosystem services for both urban and peri-urban residents [16]. However, due to urbanization the livelihoods of people residing in peri-urban areas have transitioned from agricultural activities to an increased division of labour, leading to other types of economic activities and supporting facilities [17].

Restoration of ecosystems to cope with climate change has garnered widespread attention in recent years and has led to the development of many methodological assessments of ecosystem services [18]. Landscape ecology refers to the study of ecological processes and spatial patterns across geographic areas, predominantly focusing on how changes in human activities affect landscapes and ecosystem functions [19]. Integration of landscape ecology into urban studies provides an in-depth understanding of the effects of changing landscape on ecosystem services and helps in planned decision-making. Due to the increasing rise of population and diversification of economic activities in urban areas, land use and land cover change in peri-urban areas is inevitable, leading to environmental degradation and a significant loss of ecosystem services [20, 21]. The change in land use and land cover caused by rapid urbanization negatively impacts the ecosystem services. These impacts include loss of habitat, habitat fragmentation, water management issues, and water pollution [21–23]. Loss of ecosystem services due to land use and land cover change is very rarely reversed because of livelihood shifts and migration. Therefore, land allocation for new developments and the configuration of peri-urban lands have evolved as a very significant planning issue and the restoration of ecosystem services is very crucial. Hence, managing peri-urban spaces is often problematic, and there are growing concerns in this context across South Asia [24].

Urban areas are one of the major contributors to climate change and are also innately vulnerable to the negative impacts of climate change due to the increased concentration of population, division of labour, a wide range of economic activities, huge amount of solid waste and a high percentage of impervious surface. On the other hand, untransformed peri-urban areas provide an array of ecosystem services that have the ability to mitigate a few of the negative impacts of extreme weather events [25]. Peri-urban areas with huge amounts of agricultural land provide agroecosystem services, also referred to as ecosystem services offered by agricultural activities or peri-urban agriculture benefits. Agroecosystem services offer regulating services, supporting services, provisioning services and cultural services. Peri-urban agriculture under the climate change scenario offers an important ecosystem service of regulating surface runoff and as a green infrastructure, regulates the urban microclimate by reducing the urban heat island effect, thereby moderating the impacts of extreme heat. Further, it offers open land for the integration of socio-economic and ecological interests [26, 27]. Through informed spatial planning and formulation of peri-urban area development control guidelines, ecosystem services and specifically agroecosystem services in these areas can be restored and optimized [28].

3. Peri-urban agriculture as an ecosystem service and its trade-offs

Ecosystem services is an emerging concept that integrates various ecosystem services and management strategies to address the societal challenges related to climate change, water security, well-being of human health, and quality of life [29, 30]. Ecosystem services are generally referred as the various benefits human populations achieve either, directly or indirectly, from the nature. The Millennium Ecosystem Assessment Report 2005 has classified ecosystem services into four categories. They are namely provisioning, regulating, cultural and supporting. Provisioning services refer to the goods that are obtained from the ecosystems such as food, water, wood and medicine. Regulating services refer to the benefits that are obtained from ecosystem processes such as climate regulation, water purification, pollination and erosion control. Cultural services refer to the intangible benefits that are obtained from the ecosystems such as recreation, tourism and spirituality. Supporting services refer to the ecological functions that underlie the production of ecosystem services such as water cycling, nutrient cycling, habitat for species and maintenance of genetic diversity and evolutionary processes [31].

The UN's Millennium Ecosystem Assessment [32] mentioned that unmanaged or managed natural or domesticated agricultural land and agriculture activities, irrespective of whether it is being practised in urban or peri-urban areas, have an ability to offer numerous regulating, supporting, provisioning and cultural services. These services provide environmental, cultural and ecological benefits to the people directly, hence referred to as an agroecosystem that is part of the larger network of natural ecosystems [33]. Further, the literature review highlights that agricultural land, especially paddy rice fields, an important agricultural activity and produce especially practised in South Asian countries, has the ability to provide numerous provisioning, regulating, supporting, and cultural services, thereby providing environmental, ecological, and cultural benefits. Provisioning service of paddy rice fields refers to the production of paddy rice. Regulating services refer to the services that help in regulating the environment. Paddy rice fields regulate the environment by providing groundwater recharge, alleviating flood damage, minimizing surface runoff, preventing soil erosion, and reducing the urban heat island effect, thereby regulating the microclimate. The supporting services offered by paddy fields refer to biodiversity maintenance, and cultural services refer to recreation, esthetic value of the space, indigenous farming practices and the sacred groves and rituals that are involved with the agricultural activity [26, 27].

The literature study highlights that ecosystem services are context-oriented and site-specific. Moreover, due to the multifunctional benefits, trade-offs exist amongst various aspects in terms of the priorities of each solution [34]. Trade-offs in relation to ecosystem services and urban planning refer to the land use choices that are made to increase or gain from the delivery of one or more nature-based solutions at the expense of losing or diminishing the delivery of the other nature-based solution.

Literature has categorized ecosystem services trade-offs as time-based trade-offs, spatial trade-offs, functional trade-offs, normative ethical (social equity) trade-offs, and species trade-offs. Time-based trade-offs highlight that a specific ecosystem service for a specific time has the ability to affect or alter opportunities in the future. As such, they have short-term and long-term outcomes. For instance, planning for an increase in sea level involves both long-term projections as well as short-term land uses. Spatial trade-offs are related to both scales and cross scales. These trade-offs across various geographical locations highlight that a plan or intervention in a specific area may cause either a positive or a negative impact in another area [35].

For instance, trade-offs operate at different scales; so, it may happen that a positive effect on one scale (e.g. an urban green space may have a positive impact by contributing to the quality of life for many inhabitants) but it may also have an adverse effect at another scale by displacing the lower-income households due to the increase in housing costs because of the urban green space [36]. Functional trade-offs may occur where the delivery of one or many ecosystem services may be prioritized over others. For example, coastal landscapes may be prioritized to support recreation but may lead to the loss of coastal wetlands and mangroves and lead to an increase in sea-level rise. Normative ethical trade-offs are associated with the proximity to ecosystem services, urban green spaces and the provision of ecosystem services [37]. Species trade-offs emphasize that certain ecosystem management actions tend to favor certain species and ignore others [38].

4. Agricultural resilience in peri-urban areas

Agricultural lands in peri-urban areas provide essential agroecosystem services for urban and peri-urban residents. Peri-urban water resources are under threat due to growing demand for them and resulting pressures. Livelihood shifts and migration to the urban fringes change the demands for and uses of water. At the same time, nearby cities also struggle to meet the supply needs of urban residents, requiring service providers to find additional water sources further away. This creates competition for water access and sometimes results in conflicts. Studies from peri-urban regions highlight different conflicts over water [39].

However, due to urbanization, these benefits are subjected to drastic pressure. Agricultural resilience of peri-urban areas is mainly subjected to the ability of peri-urban areas to adjust and embrace the change that these areas are likely to be subjected to such as socio-economic changes, chronic stresses and natural disasters [40–42]. Recent literature related to agricultural resilience highlights the need to realign peri-urban areas by examining the relationship between peri-urban land use policies and practices [43]. Moreover, peri-urban institutional frameworks and governance play a vital role, and it is essential to integrate proactive planning approaches to mainstream ecosystem services to enhance agricultural resilience in peri-urban area planning and development [43]. The ability of ecosystem services to enhance peri-urban resilience through the delivery of ecosystem services has been well established [44]. Changes in land use leading to decreased agricultural activities alter the ecosystem services and can negatively impact the urban environment [45].

Research on ecosystem services highlights its ability to enhance peri-urban resilience [37]. Within the human settlements context, ecosystem services, by protecting and restoring natural wetlands, have a possibility of reducing flood risk, soil erosion and groundwater recharge and through constructed wetlands, contribute towards flood reduction and decrease surface flooding. Likewise, nature-based solutions also have the ability to enhance agriculture resilience in peri-urban areas [46]. Through peri-urban agricultural practices, the impacts of heat waves can be controlled and water flow can be regulated. Urban green spaces, bio-retention areas, green infrastructure and permeable areas have the ability to enhance the extent of social interaction and cohesion building and thereby contribute positively to social and physical well-being and quality of life [47]. Moreover, the adaptive capacity of ecosystem services is highlighted by the ability to respond to climate change impacts and by empowering marginalized groups to support common-pool resource management institutions and implement local adaptive strategies such as home gardening and developing green roofs. Accordingly, ecosystem services can underpin the resilience of peri-urban areas.

5. Methodology

This chapter has undertaken a mixed method research that includes both quantitative and qualitative data collection techniques. Combining an array of methods that include mapping analysis, documentation, in-depth content analysis of various case studies, questionnaire surveys, structured and semi-structured interviews, and shared learning dialogs with different stakeholders. Initially, a quantitative analysis and mapping of the Land use and land cover over a period of time was undertaken to assess the development of land in the peri-urban area. Next, qualitative analysis, which includes an array of methods in the peri-urban area, was assessed for the ecosystem services that are offered in the peri-urban area. Later, the ecosystem services were analyzed by mapping the transition in land use and land cover change over a period of time and its potential in offering ecosystem services. Later, a participatory planning framework was proposed with a focus on agricultural planning in association with landscape metrics to ensure agricultural resilience and agroecosystem restoration.

6. Peri-urban areas in Hyderabad, Telangana

Socio-economic and environmental problems associated with increased urbanization of peri-urban areas have emerged drastically in many developing countries, especially in Southeast Asia [16, 48, 49]. Transformations in the peri-urban areas in the socio-economic sector, physical sector and environmental sectors in peri-urban areas undergo a change in land use, change is occupational patterns and change in the demand for infrastructure. The most obvious and perhaps the first change which is observed in most Indian cities is that of the land cover change. It is observed that built up in all the cities has increased significantly, and water bodies, vegetation or forest land and agricultural land have decreased in Indian cities [50].

India's rapid economic growth from the year 1970 to 2000 transformed the country from a predominately agrarian country to an industrialized economy. During these years, Telangana, erstwhile Andhra Pradesh along with many other states underwent significant changes in its urban landscape. In the city of Hyderabad, Telangana, during the year 1975, the Hyderabad Urban Development Area (HUDA) of approximately 1907 sq.km across 29 planning zones (11 zones inside municipal limits and 18 zones in the non-municipal limits or peripheral areas) was set up to regulate the urban development in the area. With the 74th Constitutional Amendment, many village panchayats were upgraded to town panchayats and municipalities; accordingly, between the years 1991 and 2001, there was an increased addition of many towns to the existing urban settlements, resulting in rapid urbanization. Accordingly, the population has gone up from 2.55 million from the year 1981 to 4.3 million in the year 1991 and 5.7 million in 2001. The driving force behind this rapid urban expansion was seen to be largely driven by political and administrative decisions. As such, by the year 2001, Telangana recorded a high change in the percentage of urban population, resulting in an unprecedented fast-paced growth rate and development that led to a significant increase in lower-order settlements (Class IV to Class VI towns). In this regard, the built-up area has transformed at an annual rate of 3.77% during the year 1973–1983 to nearly 4.95% during the year 1983–1991. Similarly, rural land of nearly 128 sq.km was transformed to business private, institutional and other land uses during this period. It was additionally observed that the urban developed area has expanded from 49.3 to 62.4% of the total land area from 1988 to 1999. Also, it was observed that there is a considerable decline in the area of wastelands (scrub land) from approximately 20.1 to 13.4%. It is noteworthy to note that the water bodies (reservoir/tank) in Telangana have reduced from 22.79 to 20.84 sq.km and this reduction was noticeable more in the urban fringes when compared to the city core.

Though this rapid urban expansion, spurred growth, it also outstretched many social, functional, spatial, and financial challenges. The zone of influence of urban centres on the surrounding nearby villages was based on various factors such as population size, income levels, proximity to transportation nodes, civic status and the overall level of modernization. As such larger urban centres with higher service sector economies and infrastructure have the ability to put forth much more influence on the surrounding villages when compared to smaller settlements [51].

Figure 1 highlights the study area. The study area selected is Medchal Mandal in, Medchal-Malkajgiri District, Telangana State, a peri-urban area of Hyderabad, Telangana. Medchal is an industrial town in the Hyderabad Metrolpolitan Development Authority in Medchal-Malkajgiri District, Telangana (refer to **Figure 2**), with a population of 190,548 as per the 2011 census. The study area includes Medchal Mandal.

These boundaries are delineated mainly keeping in mind the research interests and ecological continuity rather than only administrative boundaries. Further, the State Government has plans to develop a regional plan for peri-urban areas with a focus on preserving agriculture. Hence, it is prudent to study the ecosystems in such a peri-urban area, which is prone to rapid development of the Ecosystem Services Model in Medcalas. There is considerable potential yet in the landscape that can be sustained with rapid urban expansion in the future [52].

The study area covers 597sq kms covering approximately 81panchayat villages of the Medchal Mandal along with a few villages on the east and south. The predominant land use in this area is agricultural, covering a significant portion of the area. Hence, the primary occupation of the people here is agriculture. Rural settlements are interspersed with agricultural croplands and plantations throughout the study area. The railway line and the National Highway run in the centre of the study area from North to South, roughly dividing it into two. The area to the east of the railway line is characterized by rural villages & inland water bodies interspersed with Agricultural Cropland. Notable features to the west of the railway line are the forest lands & Scrub lands.

Urbanization trend in this area leads to a shift in land use from agricultural or natural land to urban residential including flats, individual houses and gated community and commercial developments. The loss of agricultural spaces, increased pollution, and the heat island effect (where urban areas are warmer than surrounding areas) are common issues. The village has developed through piecemeal growth,

Figure 1.
Peri-urban area of Hyderabad—Medchal Mandal, Medchal-Malkajgiri District, Telangana.

Figure 2.
Fragmented development in the study area.

resulting in fragmented infrastructure and uncoordinated settlements. **Figure 2** describes the fragment development and the existing situation of the villages. Essential services, such as proper roads and drainage systems, remain inadequate to meet the needs of the population. The lack of integrated planning has further hindered the provision of basic amenities [53].

7. Discussion

7.1 Landscape change in study area

Landscape change in the study area highlights that are is a significant change in peri-urban land use change from agricultural land use to built-up land use. This loss and fragmentation of agricultural land, particularly cropland (wet and dry), highlights that explicit loss of agroecosystem services exists spatially in the peri-urban area. Given the macro-demographic trends in Hyderabad, this pattern of loss of peri-urban agricultural land is conceivably inevitable and irresistible. However, proper urban planning and public policy might have the ability to provide guidance regarding the spatial configurations of the remaining agricultural land that is left unchanged, which will help achieve the maximum amount of agroecosystem services for the given percentage of agricultural land. This would require a proper analytical method comprising of land metrics, which help in identifying and measuring the trends and characteristics of landscape composition for quantifying agricultural landscape change and managing the agricultural land to maintain agroecosystem services, thereby enabling policymakers in taking informed planning decisions. **Figure 3** provides a detailed breakdown of the extent and percentage of each land use category, highlighting the village's development priorities.

7.2 Effect of change in agricultural landscapes on ecosystem services

Agricultural in peri-urban areas, by virtue of their situation, offer essential agroecosystem services for both urban and peri-urban residents. However, these services are under the influence of urbanization. Landscape metrics results are incorporated to deliberate the effects of change in agricultural landscapes on its ecosystem services.

7.2.1 Provisioning service

As mentioned earlier in this study, provisioning services refer to the production of paddy rice. Evaluation of provisioning services is done by evaluating the changes in the configuration and composition of paddy rice fields. The production of paddy rice

S.No.	LULC-Main class in the study area	LULC-Sub-classification in the study area	Area in sq.kms.			Gain/Loss in the time period 2005-2011 (sq.kms.)	% Gain/Loss (2005 - 2011)	Gain/Loss in the time period 2011-2015 (sq.kms.)	% Gain / Loss (2011 - 2015)	Overall Gain / loss (2005-2015) (sq.kms.)	Overall % Gain / Loss (2005 -2015)
			2005 - 2006	2011 - 2012	2015 - 2016						
1	Agricultural Land	Cropland (Wet & Dry)	311.73	391.08	348.70	+ 79.35	+ 13.30%	42.38	7.09%	+ 36.97	− 6.19%
		Plantation	10.55	10.03	25.25	0.52	0.09%	− 15.22	− 2.55%	+ 14.70	− 2.46%
		Fallow	126.39	29.97	33.06	96.43	16.14%	+ 3.10	− 0.52%	93.33	15.62%
2	Forest	Forest Plantation	3.43	3.46	3.53	+ 0.03	− 0.01%	+ 0.07	− 0.01%	+ 0.10	− 0.17%
		Scrub forest	6.13	6.15	0.00	+ 0.02	0.00%	6.15	1.03%	6.13	1.03%
		Forest Deciduous	13.47	13.49	14.92	+ 0.02	0.00%	+ 1.43	0.24%	+ 1.45	0.24%
3	Wastelands	Salt affected	0.82	0.80	0.36	0.03	0.01%	0.44	0.07%	0.47	0.08%
		Land with scrub	37.51	43.62	25.75	+ 6.11	− 1.02%	− 17.87	− 2.99%	− 11.76	− 1.97%
4	Wetlands / Water bodies	Coastal Wetlands	9.43	8.92	9.57	− 0.51	− 0.09%	+ 0.65	− 0.11%	+ 0.14	− 0.02%
		Reservoir / Lake / Tank	63.15	55.23	66.73	+ 2.08	− 0.35%	+ 1.50	− 0.25%	+ 3.58	− 0.60%
5	Built up Land	Rural Settlement Villages	10.58	14.18	50.30	+ 3.60	− 0.60%	− 36.12	− 6.05%	+ 39.72	− 6.65%
		Towns & Cities	4.23	10.51	19.27	+ 6.28	− 1.05%	+ 8.76	− 1.77%	+ 15.04	− 2.52%
Total Area in sq.kms.			597.43	597.43	597.43						

LEGEND - LULC change
negligible
low significance
moderate significance
High significance
Very high significance

Figure 3.
LULC change (Gain/Loss) for the two time periods 2005–2011, 2011–2015 & 2005–2015 (Overall) in the study area.

is one of the most important provisioning services offered by agroecosystem services as it is an essential agricultural product and the primary food in Hyderabad. Crop yields are generally measured in relation to the area; accordingly, a decrease in the paddy rice field area is directly and proportionally related to its provisioning service, highlighting a decrease in the ability of peri-urban areas to offer provisioning services. As such, a decrease in the area of paddy fields leads to a decrease or a negative effect on the economic feasibility of farming. Between 2005 and 2015, there was an increase in the region with very low Provisioning ESS potential, which is consistent with the growth of the LULC type and "Built up land- Towns & cities". The trend in the Provisioning ESS potential has been clearly improving from 2005 to 2011, but it has been declining from 2011 to 2015. Overall, the research area has a moderate potential for Provisioning ESS. Hence, an overall reduction in the area of paddy rice fields highlights a loss of provisioning services offered by farmlands.

7.2.2 Regulating service

As mentioned earlier in this study, regulating ecosystem services refers to the benefits that are obtained from the ecosystem processes such as climate regulation, water purification, pollination and erosion control. In this study, the pervious cover comprising "Water bodies—Reservoir, lakes & ponds" and "Forest lands" represents the infiltration ability of the agricultural landscape. Due to urbanization, most of the agricultural land, especially the pervious cover, is being converted into impervious cover comprising of buildings and roads that have a poor potential to offer regulating ecosystem services. Thereby, the landscape infiltration function decreases proportionally with the decrease in previous cover. Moreover, agricultural land also acts as a green infrastructure and plays an important role in regulating the urban microclimate by reducing the urban heat island effect and controlling erosion. A large area of paddy fields has the ability to maximize the cooling effect on air temperatures. Hence, the cooling function offered by paddy fields is directly proportional to the size of the paddy field. Between 2005 and 2011, there was an improvement in the area of pervious cover; between 2011 and 2015, there was a significant fall, which highlights that the impervious cover received less cooling function due to the loss of paddy fields/vegetated cover. Likewise, the evaporation of water from the waterbodies also provides an important counter to the urban heat island effect. Hence, open green areas and water surfaces play an important role in urban areas, thereby creating the urban cool-island effect [54]. With regard to regulating services offered by the paddy fields, paddy rice fields located near the rivers or canals play a significant role in flood remediation. However, it was observed that the percentages of paddy rice fields that are located within a 100 m buffer of canals or rivers decreased in all areas. This indicates that it had reduced regulatory services and contributed less towards flood regulations.

7.2.3 Cultural service

With regard to the recreation services offered by the agricultural landscape, farmland patches with different shapes and more edges in relation to the built-up land have the ability to increase cultural and recreational activities near the farmlands. Also, a cluster of paddy agricultural lands tends to create and preserve the characteristics of the rural landscape and preserve the agricultural scenery. The increase in the irregularity and complexity of the size of agricultural farmland shape of farmland provided more potentials and avenues for interaction between residents and farmland. As such we identify that agroecosystem services that are associated with paddy agricultural land includes cultural esthetics and rural characteristics. However, these ecosystem services are much related to human perception and can be determined through context and site-specific characteristics, which include micro-topography, acoustic characteristics and views. As such, further research needs to be undertaken to assess the cultural ecosystem services offered by agricultural fields.

This approach across various scales offers a broader and finer outlook for undertaking studies related to the configuration changes and composition of peri-urban agricultural landscapes. This multi-scale approach helps in identifying areas where the agricultural land has been changed to build land, thereby taking necessary steps to protect agricultural land from further conversion. Likewise, the approach also helps in identifying the built land use and directing further growth in those areas only and thereby protecting unchanged agricultural land.

8. Recommendations

Urban policy decision-makers must understand that proactive urbanization methods not only offer ecosystem restoration but also affect peri-urban residents, urban and rural population and promote environment sustainability. In the longer term, participatory planning framework and proactive urbanization with a focus on agricultural planning in association with landscape metrics has the ability to ensure agricultural resilience and agroecosystem restoration by offering food production systems, agricultural ecology and fostering agricultural knowledge amongst peri-urban youths thereby, promote sustainable peri-urbanization. Further, this study reinstates that land use management of peri-urban areas requires contextualized site and context-specific approaches to ensure agricultural resilience and restore ecosystems. This study offers three specific agricultural landscape-metrics-derived guidelines for primarily restoring ecosystems to enhance agricultural resilience, thereby effectively helping in planning and managing land use change in peri-urban landscapes. They are as follows:

8.1 Restore and maintain large areas of agricultural land

Agricultural land has the ability to provide food provisioning ecosystem service. To foster this service, it is necessary to not only restore the agricultural ecosystem, but focus has to be laid on increasing farming efficiency also. As such, agricultural land as an urban green infrastructure offers vital regulating services such as flooding regulation and groundwater recharge and infiltration, contributing to climate mitigation. Hence, preserving agricultural land helps in maintaining the veracity of agricultural ecosystem services and fostering agricultural resilience.

8.2 Restore and maintain agricultural land edges adjacent to rivers and streams

Transformation of agricultural land edges, especially adjacent to rivers and streams such as river banks, reduces groundwater infiltration and rechargeability and leads to an increase in runoff. Pervious surfaces provide benefits such as restoring the water cycle, especially agricultural land highly contributes towards recharging groundwater. Moreover, agricultural land also plays a vital role in flood regulation based on its proximity to major drainage canals, thereby providing a very important regulatory ecosystem service. Hence, it is very important to restore and maintain agricultural lands as they provide a major regulatory ecosystem services.

8.3 Restore and maintain connectivity of agricultural land with green infrastructures

Agricultural land plays a vital role in regulating the urban microclimate as a part of urban green infrastructure. Hence, careful planning of agricultural land and green infrastructure can help our urban and peri-urban areas to adapt to the adverse effects of climate change and improve not only agricultural resilience but also climate change resilience to extreme weather events. Further, agricultural land and green infrastructure planning further restore the ecosystem and enhances biodiversity and ecosystem services, thereby improving the public health and well-being of urban and peri-urban residents [55].

Due to urbanization and the impacts of climate change, agriculture practice is becoming uncertain, leading to the shift of peri-urban residents to urban areas in search of alternate livelihood opportunities. For restoring ecosystems, a proactive urbanization approach can be incorporated wherein local authorities in the peri-urban areas might offer support to farmers in formulating sustainable forms of ecosystem restoration. Such proactive urbanization could create urban farming opportunities in the cities in the forms of innovative urban farming and organic vegetable markets. On the other hand, urban planners and city authorities can also implement development control rules and zoning regulations to ensure that farming areas, water resources and green spaces are protected from urban development projects [56].

9. Conclusions

In order to attain sustainability, this research suggests using the participatory planning framework to incorporate environmental considerations into land use planning. Based on its ecosystem services potential, this framework suggests finding suitable area for future development. To comprehend the complexities of interaction between ecosystem services and land use development, a map showing the study area's ecosystem services potential and land use land cover changes over a ten-year period was created. It was found that during the initial five years, the area did not undergo many changes in land use and land cover, so the overall ecosystem services potential of the area remains unaffected. However, during the later years, the region underwent rapid urbanization and has led to a drastic reduction in the area's potential to offer ecosystem services.

Our understanding of the spatial relationship between land use land cover types and the potential of ecosystem services is supported by mapping all the ecosystem services offered (provisioning, regulatory & cultural) in the study area. The overall ecosystem services mapping demonstrates that the three major land use and land covers namely the water bodies (reservoirs, lakes, and tanks), forests (plantation & deciduous), and agricultural land (cropland and plantation), offered provisioning, regulatory and cultural services and played an important role in supplying and maintaining ecosystem services in the study area. Land use spatial analysis reveals that the western area of the region has less potential to offer ecosystem services, and hence, peri-urban development can be considered in the western direction of the region. Further, the participatory planning framework highlights that to attain environmental sustainability, the local knowledge of people with regard to the ecosystem services is necessary to be considered to assess while allocating land for development peri-urban development. Participating locals in the evaluation of ecosystem services potential will allow for further enhancement.

The participatory planning framework supports a more adaptive approach to ecosystem restoration in peri-urban areas and may be used to structure land use policy interventions. Through field research, stakeholder workshops, and local community interactions, context-specific vulnerabilities and potentials of ecosystem services in peri-urban study areas were identified. Baseline studies help in examining the potential of ecosystems and their ability in providing services. Past and present transformative pathways provide the starting point for exploring future scenarios. Accordingly, stakeholder workshops were planned wherein local community representatives, decision-makers, and other subject experts co-design transformative pathways for enhancing ecosystem restoration. The transformative pathways are expected to help in the restoration of ecosystems in peri-urban areas, through their institutional context, cope with short-term vulnerabilities and also enhance long-term resilience. This forms the intervention phase of the project. The participatory planning framework offers a conceptual approach to administer rural-to-urban transitions. A more localized, participatory planning framework at the village-scale, would be feasible. However, at a broader regional scale, the transformative pathways presented in this study are still valid.

This research has applied landscape metrics to assess agroecosystem services in peri-urban landscapes and has put forth an effort to articulate the relationship of agricultural land and its agroecosystem service with its landscape composition and configuration characteristics. Further research needs to focus on understanding the relationship between various landscape compositions and agro-ecosystem services, with an intention to inform landscape planning and decisions and guide peri-urban development in an environmentally and ecologically sustainable manner. Thereby mainstream ecosystem services to enhance agricultural resilience in peri urban areas.

Overall, this study highlights that agriculture is less practised in peri-urban areas compared to urban areas. The findings offer insightful information for urban planners and policymakers on trade-offs between spatial design and ecological preservation to achieve agricultural resilience. This research has an implication to the academic and policy debate that is necessary for operationalizing and mainstreaming ecosystem services, and thereby transforming peri-urban planning practices. Accordingly, the framework tends to have a major impact on maintaining the ecology as well as the economy of urban and peri-urban areas, thereby enhancing human well-being.

Author details

Kiranmayi Raparthi
Department of Planning, School of Architecture and Planning, Anna University, Hyderabad, India

*Address all correspondence to: kiranmayiar@gmail.com

References

[1] Tripathi YC, Tripathi G. Some important environmental problems in India and their remedies. Dimensions of Environmental Threats. 2003:376-382

[2] Chandra M. Environmental concerns in India: Problems & solutions. Journal of International Business and Law. 2015;**15**(1):1-14

[3] Ahmadi NM. Advancing urban planning in arid agricultural urbanized landscapes of Iran: Spatial modeling evidence from a rapidly developing region. Sustainable Cities and Society. 2022;**87**:1-8

[4] Shaw et al. The peri-urbanization of Europe: A systematic review of a multifaceted process. Landscape and Urban Planning. 2020;**196**:1-11

[5] Wadduwage et al. Agricultural land fragmentation at urban fringes: An application of urban-to-rural gradient analysis in adelaide. Land. 2017;**6**(2):1-28

[6] Agyeman J, Evans B, Kates RW. Greenhouse gases special: Thinking locally in science, practice and policy. Local Environment. 1998;**3**(3):245-246

[7] Ayele A, Tarekegn K. The impact of urbanization expansion on agricultural land in Ethiopia: A review. Environmental and Socio-Economic Studies. 2020;**8**(4):73-80

[8] Dadashpoor H, Ahani S. Explaining objective forces, driving forces, and causal mechanisms affecting the formation and expansion of the peri-urban areas: A critical realism approach. Land Use Policy. 2021;**102**:105232

[9] Roberts et al. Impact of rapid urbanization on the city of Bhubaneswar, India. Proceedings of the National Academy of Sciences, India Section A. 2017;**87**:845-853

[10] Rustiadi et al. Impact of continuous Jakarta megacity urban expansion on the formation of the Jakarta-Bandung conurbation over the rice farm regions. Cities. 2021;**111**:103000

[11] Raparthi K. Analytical framework for integrating climate change mitigation and adaptation in local urban planning policy. Iberoamerican. Journal of Development Studies. 2021c;**11**(1):156-181 ISSN: 2254-2035. DOI: 10.26754/ojs_ried/ijds.665 (Scopus Indexed)

[12] Berke PR, Conroy MM. Are we planning for sustainable development? An evaluation of 30 comprehensive plans. Journal of American Planning Association. 2000;**66**(1):21-33

[13] Betsill M, Bulkeley H. Looking back and thinking ahead: A decade of cities and climate change research. Local Environment. 2007;**12**(5):447-456

[14] Allen A. Environmental planning and management of the peri-urban interface: Perspectives on an emerging field. Environment and Urbanization. 2003;**15**(1):1-15

[15] Narain V, Nischal S. The peri-urban interface in shahpur khurd and karnera, India. Environment and Urbanization. 2007;**19**(1):261-273

[16] Tacoli C. Rural-urban interactions: A guide to the literature. Environment and Urbanization. 1998;**10**:147-166

[17] Boyce DE. Toward a framework for defining and applying urban indicators in plan-making. Urban Affairs Quarterly. 1970;**6**:145-171

[18] Costanza R et al. The value of the world's ecosystem services and natural capital. Nature. 1997;**378**:253-260

[19] Forman, Godron. Landscape Ecology. Global Geological Record of Lake Basins. Vol. I. Cambridge: Cambridge University Press; 1986. 432 p

[20] Yu, Ng. Spatial and temporal dynamics of urban sprawl along two urban–rural transects: A case study of Guangzhou, China. Landscape and Urban Planning. 2007;**79**(1):96-109

[21] Seto, Fragkias. Quantifying spatiotemporal patterns of urban land-use change in four cities of China with time series landscape metrics. Landscape Ecology. 2005;**20**:871-888

[22] Kroeger T, Casey F. An assessment of market-based approaches to providing ecosystem services on agricultural lands. Ecological Economics. 2007;**64**:321-332

[23] Weng. Spatiotemporal changes of landscape pattern in response to urbanization. Landscape and Urban Planning. 2007;**81**(4):341-353

[24] Campbell H. Is the issue of climate change too big for spatial planning? Planning Theory & Practice. 2006;**7**(2): 201-230

[25] Grimm NB, Faeth SH, Golubiewski NE, Redman CL, Wu J, Bai X, et al. Global change and the ecology of cities. Science. 2008;**319**:756-760

[26] Gill et al. Adapting cities for climate change: The role of the green infrastructure. Planning, Property and Environmental Management. 2007;**33** (1):115-133

[27] Gill et al. Methods of data collection in qualitative research: Interviews and focus groups. British Dental Journal. 2008;**6**:291-295

[28] Kennedy CA, Corfee-Morlot J. Past performance and future needs for low-carbon, climate-resilient infrastructure —An investment perspective. Energy Policy. 2013;**59**:773-783

[29] Khajuria A, Ravindranath NH. Climate change in context of Indian agricultural sector. Journal of Earth Science & Climatic Change. 2012;**3**:11

[30] Raparthi K. Assessing the role of nature-based solutions in urban resilience and climate change adaptation. In: Loon LY, Subramaniyan M, Gunasekaran K, editors. Advances in Construction Management. Lecture Notes in Civil Engineering. Vol. 191. Singapore: Springer; 2022. DOI: 10.1007/978-981-16-5839-6_2

[31] Bolund P, Hunhammar S. Ecosystem services in urban areas. Ecological Economics. 1999;**29**:293-301

[32] UN's Millennium Ecosystem Assessment. Ecosystems and Human Wellbeing. United Nations: Data Booklet; 2005

[33] Zhang et al. Ecosystem services and dis-services to agriculture. Ecological Economics. 2007;**64**(2):253-260

[34] Nicholls RJ. Coastal megacities and climate change. GeoJournal. 1995;**37**(3): 369-379

[35] Parmesan C, Yohe G. A globally coherent fingerprint of climate change impacts across natural systems. Nature. 2003;**421**:37-42

[36] Raparthi K. Assessing the relationship between urban planning policies, gender and climate change mitigation: Regression model evaluation

of Indian cities. Journal of Urban Planning and Development. 2021a;**147**(4):1-16. DOI: 10.1061/(ASCE)UP.1943-5444.0000440

[37] Kabisch N, at al. Nature-based solutions to climate change mitigation and adaptation in urban areas: Perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecology and Society. 2016;**21**(2):1-15

[38] Parris et al. The seven lamps of planning for biodiversity in the city. Cities. 2018;**83**(31):44-53

[39] Raparthi K. Assessing the potential of urban voids in promoting resilient and livable sustainable cities. In: gis.Science—Die Zeitschrift fur Geoinformatik. Germany: Wichmann Verlag; 2021b. 3/2021

[40] Alberti, Marzluff. Ecological resilience in urban ecosystems: Linking urban patterns to human and ecological functions. Urban Ecosystems. 2004;**7**(3):241-265

[41] Alberti et al. Integrating humans into ecology: Opportunities and challenges for studying urban ecosystems. BioScience. 2003;**53**(12):1169-1179

[42] Pickett et al. Getting a cue: The need to belong and enhanced sensitivity to social cues. Personality and Social Psychology. 2004;**30**(9):1095-1107

[43] Coaffee J. Towards next-generation urban resilience in planning practice: From securitization to integrated place making. Planning Practice & Research. 2013;**28**(3):323-339

[44] Ainscough et al. Navigating pluralism: Understanding perceptions of the ecosystem services concept. Ecosystem Services. 2019;**36**:100892

[45] Raparthi K. "Investigating open space reservation as the new urban commons: A case of Chennai City". Nagarlok quarterly. Journal of Urban Affairs. 2020a;**LII**:57-67

[46] Raparthi K. Ability of nature based solutions through urban green space Management in Building Urban Resilience. International Journal of Urban Design. 2020b;**3**(2):46-56

[47] Raparthi K. Assessing the role of urban planning policies in meeting climate change mitigation goals in Indian cities. Journal of Urban Planning and Development. 2018;**144**(4):1-16. DOI: 10.1061/(ASCE)UP.1943-5444.0000440

[48] Firman T. Urban development in Bandung metropolitan region: A transformation to a Desa-Kota region. Third World Planning Review. 1996;**18**:1-22

[49] Hugo G. Environmental concerns and international migration. International Migration Review. 1996;**30**:105-131

[50] Raparthi K. Assessing climate change planning in Indian cities: Bridging the gap between climate change research and practice. Social Science and Humanities Journal. 2016;**1**(3):160-174

[51] Raparthi K. Analyzing the relationship between environmental planning policies and climate change: Multinomial logit regression model evaluation of Tarrant County, Texas. Current Urban Studies, Scientific Research Publishing. 2015;**3**(1):1-10

[52] Raparthi K. Assessing smart growth strategies in Indian cities: A grounded theory approach to planning practice. Journal of Urban Planning and Development. 2014;**141**(4):1-10. DOI: 10.1061/(ASCE)UP.1943-5444.0000267

[53] Sassen S. Urban transport scenarios in India and its linkages with energy and environment. Urban Transport Journal. 1991;**2**(1):12-20

[54] Nakayama, Hashimoto. Analysis of the ability of water resources to reduce the urban heat island in the Tokyo megalopolis. Environmental Pollution. 2010;**159**(8-9):2164-2173

[55] The Chartered Institution of Water and Environmental Management (CIWEM). Multi-Functional Urban Green Infrastructure. 2010

[56] Tol RSJ. Equitable cost-benefit analysis of climate change policies. Ecological Economics. 2001;**36**(1):71-85

Section 2

Environmental Restoration

Chapter 3

Lithium, Rubidium and Cesium Chemistry in Selected Soils along the Mississippi River in Southeastern Missouri

Michael Aide

Abstract

Lithium, rubidium and cesium are elements from Group 1 of the Periodic table. Lithium is an emerging concern for soil/sediment contamination because of the manufacture and disposal of lithium-ion batteries. In the soil environment, lithium, rubidium and cesium are strongly associated with the clay separate and manifest strong adsorption tendencies. Selected soils along the Mississippi River in south-central Missouri have concentrations of lithium, rubidium, and cesium that are like those associated with the world-wide literature. Lithium concentrations range from 9.1 ppm for the Menfro soils to 32.6 ppm for the Porthageville soil, with the lithium concentrations increasing with the soil's clay content. Exchangeable lithium, rubidium and cesium concentrations represent a small pool relative to the total elemental content, inferring that the biological availability may be limited. Given that the concentrations of these elements are typical for soils, these soils do not appear to be impacted by flood water from the Mississippi River; however, sediment deposition with co-adsorbed Group 1 elements. May be the source. Lithium, rubidium, and cesium ecosystem restoration protocols need to be established prior to the anticipated environmental impact is fully realized.

Keywords: alkali metals, emerging contaminants, adsorption, floodplain soils, potassium

1. Introduction

Lithium (Li), Rubidium (Rb) and Cesium (Cs) are alkali metals (Group 1) in the Periodic Table, along with Hydrogen (H), Sodium (Na), Potassium (K) and Francium (Fr). All elements have a valence of 1, where Rb in rare cases exhibits a valence of either 2 or 6 [1]. The ground state electron configurations are: (i) lithium [He] $2s^1$, (ii) rubidium [Kr] $5s^1$, (iii) cesium [Xe] $6s^1$. Other cations with a similar radius to lithium include magnesium (Mg^{2+}), iron (Fe^{2+}), aluminum (Al^{3+}), and titanium (Ti^{4+}). Lithium is the most strongly hydrated of the Group 1 elements, resulting in its chemistry resembling more like the alkaline earth elements than the alkali elements [1].

Estimates for the earth crust elemental concentrations typically center at 20–25 ppm (mg kg^{-1}) for lithium, 90–110 ppm for rubidium, and less than 1 to 6 ppm for cesium [2]. Collectively, these elements are listed as lithophiles. Acid igneous rocks (felsics) and argillaceous rocks typically show the highest concentrations of Li, Rb and Cs. Important lithium-bearing minerals include (i) petalite $(Li,Na)AlSi_4O_{10}$, (ii) lepidolite $Li_2Al_2(SiO_3)_3$, (iii) spodumene $LiAlSi_2O_6$, and (iv) eucriplite $LiAlSiO_4$ [1, 2]. Rubicline $Rb(AlSi_3O_8)$ and pollucite $Cs(Si_2Al)O_6$ are important rubidium and cesium bearing-minerals.

Typical soil concentrations are 13–38 ppm for lithium, 18 to 116 ppm for rubidium, and 1.8 to 8.0 ppm for cesium [2]. In New Zealand, Robinson et al. [3] showed that soil lithium concentrations ranged from 0.08 mg kg^{-1} to 92 mg kg^{-1} and were positively correlated with clay content. Geogenic soil Li is typically insoluble and largely unavailable to plants [3]. Shacklette et al. [4] determined the lithium concentrations from 912 samples across the conterminous United States [4]. The geometric mean lithium concentration was 20.4 ppm, with 17.3 ppm for samples from the Eastern United States and 23.3 ppm for samples from the Western United States [4].

2. Lithium chemistry in the soil environment

Lithium has recently increased its industrial utilization, especially with lithium-ion batteries, thus initiating a worldwide exploration of lithium bearing geologic resources. Commensurate with the increasing industrial utilization of lithium, environmental impacts from mining and other activities are increasingly a growing concern [5, 6].

Lithium has two environmentally stable isotopes, 6Li (7.5%) and 7Li (92.5%). In a wide variety of natural processes, lithium isotopes may fractionate significantly including: (i) mineral formation, (ii) ion exchange where lithium substitutes for magnesium and iron in phyllosilicate octahedral sites, and (iii) rock weathering. Steinhoefel et al. [7] evaluated isotope fractionation of weathered shale. The soil clays were isotopically depleted in 7Li compared to the parent material, and δ7Li values correlated with the soil Li concentration, soil pH, and availability of exchangeable sites. The strong depletion of Li and clay minerals in soils compared to bedrock is attributed partly to their export because of subsurface water flow.

In lithium treated soil, Xu et al. [8] noted that lithium amendments increased soil pH, exchangeable potassium and available ammonium nitrogen concentrations. Lithium treatment levels of 10 to 80 mg kg^{-1} increased sucrase, urease, aryl sulfatase, and peroxidase activities, whereas protease, neutral phosphatase, phytase, and lipase activities were reduced, suggesting that lithium may interfere with carbon, nitrogen, phosphorus, and sulfur soil cycling. Anderson et al. [9] examined Li exchange in soil-solution and clay mineral systems. At low concentrations, lithium was adsorbed onto bentonite, kaolinite, and vermiculite. Bentonite retained no lithium against salt displacement, whereas kaolinite and vermiculite retained a substantial portion of the total adsorbed lithium, inferring that specific bond sites vary across different phyllosilicates. Hoyer et al. [10] performed batch experiments involving Li-Na exchange on bentonite, kaolinite, and zeolite, observing that the maximum lithium sorption for bentonite and zeolite are roughly equivalent at approximately 3800–3900 ppm and kaolinite at 1300 ppm.

Adsorption isotherms conducted in alkaline soils revealed the nonlinear behavior of lithium sorption isotherm, with maximum sorption capacity for a sandy clay loam soil (1269 mg kg^{-1}) was significantly higher than for a sandy soil (369 mg kg^{-1}) [11].

3. Rubidium chemistry in the soil environment

In Israel, Kot [12] investigated the concentration and availability of lithium and rubidium in soil and natural waters. Brouwer et al. [13] determined the ion-selectivity of cesium and rubidium towards illite. The data was best simulated using a three-site surface adsorption model where small concentrations of cesium and rubidium favored a limited degree of high adsorption selectivity, especially for cesium. Tyler [14] investigated the uptake of rubidium by plants and noted that rubidium field biomass concentrations vary significantly because of soil acidity and the bioavailability of potassium.

4. Cesium chemistry in the soil environment

Cesium is an element of interest because of the release of ^{137}Cs during nuclear weapons testing or nuclear reactor accidents. Coleman et al. [15] noted than cesium was sorbed onto the cation exchange sites of montmorillonite, illite, and kaolinite and was displaced on leaching with potassium and calcium chloride solutions. Vermiculite and heated potassium saturated montmorillonite retained cesium tightly against calcium chloride displacement, but not by potassium or ammonium chloride displacement solutions. Potassium and rubidium sorbed on vermiculite were displaced more rapidly by divalent ions than monovalent ions. The exchange-displacement behavior of Cs on vermiculite and heated K^+-montmorillonite implies that interlayer spaces admit potassium and ammonium but restricts calcium's entry.

Rai and Kawabata [16] reviewed the soil behavior of radioactive Cs and the influence of K^+ on cesium plant uptake. Cesium strongly binds to the frayed edge sites of illitic clays. The high affinity potassium transporter is the main pathway for rice plant uprake, especially in low-potassium conditions. Burger and Lichtscheidl [17] summarized the literature involving stable and radioactive cesium in the environment and the effects on plants. Cesium uptake occurs through potassium and calcium transporters and will subsequently redistribute across plant tissues/organs.

Kubo et al. [18] investigated soil exchangeable potassium's influence on cesium absorption and translocation in buckwheat (*Fagopyrum esculentum*). Radioactive ^{134}Cs and ^{137}Cs concentrations in buckwheat were positively correlated with naturally occurring stable ^{133}Cs and the radioactive Cs concentrations were reduced at greater exchangeable soil potassium contents. At Fukushima (Japan), Mukai et al. [5] discovered that weathered biotite showing evidence of transforming to vermiculite appreciably adsorbed ^{137}Cs more than fresh biotite, illite, smectite, kaolinite, halloysite, allophane, imogolite.

5. The manuscript objectives

The purpose of this manuscript is to augment the soil chemistry information of three alkali elements (Li, Rb, and Cs) and to document their abundance and estimate their soil bioavailability based on selective soil extractions in selected Missouri soils adjacent to the Mississippi River.

6. Materials and methods

6.1 Study area

Soils were selected from floodplains adjacent to the Mississippi River, except for the Menfro pedons, which were selected from upland positions adjacent to the Mississippi River. The present climate is continental humid, with long hot summers with short moderate winters [19]. Missouri July maximum temperatures range from 27–34°C, with abundant July clear sky daily solar radiation values ranging from 17 to 28 MJ•m^{-2}. The mean annual precipitation is 0.91 m (36 inches). Except for the Portageville soil, all soils were never nutrient amended.

The bottomland forest is a riverfront bottomland forest or riparian forest. Canopy trees are typically silver maple (*Acer saccharinum*), bur oak (*Quercus macrocarpa*), cottonwood (*Populus deltoides*), shellbark hickory (*Carya laciniosa*), green ash *(Fraxinus pennsylvanica*), black willow (*Salix nigra*), sycamore (*Platanus occidentalis*), river birch (*Betula nigra*), hackberry (*Celtis occidentalis*), and bald cypress (*Taxodium distichum*), The understory is typically sparsely populated because of flooding.

6.2 Soil analysis

Routine soil analysis was performed by the University Missouri Cooperative Extension. An aqua-regia digestion was employed to obtain a near total estimation of elemental abundance associated with all but the most recalcitrant soil chemical environments. Aqua-regia digestion does not appreciably degrade quartz, albite, orthoclase, anatase, barite, monazite, sphene, chromite, ilmenite, rutile and cassiterite, whereas aqua-regia digestion partially degrades anorthite and phyllosilicates [20]. Homogenized samples (0.75 g) were equilibrated with 0.01 liter of aqua-regia (3 volumes HNO_3 to 1 volume HCl) in a 35°C incubator for 24 hours. Duplicated samples were shaken, centrifuged, and filtered (0.45 μm), with a known aliquot volume analyzed using inductively coupled plasma mass spectrometry (ICP-MS). Reference. samples with known elemental concentrations were employed for quality control. The sodium acetate leach involved a 60-mesh sieved 0.75 g sample leached in a sodium acetate matrix at 30°C for 1 hour. Solutions are analyzed using ICP-MS. Reference samples with known elemental concentrations were employed for quality control. A hot water extraction involved equilibrating 0.5 g samples in 0.02 L distilled-deionized water at 80°C for one hour followed by 0.45 μm filtering and elemental determination using ICP-MS. Reference samples with known elemental concentrations were employed for quality control.

7. Results and discussion

7.1 The Menfro series

The Menfro series (Fine-silty, mixed, superactive, mesic Typic Hapludalfs) consists of very deep, well-drained, moderately permeable soils formed in thick loess deposits adjacent to the Mississippi River. The sampled soil profiles present silt loam ochric epipedons (Ap, E, and BE horizons) and thick silty clay loam argillic horizons (Bt1, Bt2, Bt3 horizons). Soil pH in the A horizons is 6.4 and 4.7 for the two pedons. The Bt horizons range from pH 4.7 to pH 4.4, whereas the silt loam (loess) C horizons have neutral to slightly alkaline pH values. The soil organic matter content is greatest in the A horizons (5.4 and 4.9%, whereas the soil organic matter content in the soil profiles gradually diminish with increasing depth to 0.7% and 0.9%, respectively.

The aqua regia digestion lithium concentrations increase with transition from the eluvial to illuvial soil horizons (**Figure 1**). The eluvial to illuvial horizon transition corresponds to a textural change from silt loam to silty clay loam. The aqua regia digestion rubidium (**Figure 2**) and cesium (**Figure 3**) concentrations have similar soil profile distributions as the lithium soil profile distribution, inferring that the clay separate supports the provision and retention of these three elements. The mean lithium concentration is 9.1 ppm, the mean rubidium concentration is 18.2 ppm, the mean cesium concentration is 1.2 ppm, and the mean potassium concentration is 1490 ppm.

The water extracted potassium (**Figure 4**) and rubidium concentrations (**Figure 5**) from the Menfro series show smaller values on transition from silt loam to silty clay loam, a feature that may be attributed to (i) plant biocycling and soil organic matter mineralization, and (ii) clay mineralogy influences. Water extraction values for lithium, rubidium, and cesium have units of ppb (μg kg^{-1}). The eluvial horizons do exhibit somewhat greater X-ray diffraction peak areas, implying the greater relative presence of Al-hydroxy interlayered vermiculite (data not presented).

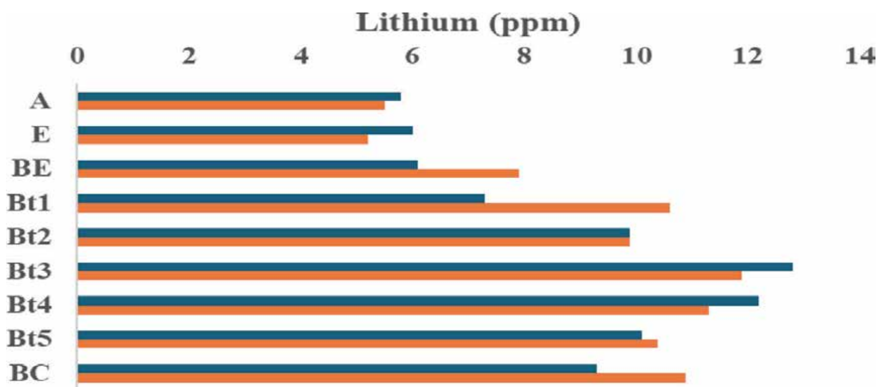


Figure 1.
Aqua regia digestion lithium concentrations by soil horizon depth for two Menfro pedons.

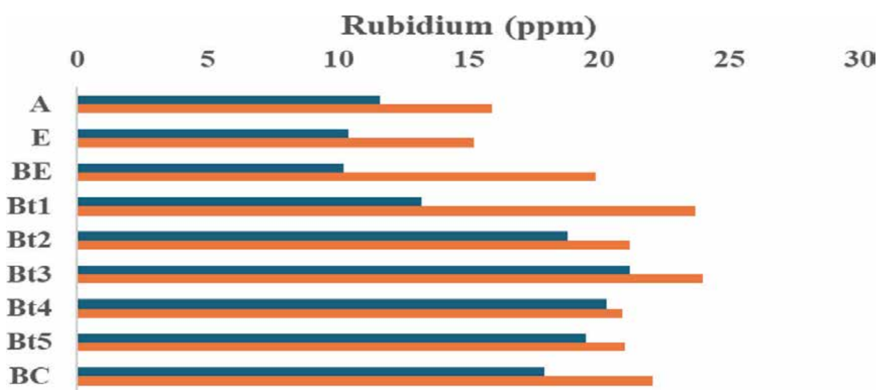


Figure 2.
Aqua regia digestion rubidium concentrations by soil horizon depth for two Menfro pedons.

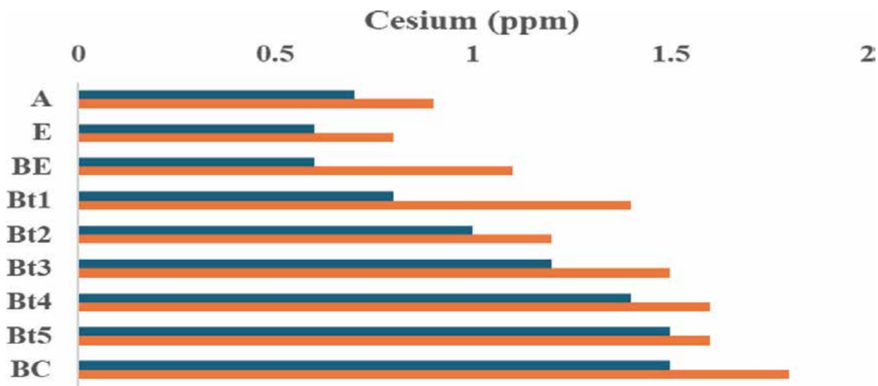


Figure 3.
Aqua regia digestion cesium concentrations by soil horizon depth for two Menfro pedons.

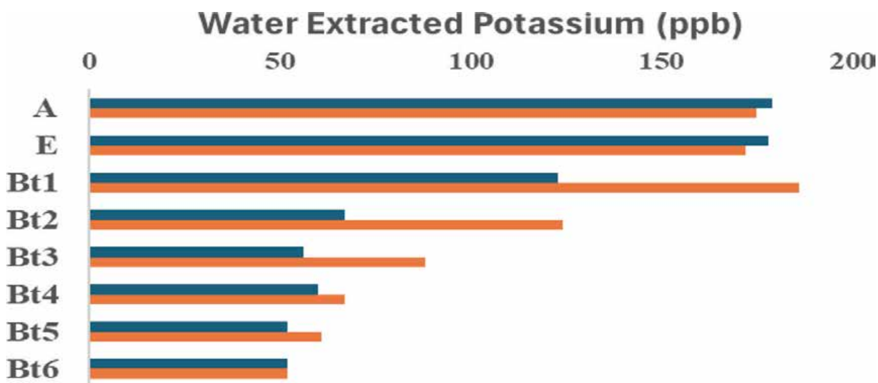


Figure 4.
Water extracted potassium concentrations from two pedons of the Menfro series.

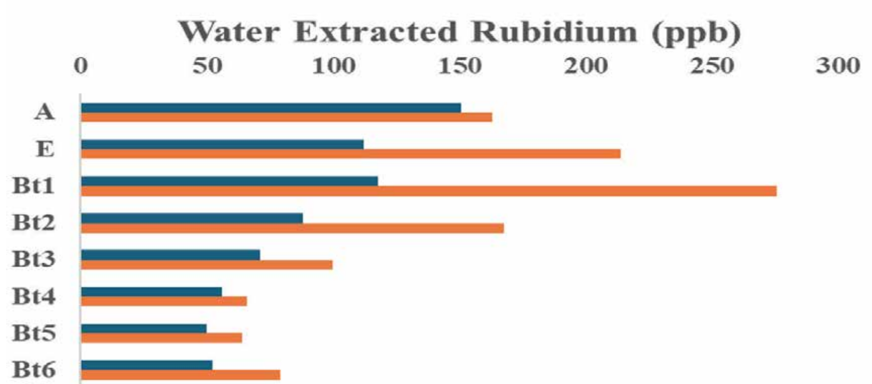


Figure 5.
Water extracted rubidium concentrations from two pedons of the Menfro series.

Water extracted lithium concentrations (**Figure 6**) show greater concentrations in the illuvial horizons, suggesting an association with clay content.

Regression analysis of the aqua regia digestion potassium concentration with water extracted lithium concentrations for two pedons of the Menfro series show a significant positive correlation. The regression equation is: [Li ppm] = 44.107 [K%] + 2.47 with r^2 = 0.88. Conversely, regression analysis of the water extracted potassium and lithium concentrations were not significant. Regression analysis of the water extracted potassium and rubidium concentrations show a significant positive correlation. The regression equation is: [Rb ppb] = 1.00[K ppb] + 8.4 with r^2 = 0.73.

7.2 The Amagon series

The Amagon series (Fine-silty, mixed, active, thermic Typic Endoaqualfs) consists of very deep, poorly-drained, slowly permeable soils that formed in loamy alluvium on low terraces in the Lower Mississippi Valley. The sampled silt loam ochric epipedon (A and E horizons) and silty clay loam argillic horizon (Btg1, Btg2 and Btg3 horizons), show slightly acidic horizons.

The mean lithium concentration is 12.1 ppm (**Figure 7**), the mean rubidium concentration is 20.8 ppm, the mean cesium concentration is 1.3 ppm, and the mean potassium concentration is 1300 ppm. The concentration of rubidium is greater than the concentration of lithium and both elements are considerably greater than cesium, which is in accordance with the prevailing literature [2, 10]. The coefficient of determinations (r^2) for K-Li, K-Rb and K-Cs are 0.62, 0.79 and 0.63, respectively. The importance of the coefficient of determinations reflects the association of these elements with (i) the soil's texture and (ii) mixed to smectite clay mineralogy.

7.3 The Portageville series

The Portageville series (Fine, smectitic, calcareous, thermic Vertic Endoaquolls) consists of very deep, poorly-drained, very slowly permeable soils formed in alluvium on low lying and level flood plains. The surface is a mollic horizon overlying Bg

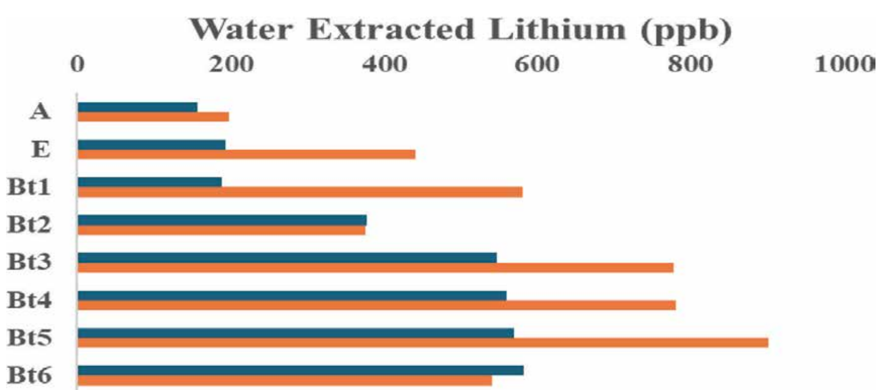


Figure 6.
Water extracted lithium concentrations from two pedons of the Menfro series.

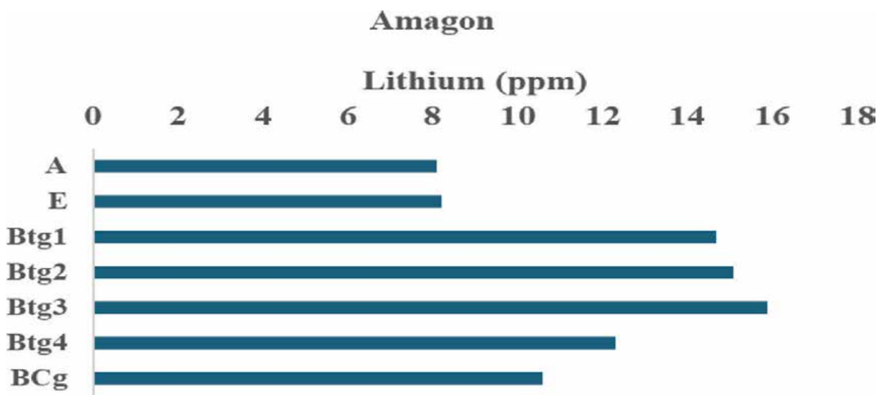


Figure 7.
Aqua regia digestion lithium concentrations by soil horizon depth for the Amagon pedon.

horizons. The soil profile pH values range from 6.2 in the surface to 6.7 in the deeper soil horizons. Soil organic matter declines from 4.2% in the surface to 3.4% in the deeper horizons.

The mean lithium concentration is 32.6 ppm (mg kg^{-1}) (**Figure 8**), the mean rubidium concentration is 48.8 ppm, the mean cesium concentration is 2.2 ppm, and the mean potassium concentration is 5200 ppm. The concentration of rubidium is greater than the concentration of lithium and both elements are considerably greater than cesium, which is in accordance with the prevailing literature [2, 10]. The lithium, rubidium, cesium and potassium concentrations are somewhat uniform across the Portageville pedon and are appreciably greater than the other soil series because of the fine textural class.

7.4 The Caruthersville and commerce series

The Caruthersville series (Coarse-silty, mixed, superactive, calcareous, thermic Typic Udifluvents) consists of deep, moderately well-drained, moderately permeable soils formed in loamy alluvium on flood plains. Seasonal high-water tables occur with peak flows of the Mississippi River. The sampled pedons consist of a fine sandy loam ochric epipedon (A horizon) overlying fine sandy loam and silt loam C horizons.

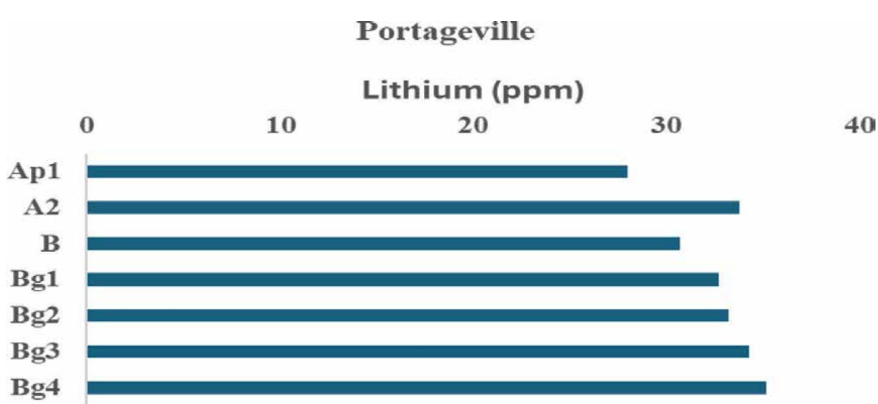


Figure 8.
Aqua regia digestion lithium concentrations by soil horizon depth for the Portageville pedon.

The soil pH varies from neutral to slightly alkaline (pH 7.7 to pH 8.1). The soil organic matter content is approximately 1.1% in the surface horizons and declines to 0.6% in the deeper soil horizons. The Commerce series (Fine-silty, mixed, superactive, non-acid, thermic Fluvaquentic Endoaquepts) consists of deep, somewhat poorly-drained, moderately slowly permeable soils that formed in alluvial sediments. The sampled pedons consist of a silty clay loam ochric epipedon (A horizon) overlying a silt clay loam cambic horizon (Bw horizons). The soil pH varies from neutral to slightly alkaline (pH 7.6 to pH 7.9). The soil organic matter content is approximately 3.4% in the surface horizons and declines to 0.6% in the deeper soil horizons.

The Commerce pedons with their silty clay loam textures have substantially greater potassium, lithium, and rubidium concentrations than the Caruthersville pedons with their generally sandy loam textures (**Table 1**). Conversely, the Caruthersville pedons do exhibit slightly greater cesium concentrations. Understanding that the Commerce and Caruthersville pedons lack eluvial-illuvial horizon sequences and the soil textures within each pedon are rather uniform, these pedons do not readily exhibit alkali element differences within the soil profile. Paired t-tests and regression equations for pooled Caruthersville and Commerce data sets show significant correlations between potassium and each of the alkali elements: (i) K-Li {[Li (ppm)] = 62.49[K%] –0.21 with r^2 = 0.99 and t-test = 1.254×10^{-8}}, (ii) K-Rb {[Rb (ppm)] = 92.07[K%] -0.5521with r^2 = 0.99 and t-test = 7.68×10^{-9}}, (iii) K-Cs {[Cs (ppm)] = 4.45[K%] +0.18 with r^2 = 0.98 and t-test = 2.75×10^{-11}}.

Acetate extractions are elemental concentrations that are recoverable with a Na-acetate solution, thus the recovered concentrations are considered biologically available. The Commerce pedons have greater recovered acetate extractable potassium, lithium and rubidium concentrations and slightly smaller cesium concentrations. The greater acetate concentrations from the Commerce pedons are presumably related to the greater aqua-regia concentrations. Considering that potassium concentrations are presented in ppm (mg kg^{-1}) units, the percentages of acetate extractable potassium to total potassium is 15.4% for the Caruthersville pedons and 12.9% for the Commerce pedons. The lithium, rubidium, and cesium total elemental concentrations have ppm units and the acetate extractions have ppb units. As an example, for rubidium the acetate extraction/aqua regia digestion ratio is 3.5% for the Caruthersville pedons and 2.2% for the Commerce pedons. The lithium and cesium ratios have similar magnitude ratios. Thus, lithium, rubidium and cesium have a smaller acetate-estimated bioavailability when compared to potassium. Stated otherwise, exchangeable lithium, rubidium and cesium appear to be more preferentially bonded to the clay separate than potassium (**Table 2**).

Statistic	Potassium	Lithium	Rubidium	Cesium
Caruthersville				
Mean	850	5.04	7.23	5.6
Standard Deviation	180	0.94	1.11	0.10
Commerce				
Mean	2280	14.1	20.5	1.19
Standard Deviation	260	1.6	2.05	0.12

Table 1.
Potassium, lithium, rubidium and cesium aqua regia digestion concentrations (ppm).

Statistics	Potassium (ppm)	Lithium (ppb)	Rubidium (ppb)	Cesium (ppb)
Caruthersville				
Mean	131	<100	253	4.8
Standard Deviation	21		53	0.6
Commerce				
Mean	293	156	445	3.9
Standard Deviation	45	52	38	0.7

Table 2.
Potassium, lithium, rubidium, and cesium acetate extraction concentrations.

8. Ecological restoration guideline research

The study area did not indicate any lithium, rubidium, or cesium concentrations that represent an environmental impact. However, the specter of environmental impact is acute, especially given the increase industrial utilization, especially for lithium. The soil chemistry of lithium, rubidium, and cesium indicates that phyllosilicate adsorption appears to be the dominant soil response. Additionally, lithium, rubidium, and cesium adsorption resists salt displacement.

The establishment of ecological guidelines necessitates future research involving: (i) determine the relationship between soil classification and nutrient accumulation, (ii) the influence of pH, element concentration, pH, oxidation–reduction, and soil organic matter complexation on element bioavailability, and (iii) establishment of soil tests to effectively estimate element uptake by vegetation.

A critical component for ecosystem restoration is determining the effectiveness of various soil reclamation protocols on known impacted sites.

9. Conclusion

The Group 1 elements of the Periodic Table include: hydrogen, lithium, sodium, potassium, rubidium, cesium and francium, where we are providing special interest to lithium, rubidium, and cesium. The mean aqua regia digestion lithium concentrations were 9.1 ppm for the Menfro pedons, 12.1 ppm for the Amagon pedon, 32.6 for the Portageville pedon, 5.0 ppm for the Caruthersville pedons, and 14.1 ppm for the Commerce pedons. The rubidium concentrations were slightly greater, whereas the cesium concentrations were smaller. As an example, the mean rubidium concentration for the Commerce pedons was 20.5 ppm and the mean cesium concentrations were 1.19 ppm. The aqua regia digestion lithium, rubidium and cesium concentrations were closely correlated with the potassium aqua regia digestion concentrations. The acetate extractable concentrations of lithium, rubidium, and cesium only represent a small portion of the total concentrations of these elements, suggesting that these alkali elements have a strong adsorption bonding energy.

Sedimentation by the Mississippi River is likely the source for the alkali elements. These sediments accumulate during annual flood events and the sediment is derived from across the massive upper Mississippi River watershed. As such, the average concentrations of lithium, rubidium and cesium reflect the watershed land mass. Immediately south of the study area exists the Mississippi and Ohio River confluence. Sampling along the Ohio and lower Mississippi Rivers would provide meaningful data for estimated the mid-content composition of alkali elements.

Author details

Michael Aide
Department of Agriculture, Southeast Missouri State University, Cape Girardeau, MO, United States

*Address all correspondence to: mtaide@semo.edu

References

[1] Lee JD. Concise Inorganic Chemistry. New York, NY: Chapman Hall; 1991

[2] Kabata-Pendias A. Trace Elements in Soils and Plants. Boca Raton FL: CRC Press; 2011

[3] Robinson BH, Yalamanchali R, Reiser R, Dickinson NM. Lithium as an emerging environmental contaminant: Mobility in the soil-plant system. Chemosphere. 2018;**197**:1-6. DOI: 10.1016/j.chemosphere.2018.01.012

[4] Shacklette HT, Boerngen JG. Lithium in surficial materials of the conterminous United States. US Geological Survey Professional Paper. 1084;**1270**:105

[5] Mukai H, Motai S, Kikuchi R, Kogure T, Hirose A, Tanoi K, et al. Cesium adsorption/desorption behavior of clay minerals considering actual contamination conditions in Fukushima. Scientific Reports. 2016;**6**:21543. DOI: 10.1038/srep21543

[6] Kanianska R, Drimal M, Varga J, Komárek M, Ahado SK, Šťastná M, et al. Critically raw materials as potential emerging environmental contaminants, their distribution patterns, risks and behaviour in floodplain soils contaminated by heavy metals. Scientific Reports. 2023;**13**(1):9597. DOI: 10.1038/s41598-023-36477-7

[7] Steinhoefel G, Brantley SL, Fantle MS. Lithium isotopic fractionation during weathering and erosion of shale. Geochimica et Cosmochimica Acta. 2021;**295**:155-177. DOI: 10.1016/j.gca.2020.12.006

[8] Xu Z, Zhang Z, Peng S, Yuan Y, Wang X. Influences of lithium on soil properties and enzyme activities. Chemosphere. 2023;**313**:137458. DOI: 10.1016/j.chemosphere.2022.137458

[9] Anderson MA, Bertsch PM, Miller WP. Exchangeable and apparent fixation of lithium in selected soils and clay minerals. Soil Science. 1989;**148**:46-52

[10] Hoyer MK, Kummer N-A, Merkel B. Sorption of lithium on bentonite, kaolin and zeolite. Geosciences. 2015;**5**(2):127-140. DOI: 10.3390/geosciences5020127

[11] Elbana TA, Osman MA. Water, Air, and Soil Pollution. 2023;**234**:33. DOI: 10.1007/s11270-022-06035-4

[12] Kot FS. On the rubidium and lithium content and availability in the sub-arid South-Eastern Mediterranean: Potential health implications. Environmental Geochemistry and Health. 2018;**40**(5):1841-1851. DOI: 10.1007/s10653-018-0134-8

[13] Brouwer E, Baeyens B, Maes A, Cremers A. Cesium and rubidium ion equilibria in illite clay. The Journal of Physical Chemistry. 1983;**87**:1213-1219

[14] Tyler G. Influence of acidity and potassium saturation on plant uptake of indigenous soil rubidium. Environmental and Experimental Botany. 1997;**38**:181-186. DOI: 10.1016/S0098-8472(97)00012-9

[15] Coleman NT, Lewis RJ, Craig D. Sorption of Cesium by soils and its displacement by salt solutions. Soil Science Society of America Journal. 1963;**27**:290-294. DOI: 10.2136/sssaj1963.03615995002700030023x

[16] Rai H, Kawabata M. The dynamics of radio-Cesium in soils and mechanism

of Cesium uptake into higher plants: Newly elucidated mechanism of Cesium uptake into Rice plants. Frontiers in Plant Science. 2020;**11**:528. DOI: 10.3389/fpls.2020.00528

[17] Burger A, Lichtscheidl I. Stable and radioactive cesium: A review about distribution in the environment, uptake and translocation in plants, plant reactions and plants' potential for bioremediation. Science of The Total Environment. 2018;**618**:1459-1485. DOI: 10.1016/j.scitotenv.2017.09.298

[18] Kubo K, Fujimura S, Kobayashi H, Ota T, Shinano T. Effect of soil exchangeable potassium content on cesium absorption and partitioning in buckwheat grown in a radioactive cesium-contaminated field. Plant Production Science. 2017;**20**(4):396-405. DOI: 10.1080/1343943X.2017.1355737

[19] Festervand DF. Soil Survey of Cape Girardeau, Scott and Mississippi Counties, Missouri. Produced in Cooperation with the United States Department of Agriculture. Printed Washington DC: United States Forest Service, and the University Missouri-Columbia; 1981

[20] Aide MT, Fasnacht M. Estimating trace element availability in soils having a seasonal water table using commercially available protocols. Communications in Soil Science and Plant Analysis. 2010;**41**:1159-1177. DOI: 10:1080/00103621003721379

Section 3

Drought Risk Assessment

Chapter 4

Perspective Chapter: Droughts Risk in Portugal – Past, Present and Future

Vanda Pires and Tânia Moura

Abstract

Extreme events are one of the greatest challenges in the context of climate change. Drought is one of the extreme phenomena that causes the most concern worldwide, as it is an event that is difficult to determine its beginning, and it can last from months to years, unlike other extreme events. Portugal is a country with recurrent episodes of drought, which creates a strong need to understand, analyze and prepare plans with a strong focus on impact reduction strategies. To better characterize and understand the risk of droughts in mainland Portugal, meteorological indices that rely on precipitation deficits were used, which allows the characterization and monitoring of drought in Portugal by determining drought onset, duration and intensity. The indices used in this study are: Palmer Drought Severity Index and Standardized Precipitation Index. The increase in the frequency of meteorological droughts that has been identified in mainland Portugal in the last decades indicates an increase in the risk and vulnerability to these phenomena, being the Southern region of Portugal being the most affected one.

Keywords: drought, precipitation, climate change, frequency, impacts

1. Introduction

The occurrence of extreme meteorological and climatic phenomena (floods and droughts) affects Portugal, with severe socioeconomic impacts that depend, to a large extent, on the degree of development and the organization of infrastructures to minimize their effects. In general, the increase in air temperature and the decrease in precipitation have led to a strong need for an evaluation of the implications on the spatial and temporal variability of some components of the water balance and, consequently, on the water cycle and hydrological systems.

Droughts are a natural phenomenon associated with a lack of precipitation, which occurs every year in several regions of the world. Drought is the most complex natural disaster and affects more people and for longer than any other. The beginning and the intensity of a drought is a gradual and cumulative process, which occurs slowly and can be difficult to detect as such.

Drought is a recurrent climatic event occurring worldwide and is intensively perceived by the Mediterranean countries [1]. The greater frequency of meteorological drought situations observed in mainland Portugal in recent decades may indicate a tendency toward an increase in risk and vulnerability to the phenomenon, which could increase the impacts, particularly in the agricultural and hydrological sectors and consequently in the social sector [2]. Although it is impossible to control the climate component, the risk reduction depends on reducing the component related to the vulnerability of these sectors.

To better understand the risk of droughts in mainland Portugal, meteorological indices allow us to characterize and understand the evolution of droughts in mainland Portugal, determining its duration, intensity and severity. In this study, two indices, the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI).

2. Methodology

The Palmer Drought Severity Index (PDSI) detects periods of drought and classifies them in terms of their intensity). Monthly monitoring of this index (or on shorter time scales) provides a good indication of the initial evolution of the drought, as well as an assessment of its intensity and duration. The calculation of the PDSI index is based on the concept of water balance, taking into account data on the amount of precipitation, air temperature and water capacity available in the soil [3]. The PDSI allows the detection of the occurrence of dry periods and classifies them (**Table 1**) in terms of intensity (mild, moderate, severe and extreme) [3]. The PDSI was developed in the USA and cannot be applied directly to mainland Portugal's climatic conditions. Despite maintaining the logical structure that underlies the definition of the PDSI index, important changes were introduced, with its calculation being fully calibrated to be adapted to the climatic conditions of Portugal [4].

The Standardized Precipitation Index (SPI), developed by McKee [5] measures the precipitation anomalies at a given location, based on a comparison between observed precipitation over a cumulative time period (e.g., 1, 3, 6, 12, 24 months) and the historical precipitation series.

Category	Classification PDSI
Extremely wet	4.00 or more
Very wet	3.00 a 3.99
Moderate wet	2.00 a 2.99
Slightly wet	0.50 a 1.99
Normal	−0.49 a 0.49
Mild drought	−0.50 a −1.99
Moderate drought	−2.00 a −2.99
Severe drought	−3.00 a 3.99
Extremely drought	−4.00 or less

Table 1.
Classification for dry/rainy periods of the PDSI index [3].

Category	Classification PDSI
2.00 or more	Extremely wet
1.50 a 1.99	Very wet
1.00 a 1.49	Moderate wet
−0.99 a 0.99	Normal
−1.00 a −1.49	Moderate drought
−1.50 a −1.99	Severe drought
−2.00 or more	Extremely drought

Table 2.
Classification for dry/rainy periods of the SPI index [5].

The historical series is fitted to a probability distribution (gamma distribution) that is transformed into a normal distribution so that the mean SPI for the location and desired period is zero [5]. This calculation can be repeated for multiple timescales. Positive SPI values indicate greater than median precipitation, while negative values indicate less than median precipitation (**Table 2**).

The indices were computed using daily and monthly data and based on the recommendations of the CCL task team (commission for climatology, World Meteorological Organization (WMO)) on the definition of extreme weather and climate events such as the following properties: threshold (determined based on historical values), temporal (starting and ending date, total duration) and spatial (area affected by) [6].

In order to characterize an extreme weather and climate event, the following properties [6]: (1) Magnitude: which measures the departure from the threshold; (2) Duration: the time interval at which the event begins and ends; (3) Extent: the geographical area affected by the event; and (4) Severity: a combination of magnitude and persistence of a drought.

3. Observed changes in precipitation

There has been a decrease in annual precipitation values in mainland Portugal, around −20 mm/decade, with the last 20 years having been particularly less rainy on the mainland (**Figure 1**). Six of the 10 driest years occurred after 2000, including 2005, the driest since 1931, 2007 the second driest and 2017 the third driest.

The reduction in precipitation values was observed in all seasons of the year, with the exception of autumn. This reduction was significant in the spring. On the other hand, it is important to highlight that the contribution of days of intense precipitation to total precipitation has increased, especially in autumn and in the Southern region. The intensity and frequency of extreme precipitation events have also been increasing [6].

Analyzing the precipitation anomalies in hydrological years since 1960 for four meteorological stations in South Portugal, it can be seen that in recent hydrological years, the accumulated precipitation values have been persistently lower than the normal value, with a very long precipitation deficit (6–10 consecutive years) (**Figure 2**).

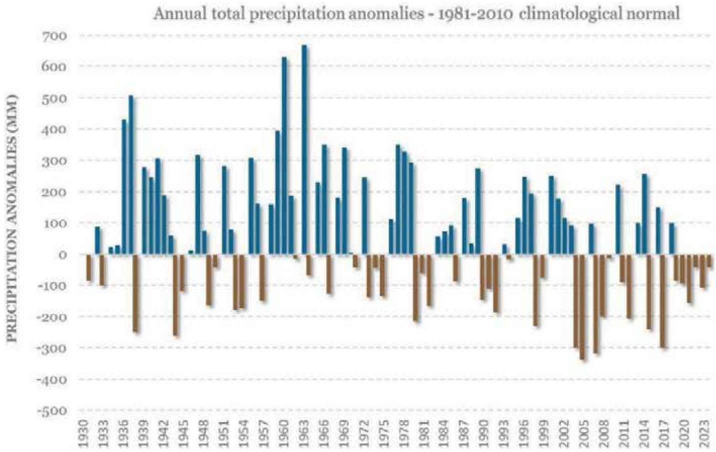


Figure 1.
Anomalies in the amount of annual precipitation in mainland Portugal, in relation to the 1981–2010 average.

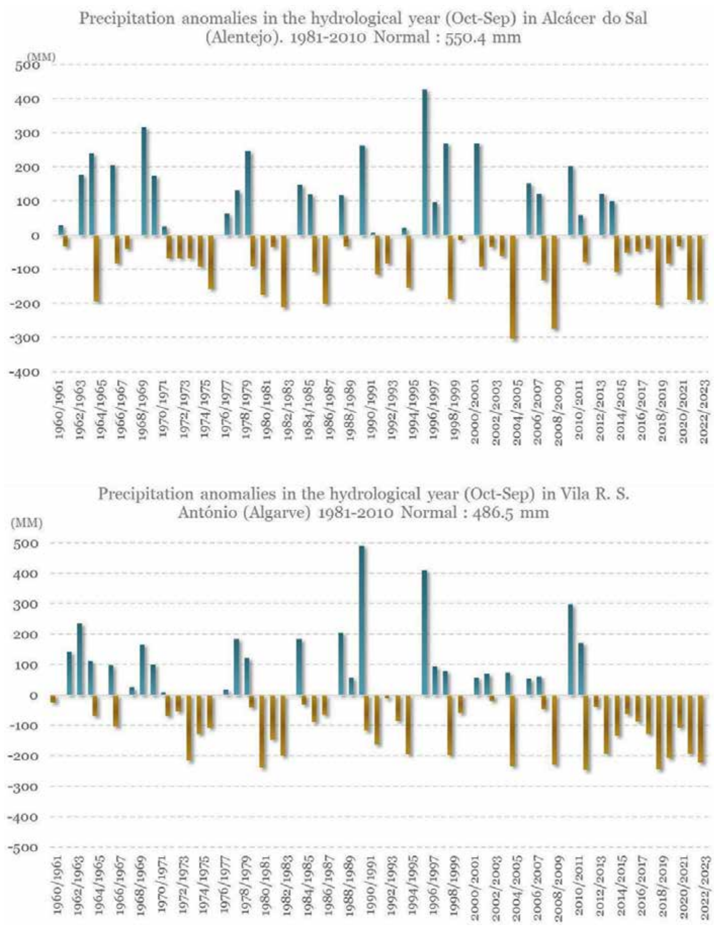


Figure 2.
Precipitation anomalies in the hydrological year (October–September) 1961 to 2023 in relation to the average annual value in the period 1981–2010 at Alcácer do Sal (top) and Vila Real de Santo António (down).

4. Droughts in mainland Portugal

4.1 Past droughts since 1901

Droughts are frequent in mainland Portugal, with disastrous consequences for agriculture, water resources and the well-being of the population. There is historical evidence over several centuries that indicates the occurrence of droughts with severe impacts in mainland Portugal [2]. Some events were even associated with an increase in mortality rates, a consequence of widespread hunger caused by the decline in dryland agricultural production.

Some historical examples of droughts in Portugal are the years 1354–1355, 1385–1398 (very long), 1504–1506, or 1733–1738, 1753 (**Figure 3**, example of a poem alluding to a drought situation). As early as the nineteenth century, there are descriptive records of a particularly long and severe event, between 1873 and 1878 [7]. The 1870s were also dramatic for the people of the Algarve region with consecutive years of drought: "there is no longer any hope that agriculture produces enough to sustain the inhabitants of the province, there will not even be enough pasture to feed the cattle" (in the Lagos newspaper "Gazeta do Algarve").

To understand the evolution of droughts in Portugal, a long time series of the PDSI index were calculated for three meteorological stations, Porto, Lisbon and Beja, in order to identify periods and years of drought during the twentieth century and early twenty-first century (**Table 3**).

Figure 4 shows the annual distribution of PDSI for four meteorological stations of mainland Portugal with a long time series. It can be seen that negative values dominate in relation to the positive values of the index since there is a larger area below the zero line, which indicates a greater frequency and duration of dry periods than rainy periods. The occurrence of years with PDSI values in the most intense drought classes (moderate or higher classification) was more frequent in the 40s, 80s, 90s and after


POEMA
SOBRE AS SECAS
Do Ano 1753.
E CHUVAS,
Cõ que
O SENHOR
DOS PASOS
DA GRASA
LISBOA:

Figure 3.
Poem about the droughts of the year 1753. And rains, which the lord of the Pasos da Grasa helped after many months, in which prayers were said throughout the kingdom (Anonymous, Lisbon, 1753) [7].

Meteorological stations	Period	Latitude	Longitude	Altitude (m)
Porto/P.R.	1922–2006	41.2322°	−8.6791°	67.7
Lisboa/I.G.	1901–2024	38.7191°	−9.1497°	77.0
Beja	1901–2024	38.0257°	−7.8676°	246.0

Table 3.
Stations with long time series.

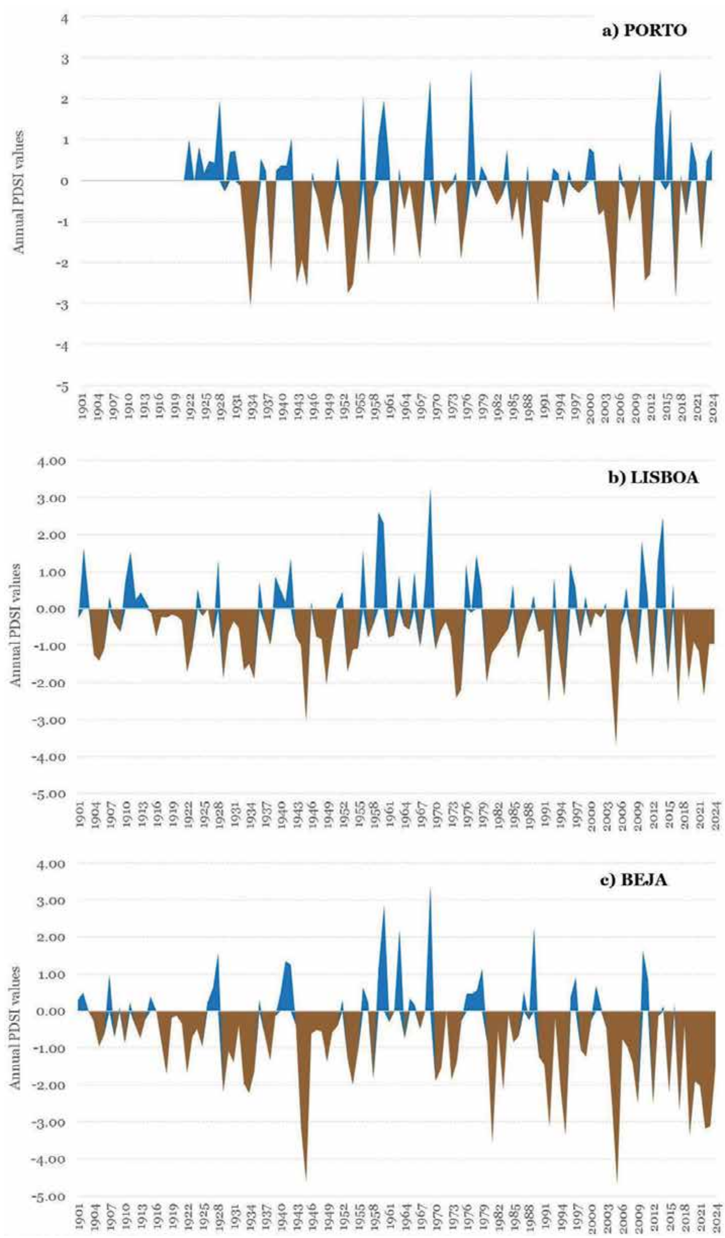


Figure 4.
Annual values of the PDSI drought index in Porto (a), Lisbon (b) and Beja (c).

2000. The two drought situations that reached the lowest PDSI values, classified as severe to extreme, occurred in 1944 and 2005 and also in 1934, in Porto, there was a year of exceptional drought.

The two drought situations that reached the lowest PDSI values, classified as severe to extreme, occurred in the years 1944 and 2005. Also, 1934, in Porto, was a year of exceptional drought.

There was a high number of droughts in Beja 28, followed by Porto with 23, and Lisbon with 21. Some drought episodes stand out, not only for their duration but also for the number of consecutive months of severe and extreme drought.

In terms of duration to refer:

- 1933–1935 in Porto (26 months), Lisbon (15 months) Beja (28 months)
- 1943–1946 in Porto (38 months), Lisbon (26 months), Beja (29 months)
- 1953–955 in Porto (25 months), Beja (24 months)
- 1973–1976 in Lisbon (28 months)
- 1991–1992/3 in Lisbon and Beja (24 months)
- 1994–1995 in Lisbon (22 months), Beja (20 months)
- 2004–2006 in Beja, (33 months), Lisbon and Porto (16 months).

In terms of intensity (number of consecutive months of severe or extreme drought), the following should be highlighted:

- 12 months – Beja, 1943–1946 and 1994–1995
- 11 months – Beja, 1994–1995
- 10 months – Beja and Porto, 2004–2006
- 9 months – Beja 1980–1981; Lisbon 2004–2006

4.2 Present droughts

A greater frequency of episodes of meteorological drought occurred in the last years in mainland Portugal, some of which have lasted for more than one wet period (autumn and winter) and dry period (spring and summer), covered a greater percentage of the territory, with the Northeast and Southern regions being the most affected [2].

Trends calculated by the least squares method and statistical significance using the Mann-Kendall test for the 5% probability level, between 1941 and 2020, show the highest frequency of drought periods in spring and summer, mainly in the Southern region of Portugal (**Figure 5**).

The monthly series of the PDSI drought index reveals that drought episodes have been more frequent and more severe since the 1980s. Likewise, the analysis of the evolution by decades (between 1961 and 2020) of the distribution of the PDSI index in mainland Portugal allows us to conclude that, in the last two decades, there has

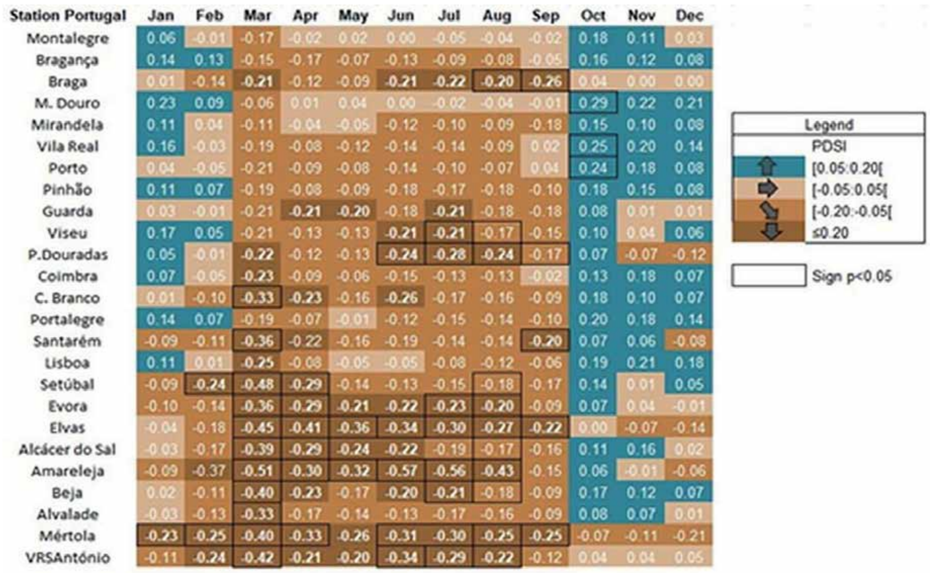


Figure 5.
Trends of PDSI index between 1941 and 2020 (least squares method; Mann-Kendall statistical significance test for 5% probability level.

been an increase in the frequency, intensity and duration of meteorological droughts, especially in the months of February to April. Since 1980, eight drought episodes with large territorial extension and great severity have been recorded (**Table 4**), with all of them with 10% of the territory in an extreme drought classification and four episodes with more than 75% of the territory in moderate or severe drought classification.

Figure 6 shows the percentage of the territory of mainland Portugal in the severe and extreme drought classes of the PDSI index from 1941 to 2024. This analysis reveals that there has been a greater frequency of more intense drought episodes since the year 2000, with a longer duration and a high spatial coverage, standing out the droughts of 2004/05, 2011/12, 2017/18 and 2021/22.

For the characterization of these drought events since 1941, it was calculated the following properties [8]: Magnitude, Duration, Extent and Severity. It was concluded that:

Year of drought	Affected territory
1980–1981	The entire territory; variable intensity (from weak to extreme); more intense in the South region (severe to extreme)
1990–1992	The entire territory; moderate to extreme intensity
1994–1995	Southern Region with greater intensity (moderate to extreme)
1998–1999	The entire territory with weak to severe intensity
2004–2005	The entire territory: the largest territorial extension and the most intense (nine consecutive months of severe and extreme drought
2011–2012	Entire territory; moderate to severe intensity
2017–2018	Entire territory; weak to extreme intensity; significant worsening in early autumn
2021–2022	Entire territory; variable intensity (from mild to extreme)

Table 4.
Drought situations between 1980 and 2024 in mainland Portugal.

DOI: http://dx.doi.org/10.5772/intechopen.1009617

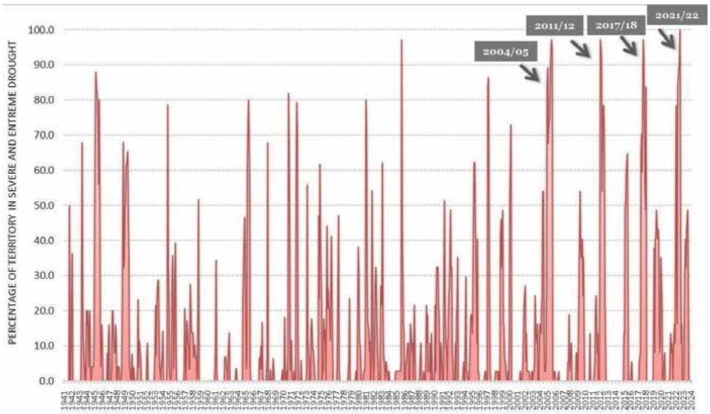


Figure 6.
Territory percentage of mainland Portugal in severe and extreme drought classes of PDSI index - 1941 and 2024.

- The 2004/05 drought was the most severe in mainland Portugal: highest magnitude, highest duration and highest severity (**Figure** 7).

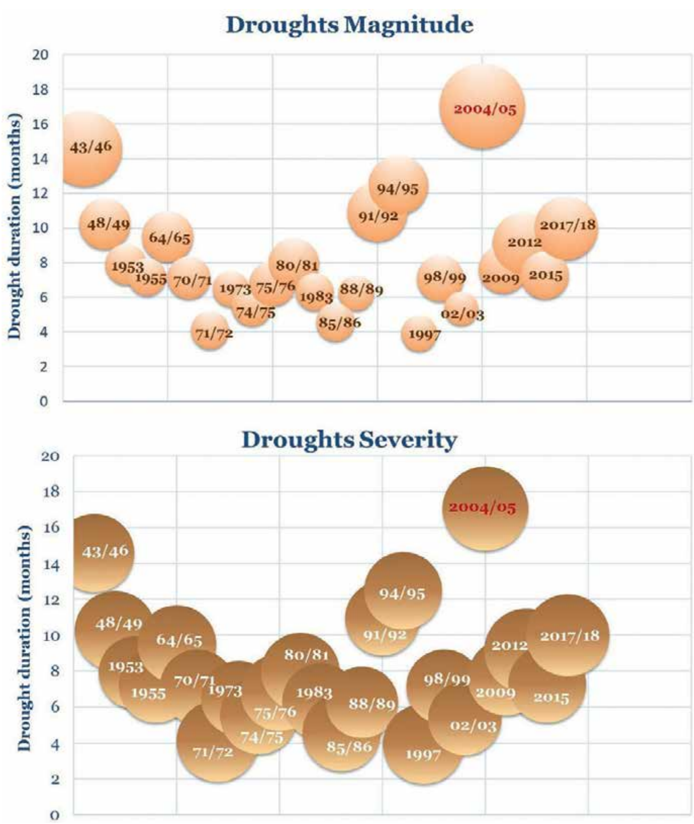


Figure 7.
Drought magnitude, duration and severity in mainland Portugal using the PDSI index.

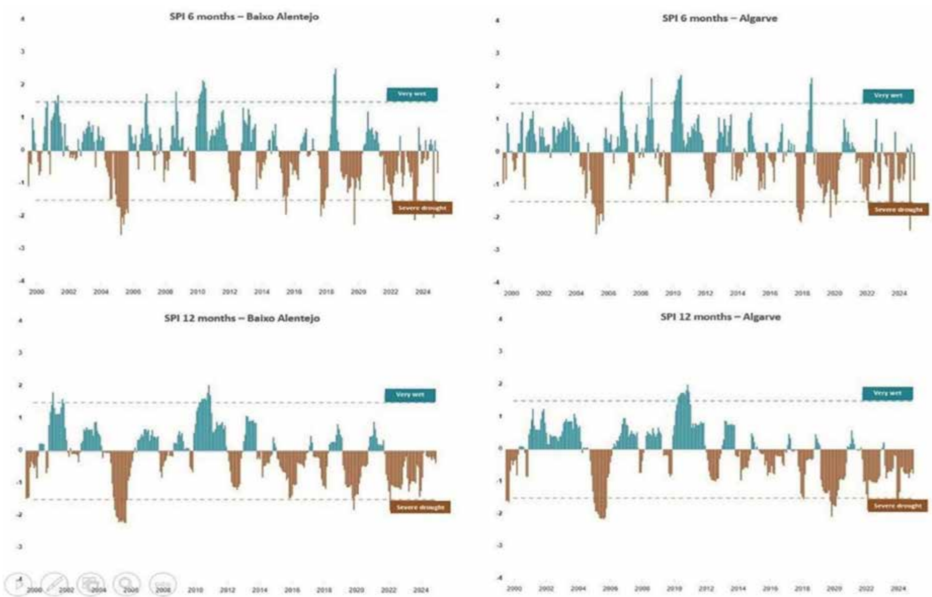


Figure 8.
Variability of the meteorological drought index, SPI in the Southern regions of Portugal (Baixo Alentejo e Algarve) between 2000 and 2024.

- The 1943/45 drought was the second one with the highest magnitude and duration.
- 2004/05, 2012 and 2017/18 droughts with most of the regions in very high severity.

The 2017/2018 drought that covered the entire territory and had significant impacts on several sectors had a different particularity associated with the temporal distribution of the drought. Unlike the previous drought situations that began in late autumn or early winter, the 2017/18 drought worsened in spring, continuing into summer, and at the end of autumn, this drought event compared to previous was the one with the highest percentage of territory in severe and extreme PDSI drought classes (97% of the territory).

Using the SPI index, it is possible to verify the impacts of drought situations after 2000 on various time scales. The 6 and 12-month time were analyzed; the SPI 6 M scale refers to meteorological and agricultural drought (rainfall deficit and soil moisture deficit, respectively), while the SPI 12 M refers to the water scarcity reflected in surface runoff and artificial reservoirs. For the Southern regions (Baixo Alentejo and Algarve) the SPI index shows the high frequency of drought episodes since 2000 (**Figure 8**). The same tendency was identified by the PDSI index, with the 12-month SPI highlighting an almost continuous period of negative values of the index in the last 10 years, with little recovery in non-drought periods.

5. Future scenarios in Portugal: Precipitation and droughts

The increased frequency of meteorological drought situations that have been observed in mainland Portugal in recent decades is indicative of an increase in the risk and vulnerability to this phenomenon, which will bring an increase in impacts, particularly at the level of the agricultural and hydrological sectors in some regions of the country and particularly in the South of Portugal.

Long-term analyses reveal substantial increases in drought risk across all scenarios, with a particularly notable increase in the Mediterranean region [9]. For prolonged periods of drought, there is a risk of irreversible aridity, which worsens with higher levels of global warming. With warming of 3°C above pre-industrial levels, an estimated 170 million people would suffer from extreme drought [9].

Future projections are based on different scenarios for the evolution of greenhouse gas (GHG) emissions, one of which is less serious (RCP4.5), corresponding to a socioeconomic evolution that controls the increase in emissions, and another more serious (RCP8.5), which results in continued growth in emissions during the twenty-first century [9].

Two of the climatic elements that most influence drought situations are precipitation, which provides moisture to the soil, and evapotranspiration, which consumes soil moisture. Climate projections made from global simulations, within the scope of the European consortium EC-Earth for Portugal [10], indicate for the end of the twenty-first century (decade 2091–2100), a decrease in annual precipitation in mainland Portugal, around −55 mm in the case of the RCP 4.5 scenario (intermediate scenario) and around of −148 mm in the case of RCP8.5 (worst scenario); and on the other hand for an increase in evapotranspiration between +77 mm in the RCP4.5 scenario and + 184 mm in the RCP8.5 scenario (**Figure 9**).

With these scenarios, a significant increase in the water deficit in mainland Portugal can be expected. At the end of this century, and considering the most serious scenario (RCP 8.5), mainland Portugal could lose, in the total volume of annual precipitation, around 14,000 hm3 of water, the equivalent of the useful storage of four Alqueva dams (**Figure 10**).

Given these scenarios of reduced precipitation in Portugal and loss of water volume, it is expected that there will be an increase in the frequency of dry periods in mainland Portugal in the future, with greater duration and severity.

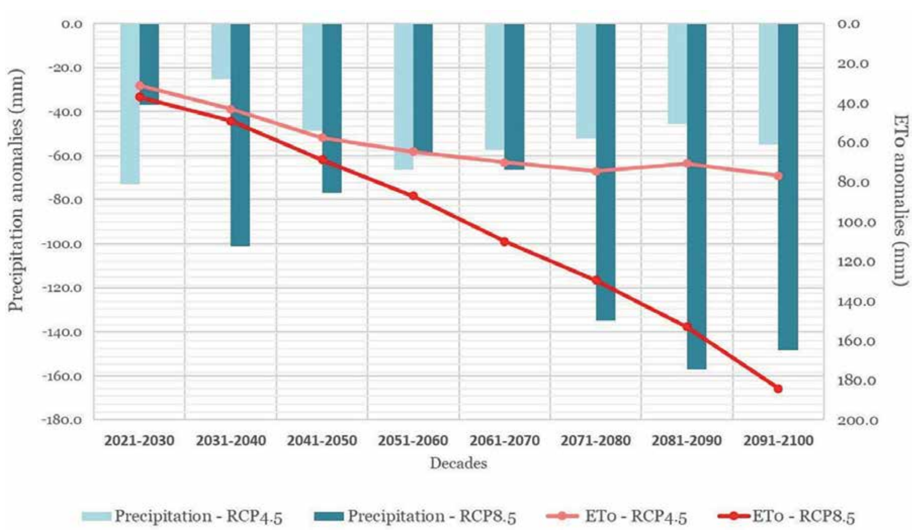


Figure 9.
Climate projections: RCP 4.5 and 8.5 scenarios of annual precipitation and evapotranspiration in mainland Portugal (difference from 1971 to 2000 period) [10].

In terms of impacts at a national level, due to frequent periods of prolonged drought in the future, there will be an increase in soil degradation in several parts of the territory, which, together with recurring forest fires that are intensified during periods of greater water scarcity, can increase the risk of desertification in several regions.

The Aridity Index over mainland Portugal projected for the two scenarios RCP4.5 and RCP8.5 (**Figure 11**), shows an increase in the semiarid zones. For RCP 8.5 the subhumid change to semiarid zones will cover the Southern of Portugal, which will lead to an increased risk of desertification in that region.

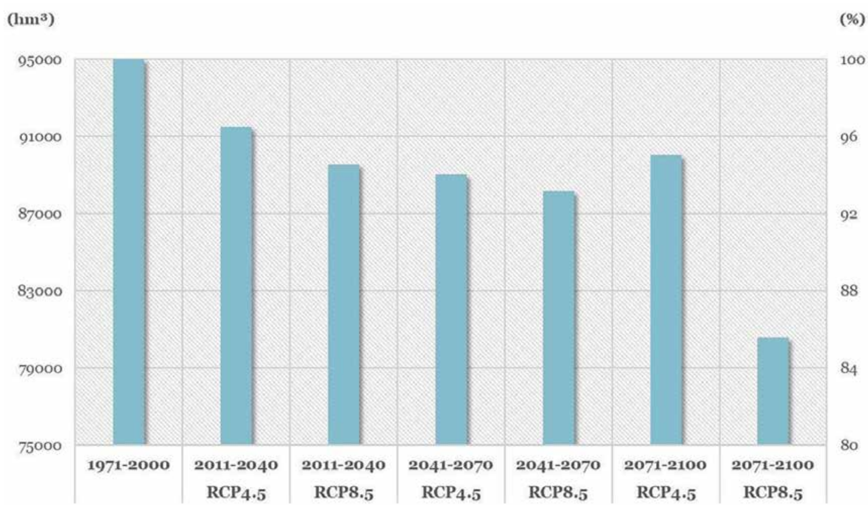


Figure 10.
Climate projections: RCP 4.5 and 8.5 scenarios of annual precipitation in mainland Portugal: precipitation volume [10].

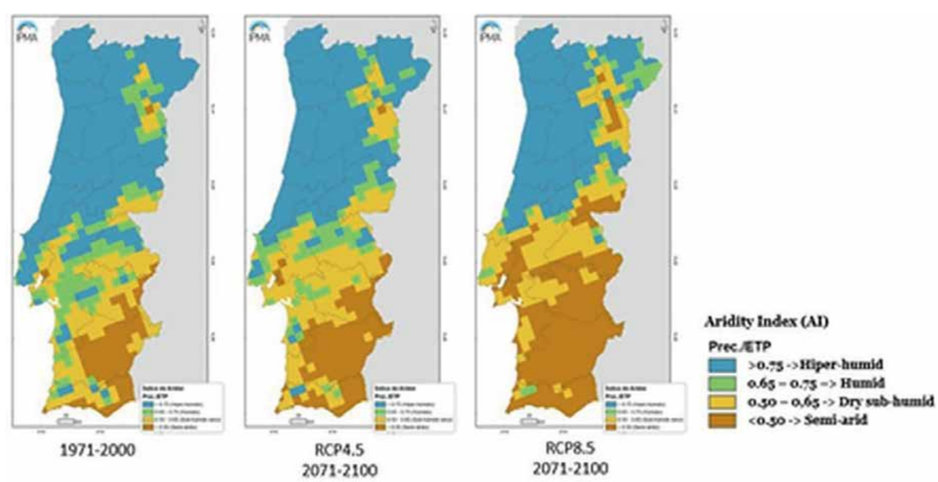


Figure 11.
Aridity Index (AI) over mainland Portugal projected for the 2071–2100 period under RCP4.5 and RCP8.5 scenarios [7, 10].

DOI: http://dx.doi.org/10.5772/intechopen.1009617

6. Conclusions

Depending knowledge about extreme events, particularly drought situations, and strengthening existing capacities is fundamental and urgent in order to understand, on the one hand, the climate changes that are being felt and, on the other hand, improve and develop support products and applications to the decision.

The increased frequency of drought situations in mainland Portugal in recent decades is indicative of an increase in the risk and vulnerability to this phenomenon, which has increased the impacts on the agricultural and hydrological sectors and consequently on various levels in Portuguese society.

Long-term analyses reveal that negative values dominate in relation to the positive values of the index, which indicates a greater frequency and duration of dry periods than rainy periods in mainland Portugal.

Trends of the PDSI index between 1941 and 2020, show the highest frequency of drought periods in spring and summer, mainly in the in Southern region of Portugal. This regional behavior reveals a substantial increase in drought episodes since 2000, according to PDSI and SPI indexes, and in the last 10 years, the drought periods dominate, with little recovery in the non-drought periods.

The most severe drought in mainland Portugal was the 2004/05 episode which had the highest magnitude, duration and severity. The droughts with most of the regions in very high severity were 2004/05, 2012 and 2017/18 events.

Climate projections carried out from global simulations, within the scope of the European consortium EC-Earth, indicate that Portugal will be warmer, leading to greater evaporation and, therefore, a decrease in the water content in the soil, thus increasing the frequency, intensity and duration of drought situations in the national territory.

The projections for the end of the twenty-first century show a decrease in precipitation in mainland Portugal, around 5% (RCP4.5) to 15% (RCP 8.5), especially in the South, where the reduction could be 30%, with the consequent impacts on water resources.

With these scenarios, a significant increase in the water deficit in mainland Portugal can be expected, which could have significant effects on the growth and development of plants and consequently on the productivity and quality of agricultural products.

The reduction in water availability in mainland Portugal will be one of the biggest challenges, which will lead to production losses, especially in dryland crops, as well as in livestock farming, with the lack of water for watering animals [7].

Acknowledgements

I would like to express my deepest appreciation to IPMA – Portuguese Sea and Atmosphere Institute and all my colleagues from the Climate and Climate Change Division that helped and supported me with an immense number of conversations and long discussions resulting in a better understanding and consolidation of the article specific thematic.

I would also like to thank the *Xevora* Project which allowed the preparation and financial support of this article.

Conflict of interest

The authors declare no conflict of interest.

Author details

Vanda Pires* and Tânia Moura
Portuguese Sea and Atmosphere Institute, I.P., Lisbon, Portugal

*Address all correspondence to: vanda.cabrinha@ipma.pt

References

[1] Pereira LS, Cordery I, Iacovides I. Coping with Water Scarcity. Addressing the Challenges. Dordrecht: Springer; 2009

[2] Pires V, Silva A, Mendes L. Drought Risk in Mainland Portugal. 2010. Rev. Territorium, N°17; 2010, pp. 27-34. @Riscos, ISBN: 0872-8941

[3] Palmer W. Meteorological drought. Research Paper. 1965;**45**:58

[4] Pires V. Frequency and Intensity of Extreme Meteorological Phenomena Associated with Precipitation. Dissertation for the Degree of Master in Earth Sciences and Engineering. Lisbon: Faculty of Sciences of the University of Lisbon; 2003

[5] Mckee TB, Doesken NJ, Kleist J. The relationship of drought frequency and duration to time scale. In: Proceedings of the Eighth Conference on Applied Climatology; 17-22 January 1993; Anaheim, California. Boston: American Meteorological Society. pp. 179-184

[6] Guidelines on the Defintion and Monitoring of Extreme Weather and Climate Events. Final draft produced by the WMO commission for climatology task team on the definition of extreme weather and climate events. Expert review in January 2018; WMO

[7] WWF. Portugal's Vulnerability to Drought and Water Scarcity. Nature Portugal Association in partnership with World Wild Fund (ANP/WWF); 2019

[8] Guidelines on the Definition and Characterization of Extreme Weather and Climate Events. 2023 ed. WMO-No. 1310. World Meteorological Organization

[9] IPCC, Pörtner HO, Roberts DC, Tignor M, Poloczanska ES, Mintenbeck K, et al. Climate Change: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK and New York, NY, USA: Cambridge University Press; 2022. p. 3056. DOI: 10.1017/9781009325844

[10] Portal do Clima [Internet]; 2015. Available from: http://portaldoclima.pt/pt/ [Accessed: January 10, 2025]

Chapter 5

Comparative Assessment of Standardised Indices for Monitoring Drought in North-Eastern South Africa

Fhumulani I. Mathivha and Selelo Matimolane

Abstract

Drought assessment provides critical data for mitigating drought risk and reducing community vulnerability, particularly in semi-arid regions like north-eastern South Africa. The South African Weather Service (SAWS) primarily uses the Standardised Precipitation Index (SPI) to monitor drought impacts on agriculture and water resources. However, SPI relies solely on rainfall data, neglecting key variables such as evapotranspiration, which plays a significant role in drought development. This study evaluates and compares the effectiveness of SPI, the Standardised Streamflow Index (SSI), and the Standardised Precipitation Evaporation Index (SPEI) in assessing drought conditions in the Luvuvhu River Catchment (LRC). Rainfall and temperature data were obtained from SAWS, while streamflow records were sourced from the Department of Water and Sanitation. The non-parametric Mann-Kendall trend test was applied for drought trends analyses across 1-, 6-, and 12-month timescales. Results indicate that mild droughts were prevalent in the study area shown by all indices at all timescales, while extreme drought events were less frequent but more pronounced events at longer timescales. The evaluation criteria further revealed SPEI as the most suitable index for drought monitoring in the LRC due to its ability to account for both rainfall and evapotranspiration, providing a more comprehensive assessment of drought conditions. These findings showcased the increasing frequency and severity of droughts in the region, emphasising the need for improved drought monitoring, early warning systems, and adaptive water resource management strategies to mitigate future drought impacts.

Keywords: climate variability, drought classification, drought indices, drought risk, environmental impacts, trend analysis

1. Introduction

Drought is a normal feature of the southern Africa's climate and an important natural disaster in this region. As it is mainly characterised by arid to semi-arid climate, southern Africa is particularly susceptible and vulnerable to drought events [1]. Globally, droughts have become more frequent and severe due to climate variability,

IntechOpen

with different regions experiencing droughts at varying scales and times. Drought assessment and analysis play a significant role in the reduction of drought risk not only in developing nations but also in most developed countries. Drought risk is determined by a population's susceptibility to the effects of drought as well as the frequency, intensity, and the geographic extent of drought. The assessment of frequency, severity, and spatial extent of drought can be achieved by drought indices. Measurements such as the variations in precipitation levels from the long-term mean value during a specific period of time serve as the foundation for these indexes [2]. Further to the deficiency in precipitation, recent literature supports the significant role that evapotranspiration plays in drought development [3].

Planning for water supplies, irrigation systems, agricultural and food security initiatives, hydropower production, water quality management, and waste disposal systems are all dependent on proper assessment and monitoring of drought conditions [4]. Standardised Precipitation Index (SPI) [5], Standardised Precipitation Evaporation Index (SPEI) [6], Palmer Drought Severity Index (PDSI) [7], Standardised Streamflow Index (SSI) [8], Surface Water Supply Index (SWSI) [9], and other drought indices have been used to accomplish this assessment. At different timescales, these indices can monitor water deficiencies in different stages of the hydrological cycle. For example, the World Meteorological Organisation (WMO) [10] indicated that while a 6-month SPI may be linked to extreme streamflow and increased reservoir levels, a 3-month SPI provides a seasonal estimation of precipitation and represents short- and medium-term moisture conditions.

The most widely used index for monitoring and assessing drought is the SPI [11, 12]. The index has the advantage of comparing drought events across different climates, taking into account different timescales at which precipitation deficit affects the hydrological cycle, unlike other indices, such as the PDSI. Szalia and Szinell [13] showed that the SPI is a more effective tool for determining the beginning and end of a drought event because it can be computed at multiple timescales. Despite this, the WMO recommends the SPI as the standard drought index [14]. The index's shortcoming is its inability to account for a catchment's water balance [15] as it is solely dependent on rainfall input. To overcome this drawback, SPEI, which includes potential evapotranspiration (PET), was developed by Vicente-Serrano et al. [6].

Numerous drought studies, including those involving drought analysis, climate change, impacts, and monitoring, have made extensive use of SPEI [16, 17]. Although SPI is popular in South Africa, the application of SPEI for drought assessment and monitoring is gaining popularity [18–22]. Edosaa et al. [21] made a comparison between SPEI and PDSI when evaluating the self-calibrating PDSI in monitoring drought in the Free State Province, and Botai et al. [22] used SPI and SPEI to define historical drought in South Africa's Free State and North West provinces. Although the SSI has been widely applied in recent years, particularly in streamflow drought studies [23–25], such has not been the case in South Africa. Notable attempts at the application of SSI in hydrological drought monitoring are documented by Mukhawana et al. and Botai et al. [26, 27] in the Cape provinces of South Africa.

Studies reviewed, evaluated and compared drought indices concerning their performance in drought assessment and monitoring [28–30]. However, Vicente-Serrano et al. [31] indicated that limited studies have compared indices and conducted reliable statistical analyses, which could enable the recommendation of the preferential use of one indicator based on objective standards for a specific region. A robust statistical analysis of drought indices to determine their suitability for drought assessment in an area improves the knowledge of drought risk and consequent impacts emanating from droughts event to the environment and regional water resources. It is against this backdrop that this study aims to evaluate the performance of SPI, SPEI and SSI in drought monitoring and analysis in the Luvuvhu River Catchment (LRC). While one might argue the choice of standardised indices to more sophisticated drought indices, it should be noted that the latter require a multitude of data, which is often not available or monitored in many developing regions. In addition, the wide range of applicability of standardised indices makes them preferable for drought monitoring in many regions of the world.

2. Material and methods

2.1 The study area

The LRC, a major tributary of the Limpopo River, is situated in the northern-most part of South Africa in Limpopo Province. The catchment covers an area of approximately 5941 km^2 at 1593 metres above sea level and lies between latitudes 22° 17′ 33.57″ S & 23° 17′57.31″ S and longitudes 29° 49′46.16″ E & 30° 23′32.02″ E. The Luvuvhu River rises in the Soutpansberg Mountain range and flows through the Levubu valley, a variety of settlements, the Kruger National Park (KNP), and empties into the Limpopo River at the South African border with Mozambique, within which the catchment under study lies in a drought corridor (between 20° and 25°S) [32]. Rainfall in the region is highly variable, with high rainfall experienced in the Tshakhuma and Levubu areas, while downstream locations such as the Mhinga Village receive relatively low rainfall during the wet season (**Figure 1**).

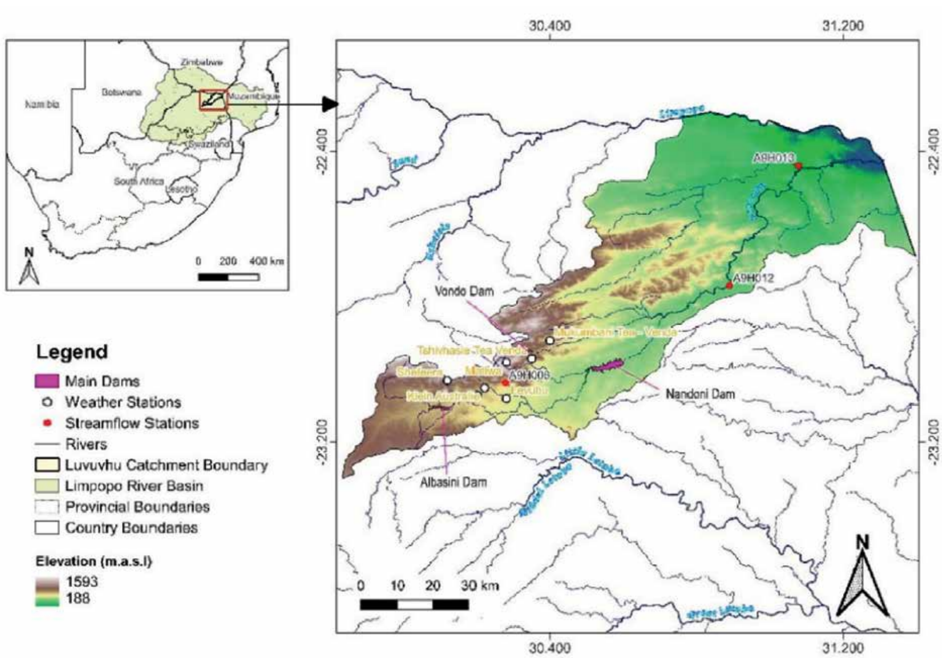


Figure 1.
The study area map (Luvuvhu River Catchment) in the context of South Africa and the Limpopo River Basin showing the catchment elevation and catchment hydrology as well as weather stations and streamflow stations.

2.2 Data requirements and analysis

To achieve the goal of the study, rainfall, temperature, and streamflow were collected from various monitoring organisations. Monthly rainfall and temperature data for seven weather stations were sourced from the South African Weather Services (SAWS), while streamflow data from three stations were obtained from the Department of Water and Sanitation (DWS) for the period from 1986 to 2016.

2.2.1 Standardised indices formulation

2.2.1.1 SPI

The SPI, SSI and SPEI were computed for all the stations at 1-, 6- and 12-monthly timescales. The rainfall data was fitted into a probability density function to determine the rainfall deficit using SPI. A gamma distribution function was selected because it provides a good fit to rainfall time series data [33]. The gamma function applies for values of rainfall $x > 0$ for the rainfall time series. In the case of non-zero values, the cumulative probability of both zero and non-zero values had to be calculated. Eq. (1) defines a function H(x) that represents this probability.

$$H(x) = q + (1 - q) f(x; \alpha, \beta) \tag{1}$$

where q is the probability of zero rainfall and H(x) is the cumulative probability. The ratio /n is used to estimate q if m is the number of zeroes and n the number of observations in the rainfall time series. The cumulative probability is converted to a standard normal so that the *SPI* variance is zero and one, respectively. This phase is completed through an approximation transformation, as discussed by Mishra and Desai [34], which was adopted. This is achieved as follows:

$$SPI = k - \frac{C_0 + C_1 k + C_2 k^2}{1 + d_1 k + d_2 k^2 + d_3 k^3} \tag{2}$$

The value of *k* in Eq. (9) was determined from the functions given in Eq. (3).

$$k = \sqrt{\ln\left(\frac{1}{1 - H(x)^2}\right)} \tag{3}$$

where c_0, c_1, c_2, d_1, d_2 and d_3 are 2.515517, 0.802853, 0.010328, 1.432788, 0.189269 and 0.001308, respectively [35].

2.2.1.2 SPEI

The original SPI's calculating process serves as the foundation for the SPEI. The SPEI uses the difference between precipitation and Potential Evapotranspiration (PET) on a weekly or monthly basis [6]. This study used the Hargreaves and

Samani temperature-based method for PET estimation because of the intricate computation of the PET, which involves many parameters (i.e., surface temperature, air humidity, soil incoming radiation, water vapour pressure, and ground-atmosphere latent and sensible heat fluxes) [36], some of which are not monitored in the study area. By substituting a three-parameter distribution (i.e., SPEI requirement) for the two-parameter distribution, the SPI approach was altered [6]. By substituting a three-parameter distribution (i.e., SPEI requirement) for the two-parameter distribution, the SPI approach was altered [6] to achieve SPEI estimation over the study area. The latter proposed using L-moments to generate the best fit three-parameter distribution; the specific steps to accomplish this are available in Ref. [37]. The classical approximation outlined in Ref. [38] was followed to yield SPEI, as shown in Eq. (4).

$$\mathrm{SPEI} = \mathrm{W} - \frac{\mathrm{C}_0 + \mathrm{C}_1\mathrm{W} + \mathrm{C}_2\mathrm{W}^2}{1 + \mathrm{d}_1\mathrm{W} + \mathrm{d}_2\mathrm{W}^2 + \mathrm{d}_3\mathrm{W}^3} \tag{4}$$

where $\mathrm{W}\, si\sqrt{-2\ln(\mathrm{P})}$ for $P \leq 0.5$ and P is the chance of surpassing a threshold value indicated by D value, $P = 1 - F(x)$. If $\mathrm{P} > 0.5$, then P is replaced by $1 - \mathrm{P}$ and the sign of the resultant SPEI is reversed. The constants C_0, C_1, C_2, d_1, d_2, and d_3 are as defined in Eq. (2). The CRAN package "spei" in R was used to calculate SPEI.

2.2.1.3 Standardised streamflow index (SSI)

This study used the method described in Ref. [39] to determine the SSI, which used the empirical Gringorten plotting position [40] to estimate the marginal likelihood of streamflow. By using such an empirical approach, the parametric probabilities can be derived without the need for the original distribution (two-term gamma probability density function and cumulative gamma distribution function) used in SPI. Following the classical approximation as described by Abramowitz and Stegun [38], Entekhabi et al., and Edwards and McKee [41, 42], SSI is computed using Eq. (5).

$$SSI = \mathrm{t} - \frac{\mathrm{C}_0 + \mathrm{C}_1\mathrm{t} + \mathrm{C}_2\mathrm{t}^2}{1 + \mathrm{d}_1\mathrm{t} + \mathrm{d}_2\mathrm{t}^2 + \mathrm{d}_3\mathrm{t}^3} \tag{5}$$

The constants C_0, C_1, C_2, d_1, d_2, and d_3 are as defined in Eq. (2), while t is given by Eq. (6).

$$\mathrm{t} = \sqrt{\ln\frac{1}{\mathrm{P}^2}}, \tag{6}$$

The SPI classification categories (**Table 1**) as described by McKee et al. [5] are adopted to categorise the different drought events. The standardised indices use a classification system whereby wet conditions are indicated by positive values and negative values represent dry conditions. Therefore, positive SPI, SPEI and SSI values

SPI	Classification
> 2.0	Extremely wet
1.5 to 1.99	severely wet
1.00 to 1.49	Moderately wet
−0.99 to 0.99	Near normal
−1.00 to −1.49	Moderate dry
−1.5 to −1.99	Severe dry
< −2.0	Extremely dry

Table 1.
Drought category classification of occurrence per each SPI/SPEI/SSI classification [5].

show greater than median precipitation, while negative values are indicative of less than median precipitation.

2.2.2 Drought trends and significant

The Mann-Kendall (MK) non-parametric trend test [43, 44] was used to detect the significance of drought trends in the study area. The trend methodology is recommended by the WMO while studying trends of hydrometeorological data. The non-parametric test compares the relative magnitudes of the samples and provides information on whether the null hypothesis can be rejected or accepted [45]. The null hypothesis (H_0) that suggests there is no trend is tested against the alternative hypothesis (H_1), which suggests there is an increasing or decreasing trend. If the p-value is less than the alpha, H_0 is rejected, which indicates that there is a trend in the time series. On rejecting the null hypothesis, the results are said to be statistically significant. The test has been widely used in hydrometeorological trend analysis studies and showed good performance [46–48]. Studies such as Damberg and AghaKouchak and Golian et al. [49, 50] applied the Mann-Kendall trend test in studying droughts. The test statistic S is calculated using Eq. (7) and Eq. (8).

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sign\left(X_j - X_k\right) \tag{7}$$

$$Sgn\left(y_i - y_k\right) = \begin{cases} +1 \text{ if } \left(y_i - y_k\right) > 0 \\ 0 \text{ if } \left(y_i - y_k\right) = 0 \\ -1 \text{ if } \left(y_i - y_k\right) < 0 \end{cases} \tag{8}$$

The average value of S is E[S] = 0. The value of the S statistic is associated with the test statistics τ_i, and this is computed using Eq. (9).

$$\tau = \frac{S}{n(n-1)/2} \tag{9}$$

This study considered a 5% confidence level, where the null hypothesis of no trend was rejected if $|z| > 1.96$.

2.2.3 Evaluating indices accuracy

For the evaluation of the standardised indices, an approach described in Ref. [29] was used. Six criteria—robustness, tractability, sophistication, transparency, extendibility, and dimensionality—are suggested by the latter authors based on these desirable attributes. A judgement criterion by Keyantash and Dracup [29] was applied to ascertain whether a drought index had desired characteristics and was helpful in detecting drought in the study area. To identify the best index for drought evaluation, this study used just five selection criteria; this is since the transparency criteria primarily address dimensionality. The five decision criteria were given a raw score ranging from 1 to 5 to evaluate the overall use of an indicator. The qualitative and quantitative evaluation of each metric serves as the basis for the individual raw ratings, as mentioned in Ref. [51]. While the qualitative evaluation is based on the results of earlier research on evaluating indices and the computational components of the index, the quantitative evaluation is based on how successfully the index mimicked past droughts. The sum of the weighted scores (i.e., raw scores multiplied by the relative importance factor) was the total for each index. Regarding relative relevance, Ketantash and Dracup [29] prioritised robustness with a weight of 8 and a relative value of 28%, followed by tractability with a weight of 6 and 21%, then transparency sophistication and extendibility with a weight of 5 and 17%, respectively. This study added the relative value of dimensionality to transparency, making it 17% with a weight of five, as transparency covers dimensionality. The comparative assessment for the corresponding indices in the LRC then uses the total of the weighted scores. Since the index raw scoring was compared to those assigned by Barua [51], a sensitivity analysis was not performed for this study.

3. Results and discussion

3.1 Historical drought assessment

3.1.1 Indices-based drought evaluation in Luvuvhu River catchment

All standardised indices were analysed at three timescales (1-, 6- and 12-month) and further used to detect historical drought in the LRC for the duration of 30 hydrological years (September 1986 to August 2016). Notable historic droughts, i.e., 1987/88, 1991/92, 1994/96, 2001/02 and 2014/16, were the focus regarding the historical assessment of drought for indices comparison in this study. The analysis of all SPI, SPEI and SSI time scales successfully detected all the notable drought years as reported in literature [52–55] and further detected more drought years. **Table 2** shows historical drought category occurrences for SPI, while **Tables 3** and **4** show the same for SPEI and SSI, respectively. Mild droughts dominated the catchment, with all stations reporting drought incidences over 60%, with the exception of Mat Station, which showed an occurrence of 55.43% at the 6-month timescale. While severe drought cases ranged between 0.36 and 16.77%, moderate cases ranged between 7.88 and 27.05%. Extreme droughts were the least found and ranged between 0% and 21.61%. Mazibuko et al. [55] found that SPI characterised the 2015/2015 drought as

Station	Timescale	Mild (%)	Moderate (%)	Severe (%)	Extreme (%)
KA	1	76.6	14.89	6.38	1.6
	6	68.78	19.88	7.83	3.61
	12	73.75	16.25	7.5	1.88
Lev	1	71.08	18.63	9.8	0.49
	6	67.03	9.89	11.54	11.54
	12	68.49	7.88	3.03	20.61
Mat	1	61.62	24.75	12.12	1.52
	6	55.43	21.2	11.41	11.96
	12	60.77	18.79	8.29	12.16
Muk	1	82.26	10.75	6.45	0.54
	6	65.22	15.53	9.94	8.7
	12	61.49	13.51	14.87	10.14
Nooit	1	82.81	10.94	5.21	1.04
	6	62.84	27.87	7.65	1.64
	12	65.56	26.67	7.78	0
Shef	1	73.08	21.15	5.29	0.48
	6	69.56	27.05	2.9	0.48
	12	80.51	15.9	0.36	0
Tshi	1	78.95	10.53	8.77	1.75
	6	73.41	14.45	5.78	6.36
	12	66.46	11.18	16.77	5.59

Table 2.
Analysis of SPI historical drought categories.

extreme. The study noted that the majority of extreme droughts were observed at the 6- and 12-month timescales, which is it was observed that increased SPI time scales increase with drought severity.

For SPEI, mild, moderate, severe and extreme drought conditions ranged in all stations considering the respective timescales. Stations Muk and Mat showed the highest percentages of extreme droughts at 6.14% for the 12th timescale. This, however, is still less than the proportion of extreme drought occurrence that SPI depicted at the same period. The inclusion of evapotranspiration as an input in the formulation of SPEI may be the cause of the difference between SPI and SPEI drought analysis. The relationship between increased drought categories and timescale as noted by SPI is also notable in **Table 3** for SPEI.

The SSI categorised mild, moderate, severe and extreme drought across the streamflow stations at different timescales over the period considered in this study period, as depicted in **Table 4**. While the categories classification of SSI is like the two standardised indices, streamflow station A9H012 depicted higher extreme droughts at the 6th and 12th timescales compared to severe droughts over the same timescales.

Although drought was detected in all months of the year, the majority were between the months of September and March, and this is because the study area

Station	Timescale	Mild (%)	Moderate (%)	Severe (%)	Extreme (%)
KA	1	68.28	23.66	5.91	0.02
	6	63.79	27.59	8.05	0.575
	12	65.68	17.16	15.98	1.18
Lev	1	65.91	22.35	2.24	0.56
	6	66.67	16.67	16.67	0
	12	65.66	12.65	21.69	0
Mat	1	67.9	26.84	5.26	0
	6	65.35	25.57	8.52	0.57
	12	69.14	14.2	10.49	6.14
Muk	1	68.42	23.68	7.37	0.53
	6	65.36	25.7	6.7	2.23
	12	69.33	14.11	10.42	6.14
Nooit	1	66.86	24	7.43	1.14
	6	63.28	25.42	10.72	0.57
	12	61.15	23.08	14.2	1.18
Shef	1	68.51	21.55	7.74	2.21
	6	68.36	23.72	6.21	1.7
	12	70.88	21.43	6.05	1.65
Tshi	1	70.97	23.12	4.2	1.61
	6	68.11	21.08	10.27	0.54
	12	65.06	19.88	15.06	0

Table 3.
Analysis of SPEI historical drought categories.

received its rainfall over the summer months. While Mason and Tyson [52], Chikoore and Mazibuko et al. [54, 56] reported the 1991/92 drought, for example, as the most extreme in the region, resulting in major economic losses, only the KA station revealed this extreme event at 6- and 12-time scales. The period from 2012 to 2015 saw the most severe drought cases across all stations and time frames; at a 12-month timescale, the stations such as Lev recorded 35 drought months over this period. In most stations at the 6-timescale, the drought of 2014/16 dominated the severe category and was shown to be more severe than the drought of 1991/92.

The 1991/92 drought was prominently portrayed by the SSI at all stations; nevertheless, the SSI classified these drought occurrences as extreme on record rather than severe, as compared to the precipitation-based indices (SPI and SPEI). According to the precipitation-based indices considered in this study, they showed that over the study period, the 2014/16 drought was the most extreme. Since streamflow is majorly dependent on precipitation, there may be a lag between precipitation deficit and a decrease in streamflow, which could explain how SSI behaves in comparison to precipitation-based indices. Streamflow and baseflow drought occur around 7 and 11 months, respectively, after the end of a meteorological drought [56]. The extreme case of 2014/16 will, therefore, be noticeable in the 2016/17 hydrological year, which the current study period does not include. Comparing SSI to precipitation-based

Station	Timescale	Mild (%)	Moderate (%)	Severe (%)	Extreme (%)
A9H006	1	93.78	5.7	0.52	0
	6	68.02	24.27	7.61	0
	12	54.75	31.84	12.41	0
A9H012	1	69.94	13.5	10.43	6.14
	6	73.91	14.29	3.11	8.7
	12	69.23	18.59	3.85	8.33
A9H013	1	70.05	23.35	6.09	0.51
	6	68.06	25.66	3.14	3.14
	12	78.67	11.85	7.11	2.27

Table 4.
Analysis of SSI historical drought categories.

standardised indices, the index ranked second-highest for extreme droughts after the SPI at the 12-month timescale. Mathivha et al. [54] reported a good correlation between SPI and SSI regarding historical drought assessment over the LRC. Since up to 93.78% of the drought occurrences were classified as mild, the index results do not show that the catchment experiences extreme drought. The results of SSI concur with those of SPI and SPEI in that, during the studied period, mild droughts were predominated in the catchment area at all time scales.

3.1.2 Drought trends in the Luvuvhu River catchment and their significance

The MK non-parametric trend test was conducted to detect drought trends, as shown in **Figure 2(A)–(C)** for SPI, SSI and SPEI, respectively. The analysis is carried out over the various timescales (i.e., 1, 6, and 12 months), taking into consideration historical drought occurrences for all selected stations. At a 95% confidence level, all standardised indices rejected the null hypothesis, which stated that the drought time series data did not show a monotonic trend. SPI drought trends were found to be negative in all stations across all timescales apart from Tshi and Shef at the 12th and 6th month timescales, respectively. Across the three timescales, two stations (Lev and Mat) revealed the most significant negative SPI trends, while Muk stations only revealed the same at the 1st and 6th timescale. SPEI showed a significant negative trend in all timescales across all the stations apart from Shef and Tshi stations for the period considered in this study. Only one station (Lev) showed a positive SPEI trend that was significant at the 6th timescale. SSI showed a 55.56% positive trend for station A9H012 at all timescales and for station A9H012 at the 1st and 6th months' timescale. About 75% of the negative drought trends were shown to be insignificant, and 25% were significant, while 60% of positive drought trends were found to be insignificant. Many significant negative trends revealed across the three standardised indices are indicative of the least likely randomness in the data but show a clear pattern of the catchment experiencing more drought episodes.

3.1.3 Evaluating indices accuracy

The total weighted scores based on five evaluation criteria (i.e., robustness, tractability, sophistication, transparency, and extendibility) for all standardised indices are presented in **Table 5**.

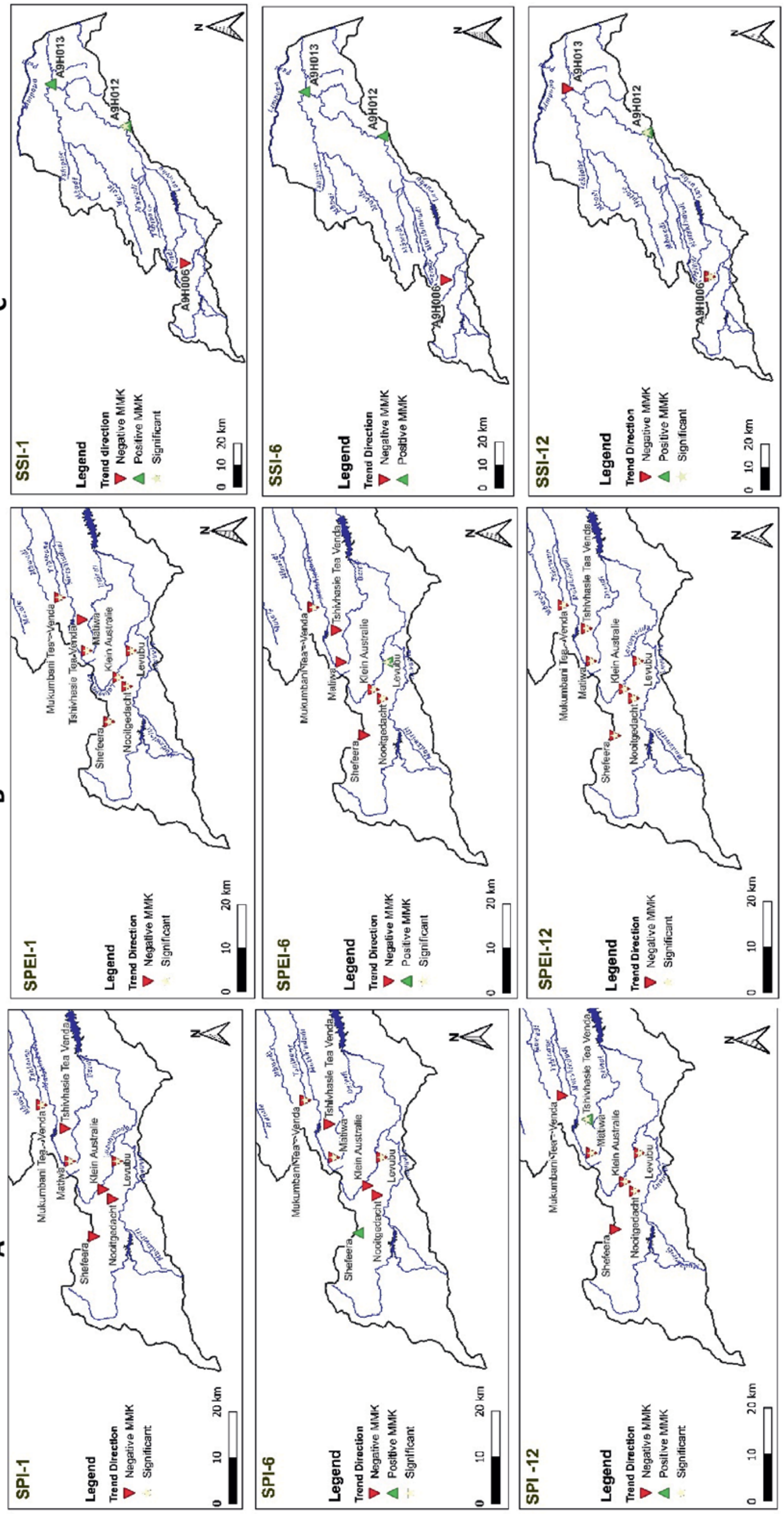


Figure 2.
Trends direction and significance (A) SPI, (B) SPEI and (C) SSI for all the stations over the study area for all the considered timescales in the study.

Drought index	Raw scores (1–5)					Total weighted scores
	Robustness	Tractability	Sophistication	Transparency	Extendibility	
SPI	2	5	2	5	5	106
SPEI	5	4	5	4	4	129
SSI	5	5	4	5	2	125

Table 5.
Indices scores based on weighted evaluation criteria.

Robustness, which accounts for some degree of fluctuation, shows how useful a drought index is across a broad variety of physical conditions. Instead of being susceptible to unreasonable fluctuations, a robust index should ideally be responsive [29]. Raw scores of five and two were assigned to SPEI & SSI and SPI, respectively (**Table 5**). SPEI and SSI were not temperamental, and their response was positive in detecting historical drought in the LRC. The SSI and SPI agreed with the SPEI historical drought detection. Studies such as Kim et al. [57] have seen that even when heavy rainfall is experienced right before the period of interest, SPI tends to overstate rainfall scarcity. Because SPI is dependent on rainfall and does not provide a comprehensive picture of watershed water availability, it was given a raw score of two. Tractability deals with the practical aspects of an index. Keyantash and Dracup [29] reported that a tractable index requires a low level of numerical computations and sparsely observed data. SPI and SSI were assigned a raw score of five, while SPEI received a raw score of four. Since SPI and SSI require fewer input variables (such as rainfall and streamflow) and are easier to calculate than SPEI, they were found to be more practical of the three indices and were given the highest raw scores.

Transparency considers the clarity of the objective behind a respective drought index [29]. This is an important decision criterion, as a pragmatic index should not be understood only by the scientific community but by all stakeholders affected by drought. The easier to understand indices are usually those that require less input data variables and are widely understood, including SPI and SSI, which were both assigned a raw score of five. Although SPEI has two input variables, challenges may arise if evaporation data is not available and the index is deemed easier to understand by different stakeholders; therefore, SPEI was assigned raw scores of four, as indicated in **Table 5**. The sophistication decision criteria consider the conceptual merits of drought characterisation [29]. The latter study further indicated that a drought measurement technique may be less understood but may be sophisticated from a proper perspective. In characterising drought for this study, SPEI, SPI, and SSI showed the best strength, as they were all able to detect the most severe drought in the catchment and were assigned raw scores of five, two and four, respectively.

Extendibility describes the degree to which an index may be extended across time to alternate drought scenarios [29]. Historical data was used for all the indices considered in this study (i.e., rainfall, streamflow, and temperature). However, if modelled future long-term data is made available, the extension of an index is possible. Raw scores of five, four and two were assigned to SPI, SPEI and SSI, respectively. That is because the computation of SPI and SPEI are relatively less complex, and some of their future data variables are already available on certain platforms. Meanwhile, for the computation of SSI, streamflow should be forecasted first, and this requires modelling skills, which may be challenging.

As shown in **Table 5**, the overall index evaluation of the drought indices is in terms of the total weighted score. The SPEI, SSI and SPI showed an overall score of 129, 125 and 106, respectively. From the evaluation criteria employed, SPEI was found to be the better index when comparing it to SPI and SSI, making it more suitable for drought monitoring in the Luvuvhu River Catchment. For historical drought detection, the SPEI modelled the drought characteristics better and showed the severity of the 1991/92 drought. Further to the 1991/92 drought, the index also demonstrated the severity of the prolonged 2014/16 drought and suggested that the severity and intensity superseded that of the 1991/92 drought. This was also shown by SSI at a 1-month timescale. The second ranking was SSI; it is easily understandable with minimal data requirements, and the computation is not rigorous. Since the index is solely dependent on streamflow, it is disadvantaged in the scoring system. Although it did not rank the highest, SPEI was still considered to reflect water deficiency in the hydrological system at longer timescales. Based on **Table 5**, the SPEI was found to be superior compared to the other indices. Van Loon [58] reported that during the dry season, potential evapotranspiration is typically higher than precipitation, which may indicate that evapotranspiration has a greater role in the onset of drought. The cascading effects of increased evapotranspiration and reduced precipitation are noticeable in water resources in rivers during the same dry season. Therefore, a drought index which accounts for PET is likely more useful to give a good picture of drought in an area, especially in a semi-arid environment where PET is generally higher.

4. Environmental impacts of drought in the study area

Drought is a recurring natural hazard in Limpopo Province, significantly affecting various environmental components such as water resources, vegetation cover, soil health, and biodiversity. The comparative analysis of standardised drought indices (SPI, SPEI, and SSI) conducted in the Luvuvhu River Catchment (LRC) provides a critical understanding of the impacts of drought on the province's environment. The findings suggest that while mild droughts dominate the region, severe and extreme droughts have also occurred, particularly during prolonged dry periods such as 1991/92 and 2014/16. These drought events have detrimental environmental consequences, which are discussed below.

4.1 Water resources depletion

The findings of the study indicate that prolonged drought conditions significantly affect both surface and groundwater resources in Limpopo Province, with far-reaching consequences for water availability, ecosystems, and human livelihoods. The SSI detected recurrent periods of low streamflow, particularly during major drought years such as 1991/92 and 2014/16, highlighting the vulnerability of the LRC to water scarcity [59]. This is consistent with findings from Mathivha et al. and Botai et al. [48, 60], who reported that droughts in South Africa have led to significant reductions in river discharge and reservoir levels, affecting both rural and urban water supply systems. One notable example is the impact of the 2014/16 drought on the Middle Letaba Dam, which supplies water to agricultural and domestic users in the region. During this period, dam levels dropped to below 10%, leading to water rationing in communities such as Giyani [61]. Similarly, the Nzhelele and

Mutale Rivers, key tributaries of the Limpopo River, experienced drastic reductions in flow, affecting local farmers who depend on these water sources for irrigation [59]. Furthermore, groundwater resources, which serve as an alternative supply during surface water shortages, were also affected. Studies by Rankoans and Rakgwale and Oguttu [62, 63] show that declining rainfall and increased abstraction during drought periods led to a significant drop in borehole yields in parts of Limpopo Province, conditions that often lead to extreme water scarcity.

4.2 Vegetation stress and land degradation

Drought-induced vegetation stress and land degradation are major environmental concerns in Limpopo Province. As presented in this study, the SPEI shows that high evapotranspiration rates accelerate soil moisture loss, worsening drought conditions. In a semi-arid region like Limpopo, where rainfall is already erratic, prolonged droughts have devastating effects on vegetation health and land stability. One striking example is the degradation of grazing lands in the Vhembe and Mopani districts, where many small-scale farmers depend on natural vegetation for livestock [64]. During the severe 2014/16 drought, widespread loss of grass cover left soils unprotected, leading to increased surface runoff and soil erosion [19]. Overgrazing further intensified the problem, as livestock concentrated on the remaining sparse vegetation, leaving the land barren. This aligns with findings from Maluleke et al. [65], who observed that drought-driven overgrazing accelerates soil erosion and desertification in Limpopo's rangelands. Another concerning impact of vegetation loss is the expansion of gully erosion, particularly in rural areas like Giyani and Nzhelele. As plant cover diminishes, deep gullies form, making land unsuitable for cultivation and reducing its long-term productivity [66]. The Kruger National Park, a key biodiversity hotspot, has also seen drought-related changes in vegetation, affecting herbivores and leading to shifts in wildlife distribution [67].

4.3 Biodiversity and ecosystem disruptions

Drought significantly disrupts biodiversity and ecosystem stability in Limpopo Province, particularly in its savannahs, wetlands, and riverine environments. The reduction in rainfall and streamflow alters habitat conditions, making it difficult for water-dependent species to survive, affecting both flora and fauna. One of the most affected areas is the Kruger National Park, where drought-related water shortages have historically led to significant declines in herbivore populations. During the severe 2014/16 drought, elephant and buffalo herds were forced to migrate in search of water, increasing competition and conflict at remaining waterholes [67]. Wetlands such as the Makuleke wetlands, a Ramsar site and one of South Africa's most important species habitats, also suffer during droughts. Drying floodplains reduce breeding grounds for fish and waterbirds, impacting a wide variety of species depending on the floodplain in this arid landscape. These include the globally vulnerable Mozambique tilapia (*Oreochromis mossambicus*), the critically endangered African longfin eel (*Anguilla mossambica*) and several rare bird species, including the white-backed vulture (*Gyps africanus*) and the African pygmy goose (*Nettapus auritus*). Additionally, the loss of aquatic vegetation due to prolonged dry spells affects smaller waterbird species, such as black-winged stilts (*Himantopus himantopus*) and lesser moorhens (*Gallinula angulata*), which depend on shallow wetlands for foraging.

4.4 Increased wildfire risks

Drought conditions in the region significantly heighten the risk of wildfires, as reduced precipitation and rising temperatures create dry, flammable landscapes. This study highlights that prolonged drought detected by SPI and SPEI are conditions that often coincide with an increased risk of fire outbreaks. This is particularly evident in Kruger National Park, where the 2014/16 drought led to frequent wildfires, destroying vast tracts of vegetation [65]. Rural areas such as Mopani and Vhembe Districts are also vulnerable, where wildfires threaten farmlands and rural settlements. In 2018, a severe fire in the Soutpansberg region scorched thousands of hectares of grazing land, leaving livestock farmers with devastating losses. Moreover, these fires release elevated amounts of carbon dioxide and particulate matter into the atmosphere, worsening air quality and contributing to climate change [68]. This impact is complex, as the impact of changes in air quality may be felt in different regions over time.

4.5 Reduced agricultural productivity and soil health

Drought conditions in Limpopo Province have a profound impact on agriculture, leading to lower crop yields, food insecurity, and long-term soil degradation [63]. Nembilwi et al. [19] found that the 2014/16 drought was particularly severe, mirroring widespread reports of agricultural losses across the province [69]. During this period, staple crops such as maize and sorghum suffered significant yield reductions, with some farmers experiencing total crop failures [70]. In areas like Mopani and Sekhukhune Districts, prolonged drought depleted soil moisture, reducing nutrient cycling and availability and causing widespread crop wilting. The lack of rainfall also accelerated soil degradation, with increased salinisation reported in irrigated farmlands [64]. Overgrazing, combined with drought stress, further worsened land conditions, leading to reduced pasture quality for livestock.

4.6 Long-term climate variability and drought intensification

The Mann-Kendall trend analysis confirms a statistically significant increase in drought frequency and severity in Limpopo Province, reinforcing global climate projections that warn of worsening drought conditions in the region [69]. The increasing trend in SPEI highlights the role of rising temperatures and evapotranspiration in intensifying drought impacts [59, 70]. Historical data shows that extreme drought events, such as those in 1991/92 and 2014/16, are becoming more frequent and prolonged [60, 71]. Studies [70, 72] also indicate that rainfall patterns in Limpopo are shifting, with shorter rainy seasons and prolonged dry spells leading to reduced groundwater recharge and declining agricultural productivity. Without urgent adaptation strategies, such as improved water management, climate-resilient agriculture, and reforestation, Limpopo's ecosystems and livelihoods will face mounting stress.

5. Conclusions and recommendations

This study conducted a comparative analysis of three standardised drought indices, namely, SPI, SPEI, and SSI, to evaluate their effectiveness in monitoring drought conditions in the LRC, a region characterised by high climatic variability and susceptibility to droughts. The findings indicate that all indices successfully identified major historical drought events, including the significant droughts of 1987/88, 1991/92, 1994/96, 2001/02, and 2014/16; however, their ability to capture drought severity and trends varied significantly. SPEI emerged as the most robust and comprehensive index, as it incorporates both precipitation and potential evapotranspiration, making it particularly responsive in semi-arid environments where water balance dynamics play a critical role in drought development. SPI, despite its widespread application, was limited by its reliance solely on precipitation data. In contrast, SSI provided valuable insights into hydrological drought by analysing streamflow variations, but its applicability was constrained by the need for extensive and high-quality streamflow records, which in most developing countries fail to monitor continuously. The MK trend analysis revealed statistically significant increasing drought trends across multiple timescales, particularly when assessed using SPEI, reinforcing concerns about the intensification of drought conditions in the region. The 2014/16 drought was identified as one of the most severe on record, surpassing the historically significant 1991/92 drought in intensity across several stations. These findings align with broader climate change projections, which anticipate increased drought frequency and severity in semi-arid regions.

In addition to evaluating indices performance, the study highlighted the far-reaching environmental impacts of drought in the LRC, including water resource depletion, vegetation stress, biodiversity disruptions, increased wildfire risks, and reduced agricultural productivity. The results highlight the need for improved drought monitoring and early warning systems, particularly with the rising influence of climate change on regional drought patterns. Given the strengths and limitations of different indices, the study recommends the adoption of a multi-index approach application of SPI, SPEI, and SSI for a more comprehensive drought monitoring in the region of study. Furthermore, climate and hydrological monitoring networks through increased investment in weather stations and streamflow gauges should be strengthened, as such data are a prerequisite in improving the accuracy and reliability of drought monitoring and assessments. This is particularly important for indices like SSI, which require consistent and high-quality streamflow data. Additionally, enhancing data-sharing mechanisms among government agencies, research institutions, and local stakeholders can potentially facilitate more comprehensive and real-time drought monitoring.

Acknowledgements

This chapter emanates from a PhD thesis that was submitted to the University of Venda in September 2020. The author acknowledges the South African Weather Services and the National Department of Water and Sanitation for providing the hydrometeorological data utilised in this study. Additionally, the authors extend their appreciation to Ms. Mary Nkosi for her valuable assistance in preparing the GIS maps included in this chapter.

Conflict of interest

The authors declare no conflict of interest.

Author details

Fhumulani I. Mathivha[1*] and Selelo Matimolane[2]

1 Department of Water and Sanitation, University of Limpopo, Sovenga, South Africa

2 Equitable Education and Economies, Human Sciences Research Council, Pretoria, South Africa

*Address all correspondence to: fhumulani.mathivha@icloud.com

References

[1] Chivangulula FM, Amraoui M, Pereira MG. The drought regime in southern Africa: A systematic review. Climate. 2023;**11**(7):147. DOI: 10.3390/cli11070147

[2] Nosrati K, Zareiee AR. Assessment of meteorological drought using SPI in West Azarbaijan Province, Iran. Journal of Applied Sciences and Environmental Management. 2011;**15**(4):589-596

[3] Hong S, Deng H, Zheng Z, et al. The influence of variations in actual evapotranspiration on drought in China's Southeast River basin. Scientific Reports. 2023;**13**:21336. DOI: 10.1038/s41598-023-48663-8

[4] Abad MBJ, Zade AH, Rohina A, Delbalkish H, Mohagher SS. The effect of climate change on flow regime in Basher River using two meteorological and hydrological standards. International Journal of Agriculture and Crop Sciences. 2013;**5**:2852-2857

[5] McKee TB, Doesken NJ, Kleist J. The relationship of drought frequency and duration of time scales. In: Eighth Conference on Applied Climatology. Anaheim, CA: American Meteorological Society; 1993. pp. 179-186

[6] Vicente-Serrano SM, Begueria S, López-Moreno JI. A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. Journal of Climate. 2010;**23**:1696-1718

[7] Palmer WC. Meteorological Drought. Vol. 45. Washington, DC: U.S. Weather Bureau Research Paper; 1965. p. 58

[8] Modarres R. Streamflow drought time series forecasting. Stochastic Environmental Research and Risk Assessment. 2007;**21**:223-233

[9] Shafer BA, Dezman LE. Development of a surface water supply index (SWSI) to assess the severity of drought conditions in snowpack runoff areas. In: Proceedings of the West Snow Conference. Fort Collins: Colorado State University; 1982. pp. 164-175

[10] World Meteorological Organisation (WMO). Standardized Precipitation Index: User Guide. Geneva: WMO; 2012

[11] Rouault M, Richard Y. Intensity and spatial extent of droughts in southern Africa. Geophysical Research Letters. 2005;**32**:L15702. DOI: 10.1029/2005GL022436

[12] Türk M, Tatl H. Use of the standardized precipitation index (SPI) and a modified SPI for shaping drought probabilities over Turkey. International Journal of Climatology. 2009;**29**(15):2270-2282

[13] Szalai S, Szinell C. Comparison of two drought indices for drought monitoring in Hungary—A case study. In: Vogt JV, Somma F, editors. Drought and Drought Mitigation in Europe. Dordrecht: Springer; 2000. pp. 127-147. DOI: 10.1007/978-94-015-9472-1_12

[14] Hayes M, Svoboda M, Wall N, Widhalm M. The Lincoln declaration on drought indices: Universal meteorological drought index recommended. Bulletin of the American Meteorological Society. 2010;**92**(4):485-488. DOI: 10.1175/2010BAMS3103.1

[15] Mosad A, Alazba AA. Drought forecasting using stochastic models in a hyper-arid climate. Atmosphere. 2015;**6**:410-430

[16] Vicente-Serrano SM, Lasanta T, Gracia C. Aridification determines changes in leaf activity in *Pinus halepensis* forests under semiarid Mediterranean climate conditions. Agricultural and Forest Meteorology. 2010;**150**:614-628

[17] Sohn S-J, Ahn J-B, Tam C-Y. Six month-lead downscaling prediction of winter to spring drought in South Korea based on a multimodel ensemble. Geophysical Research Letters. 2013;**40**(3):579-583

[18] Theron SN et al. Using SPI and SPEI for baseline probabilities and seasonal drought prediction in two agricultural regions of the Western cape, South Africa. Water SA. 2023;**49**(2):103-116

[19] Nembilwi N, Chikoore H, Kori E, Munyai RB, Manyanya TC. The occurrence of drought in Mopani District municipality, South Africa: Impacts, vulnerability and adaptation. Climate. 2021;**9**(4):61. DOI: 10.3390/cli9040061

[20] Masupha TE, Moeletsi ME. Use of standardized precipitation evapotranspiration index to investigate drought relative to maize, in the Luvuvhu River catchment area, South Africa. Physics and Chemistry of the Earth, Parts A/B/C. 2017;**102**:1-9

[21] Edosaa DC, Woyessa YE, Welderufael WA. Spatiotemporal analysis of drought using self-calibrating palmer drought severity index in the central region of South Africa. Theoretical and Applied Climatology. 2016;**126**:643-657

[22] Botai CM, Botai JO, Dlamini LC, Zwane NS, Phaduli E. Characteristics of droughts in South Africa: A case study of Free State and northwest provinces. Water. 2016;**8**:439. DOI: 10.3390/w8100439

[23] Ren M, Jiang S, Ren L, et al. A new non-stationary standardized streamflow index using the climate indices and the optimal anthropogenic indices as covariates in the Wei River basin, China. Journal of Hydrology: Regional Studies. 2024;**51**:101649. DOI: 10.1016/j.ejrh.2023.101649

[24] Anderson ES, Schilling KE. Expanding the applications of the standardized streamflow index through regionalization. Journal of the American Water Resources Association. 2024;**60**(4):837-850. DOI: 10.1111/1752-1688.13205

[25] Tijdeman E, Stahl K, Tallaksen LM. Drought characteristics derived based on the standardized streamflow index: A large sample comparison for parametric and nonparametric methods. Water Resources Research. 2020;**56**:e2019WR026315

[26] Mukhawana MB, Kanyerere T, Kahler D. Review of in-situ and remote sensing-based indices and their applicability for integrated drought monitoring in South Africa. Water. 2023;**15**:240. DOI: 10.3390/w15020240

[27] Botai CM, Botai JO, de Wit JP, et al. Hydrological drought assessment based on the standardized streamflow index: A case study of the three cape provinces of South Africa. Water. 2021;**13**:3498. DOI: 10.3390/w13243498

[28] Fung KF, Huang YF, Koo CH. Assessing drought conditions through temporal pattern, spatial characteristic and operational accuracy indicated by SPI and SPEI: Case analysis for peninsular Malaysia. Natural Hazards. 2020;**103**:2071-2101

[29] Keyantash J, Dracup JA. The quantification of drought: An evaluation of drought indices. Bulletin of the American Meteorological Society. 2002;**83**:1167. DOI: 10.1175/

1520-0477(2002)083<1191:TQODAE>2.3.CO;2

[30] Barua S, Ng AWM, Perera BJC. Drought assessment and forecasting: A case study on the Yarra River catchment in Victoria, Australia. Australian Journal of Water Resources. 2012;**15**(2):95-108. DOI: 10.7158/W10848.2012.15.2

[31] Vicente-Serrano SM, Beguería S, Lorenzo-Lacruz J, Camarero JJ, López-Moreno JI, Azorin-Molina C, et al. Performance of drought indices for ecological, agricultural, and hydrological applications. Earth Interactions. 2012;**16**(10):1-27

[32] Usman MT, Reason CJC. Dry spell frequency and their variability over southern Africa. Climate Research. 2004;**26**:199-211

[33] Chandler RE, Wheater GS. Analysis of rainfall variability using generalized linear models: A case study from the west of Ireland. Water Resources Research. 2002;**38**(10):1192-1202

[34] Mishra AK, Desai VR. Drought forecasting using feed-forward recursive models. Ecological Modelling. 2006;**198**:127-138

[35] Bezdan J, Bezdan A, Blagojevic B, Mesaroš M, Pejic B, Vraneševic M, et al. SPEI-based approach to agricultural drought monitoring in Vojvodina region. Water. 2019;**11**:1481

[36] Allen RG, Pereira LS, Raes D, et al. Crop evapotranspiration: Guidelines for computing crop water requirements. In: FAO Irrigation and Drainage Paper 56. Rome: FAO; 1998

[37] Hosking JRM. L-moments: Analysis and estimation of distributions using linear combinations of order statistics. Journal of the Royal Statistical Society Series B (Statistical Methodology). 1990;**52**:105-124

[38] Abramowitz M, Stegun IA, editors. Handbook of Mathematical Functions. New York: Dover; 1965

[39] Farahmand A, Agha KA. A generalized framework for deriving nonparametric standardized drought indicators. Advances in Water Resources. 2015;**76**:140-145. DOI: 10.1016/j.advwatres.2014.11.012

[40] Gringorten I. A plotting rule for extreme probability paper. Journal of Geophysical Research. 1963;**68**:813-814. DOI: 10.1029/JZ068i003p00813

[41] Entekhabi D, Rodriguez-Iturbe I, Castelli F. Mutual interaction of soil moisture state and atmospheric processes. Journal of Hydrology. 1996;**184**:3-17

[42] Edwards DC, McKee TB. Characteristics of 20th century drought in the United States at multiple time scales. In: Climatology Report No. 97-2. Fort Collins: Colorado State University, Department of Atmospheric Science; 1997

[43] Mann HB. Non-parametric tests against trend. Econometrica. 1945;**13**(3):245-259

[44] Kendall M, Gibbons JD. Rank Correlation Methods. 5th ed. London: Edward Arnold; 1990

[45] Helsel DR, Hirsch RM. Chapter A3. In: Statistical Methods in Water Resources Techniques of Water Resources Investigations. Book 4. Reston, VA: U.S. Geological Survey; 2002. p. 522. Available from: http://water.usgs.gov/pubs/twri/twri4a3

[46] Zhang X, Lucie AV, Hogg WD, Niitsoo A. Temperature and precipitation

trends in Canada during the 20th century. Atmosphere. 2000;**38**:395-429

[47] Nenwiini S, Kabanda TA. Trends and variability assessment of rainfall in Vhembe, South Africa. Journal of Human Ecology. 2013;**42**(2):171-176

[48] Mathivha FI, Mabala L, Matimolane S, Mbatha N. El Niño-induced drought impacts on reservoir water resources in South Africa. Atmosphere. 2024;**15**(3):249. DOI: 10.3390/atmos15030249

[49] Damberg L, Agha KA. Global trends and patterns of drought from space. Theoretical and Applied Climatology. 2014;**117**:441-448

[50] Golian S, Mazdiyasni O, Agha KA. Trends in meteorological and agricultural droughts in Iran. Theoretical and Applied Climatology. 2015;**119**:679-688. DOI: 10.1007/s00704-014-1139-6

[51] Barua S. Drought assessment and forecasting using a nonlinear aggregated drought index [dissertation]. Melbourne: Victoria University; 2010

[52] Mason SJ, Tyson PD. The occurrence and predictability of droughts over southern Africa. In: Wilhite DA, editor. Drought: A Global Assessment. London: Routledge; 2000. pp. 113-134

[53] Chikoore H. Drought in Southern Africa: Structure, characteristics and impacts [dissertation]. Kwa Dlangezwa: University of Zululand; 2016

[54] Mathivha FI, Nkosi M, Mutoti MI. Evaluating the relationship between hydrological extremes and groundwater in Luvuvhu River catchment, South Africa. Journal of Hydrology: Regional Studies. 2021;**37**:100897. DOI: 10.1016/j.ejrh.2021.100897

[55] Mazibuko SM, Mukwada G, Moeletsi ME. Assessing the frequency of drought/flood severity in the Luvuvhu River catchment, Limpopo Province, South Africa. Water SA. 2021;**47**(2):172-184. DOI: 10.17159/wsa/2021.v47.i2.10913

[56] Yang Y, McVicar TR, Donohue RJ, Zhang Y, Roderick ML, Chiew FHS, et al. Lags in hydrologic recovery following an extreme drought: Assessing the roles of climate and catchment characteristics. Water Resources Research. 2017;**53**:4821-4837. DOI: 10.1002/2017WR020683

[57] Kim DW, Byun HR, Choi KS. Evaluation, modification, and application of the effective drought index to 200-year drought climatology of Seoul, Korea. Journal of Hydrology. 2009;**378**:1-12. DOI: 10.1016/j.jhydrol.2009.08.021

[58] Van Loon AF. Hydrological drought explained. Wiley Interdisciplinary Reviews Water. 2015;**2**:359-392

[59] Odiyo JO, Makungo R, Nkuna TR, Chikoore H. Hydrological Modelling of Climate Change Impacts for Development of Adaptation Strategies: The Case of Luvuvhu River Catchment, Limpopo. Pretoria, South Africa: Water Research Commission; 2020

[60] Botai CM, Botai JO, De Wit JP, Ncongwane KP, Adeola AM. Drought characteristics over South Africa: A detailed assessment based on the standardized precipitation evapotranspiration index (SPEI). Water SA. 2017;**43**(4):612-626

[61] Kanjere M, Thaba-Nkadimene K, Lekoana M. Water shortage management at Letaba water catchment area in Limpopo Province, South Africa. Mediterranean Journal of Social Sciences. 2014;**5**:1356. DOI: 10.5901/mjss.2014.v5n27p1356

[62] Rankoana SA. Climate change impacts on water resources in a rural community in Limpopo province, South Africa: A community-based adaptation to water insecurity. International Journal of Climate Change Strategies and Management. 2020;**12**(5):587-598. DOI: 10.1108/IJCCSM-04-2020-0033

[63] Rakgwale TJ, Oguttu JW. The impact of the 2014-2016 drought in Greater Letaba local municipality: How the farmers coped and factors that were significantly associated with loss of animals. International Journal of Disaster Risk Reduction. 2020;**50**:101869. DOI: 10.1016/j.ijdrr.2020.101869

[64] Scheiter S, Pfeiffer M, Behn K, Ayisi K, Siebert F, Linstädter A. Managing southern African rangeland systems in the face of drought: A synthesis of observation, experimentation and modeling for policy and decision support. In: von Maltitz GP, et al. Sustainability of Southern African Ecosystems under Global Change. Ecological Studies, 248. Cham: Springer; 2024. pp. 1-16. DOI: 10.1007/978-3-031-10948-5_16

[65] Maluleke P, Moeletsi ME, Tsubo M. Analysis of climate variability and its implications on rangelands in the Limpopo Province. Climate. 2024;**12**(1):2. DOI: 10.3390/cli12010002

[66] Baade J, Aucamp I, Collett A, et al. Soil erosion, research and soil conservation policy in South Africa. In: Maltitz G, Midgley G, Veitch J, et al., editors. Sustainability of Southern African Ecosystems under Global Change: Science for Management and Policy Interventions. Cham: Springer; 2024. pp. 335-368. DOI: 10.1007/978-3-031-10948-5_29

[67] Malherbe J, Smit I, Wessels K, Beukes P. Recent droughts in the Kruger National Park as reflected in the extreme climate index. African Journal of Range & Forage Science. 2020;**37**:1-17. DOI: 10.2989/10220119.2020.1718755

[68] Konovalov IB, Beekmann M, Kuznetsova IN, Yurova A, Zvyagintsev AM. Atmospheric impacts of the 2010 Russian wildfires: Integrating modelling and measurements of an extreme air pollution episode in the Moscow region. Atmospheric Chemistry and Physics. 2011;**11**:10031-10056. DOI: 10.5194/acp-11-10031-2011

[69] Tfwala CM, van Rensburg LD, Schall R, Dlamini P. Drought dynamics and interannual rainfall variability on the Ghaap plateau, South Africa, 1918-2014. Physics and Chemistry of the Earth, Parts A/B/C. 2018;**107**:1-7. DOI: 10.1016/j.pce.2018.09.003

[70] Shikwambana S, Malaza N, Shale K. Impacts of rainfall and temperature changes on smallholder agriculture in the Limpopo Province, South Africa. Water. 2021;**13**(20):2872. DOI: 10.3390/w13202872

[71] Franchi F, Mustafa S, Ariztegui D, et al. Prolonged drought periods over the last four decades increase flood intensity in southern Africa. Science of Total Environment. 2024;**924**:171489. DOI: 10.1016/j.scitotenv.2024.171489

[72] Makungo R, Mashinye MD. Long-term trends and changes in rainfall magnitude and duration in a semi-arid catchment, South Africa. Journal of Water and Climate Change. 2022;**13**(6):2319-2336

Edited by Humood Naser and Sener Akıncı

This book, *Restoring Ecosystems and Assessing Drought Risk - Approaches and Practices*, highlights interdisciplinary research and case-based insights focused on ecosystem restoration and drought risk monitoring. It presents five chapters that span diverse ecological regions and methodological approaches. Chapter 1 examines the long-term ecological and social impacts of plantation forests in the Ethiopian highlands. It emphasizes the role of effective forest management in restoring degraded landscapes, which includes mixed-species plantations and local knowledge integration. Chapter 2 focuses on peri-urban landscapes, emphasizing the importance of local engagement and spatial planning in enhancing agri-ecosystem services. It provides a participatory planning model aimed at integrating ecosystem services into urban development policies. Chapter 3 provides an important case study on emerging soil contaminants and the need for baseline assessments and targeted restoration protocols in floodplain environments affected by industrial and geochemical dynamics. Chapter 4 investigates historical drought trends using key meteorological indices. It demonstrates increasing drought frequency and severity, particularly in southern Portugal, and calls for improved planning and mitigation strategies. Chapter 5 evaluates multiple drought indices to identify the most effective tools for capturing complex drought dynamics in South Africa. It emphasizes the importance of a more comprehensive assessment of drought conditions and recommends enhanced monitoring for adaptive water resource management. The book provides a comprehensive overview of contemporary research and approaches in ecosystem restoration and drought risk assessment. It offers valuable insights for researchers, practitioners, planners, and policy makers working across disciplines to address the twin challenges of ecosystem degradation and climate vulnerability.

J. Kevin Summers, Environmental Sciences Series Editor

ISSN 2754-6713
ISBN 978-1-83634-903-7
9 781836 349037

Published in London, UK

IntechOpen