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REVIEW ARTICLE

Strengthening drought management through institutional partnerships in Tamil Nadu

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Abstract

Tamil Nadu, with its distinctive climatic conditions and significant reliance on monsoon rainfall, frequent grapples with drought. Effective drought management in the state relies on the collaborative efforts of diverse institutions, including government institutions, public-private partnerships, non-governmental organizations and research institutions. This review evaluates the strategies implemented by these entities-such as water resource optimization, agricultural interventions, the promotion of drought-resistant crop varieties and the implementation of sustainable farming practices. It further assesses the policy frameworks, institutional responsibilities and cooperative actions that shape drought management initiatives. Through a comprehensive analysis of institutional responses to water scarcity in Tamil Nadu, this review provides valuable insights for enhancing policy development and fostering more resilient drought management practices in the future.

Keywords: climate resilience; drought management; institutional roles; policy frameworks; Tamil Nadu

Introduction

Climate change has emerged as a critical concern worldwide of the 21st century, resulting in extensive socio-economic and environmental consequences (1). According to the Intergovernmental Panel on Climate Change, Climate change involves prolonged alterations in climate patterns, exacerbated by human activities. These shifts occur through both incremental changes, such as rising temperatures and modified precipitation patterns and sudden climatic disasters like floods and cyclones and droughts, thereby jeopardizing both human systems and natural ecosystems. Farming communities are particularly vulnerable to these risks due to their heavy reliance on seasonal rainfall and the stability of local ecosystems (2, 3).

Among the various climate-related hazards, droughts represent one of the most damaging and slow-onset climate-related threats. They reduce precipitation, drain soil moisture, deplete groundwater and negatively impact livestock systems and crop productivity (4, 5). In India, both dry and typically humid regions are affected by frequent and widespread droughts. These events are often caused or made worse by phenomenon like El Niño, which interferes with monsoon cycles (6, 7). These slow onset of drought progressively undermines food security, increase poverty and places significant strain on regional economies (8, 9).

Drought management, however, is not merely a technological challenge but a fundamentally institutional one. Institutions influence how societies understand, prepare for and respond to climate-related hazards. These range from formal structures-such as government agencies and legal frameworks-to informal mechanisms like community norms and traditional practices (10, 11). Effective drought management strategies depend on the presence of strong institutional capacity characterized by effective governance frameworks, informed risk perception and empowered decision making as well as adaptive capacity, which includes access to material assets, reliable infrastructure and resilient financial mechanisms (12, 13).

In India and other countries, institutional responses to drought have often been reactive, fragmented and hindered by jurisdictional overlaps (14, 15). Despite the capacity of public and research institutions to facilitate knowledge exchange, build capacity and coordinate resources, current drought strategies frequently fail to integrate scientific insights with local conditions and governance needs (16-18).

Understanding the institutional aspects of drought risk reduction is therefore vital, especially in complex, multi-tiered governance systems like India's. Coordinated efforts across national, state and local levels are crucial for responsive and integrated action (19, 20). This review

synthesizes current literature to examine how institutions influence drought management strategies, emphasizing the integration of adaptive and institutional capacities to build long-term resilience. By doing so, it aims to identify key gaps and inform future interventions for managing drought in the context of a changing climate (21).

Methodology

A comprehensive literature synthesis was conducted by retrieving peer-reviewed publications, reports and newspaper articles from a variety of database and sources, including

- Scopus
- Google scholar
- Web of Science
- CeRA
- AGRIS
- Official government portals
- ERIC

Scopus

To comprehensively examine the role of institutional partnerships in drought management in Tamil Nadu, a systematic search was conducted using the scopus database. This platform was selected for its difficult collection of high-quality, peer-reviewed articles, conference proceedings and institutional reports. The search was designed to identify literature that investigates institutional frameworks, collaborative approaches and policy-driven solutions in the context of drought mitigation.

Fig. 1 illustrated the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram for this study. The review process followed the PRISMA framework to ensure a clear and structured approach. A comprehensive search strategy was employed to retrieve relevant and credible literature regarding institutional roles in climate change management. Targeted keywords and boolean operators such as "AND" and "OR" were used to refine the search within the scopus database, ensuring fine-tuned to yield focused and high-quality results. The search string included:

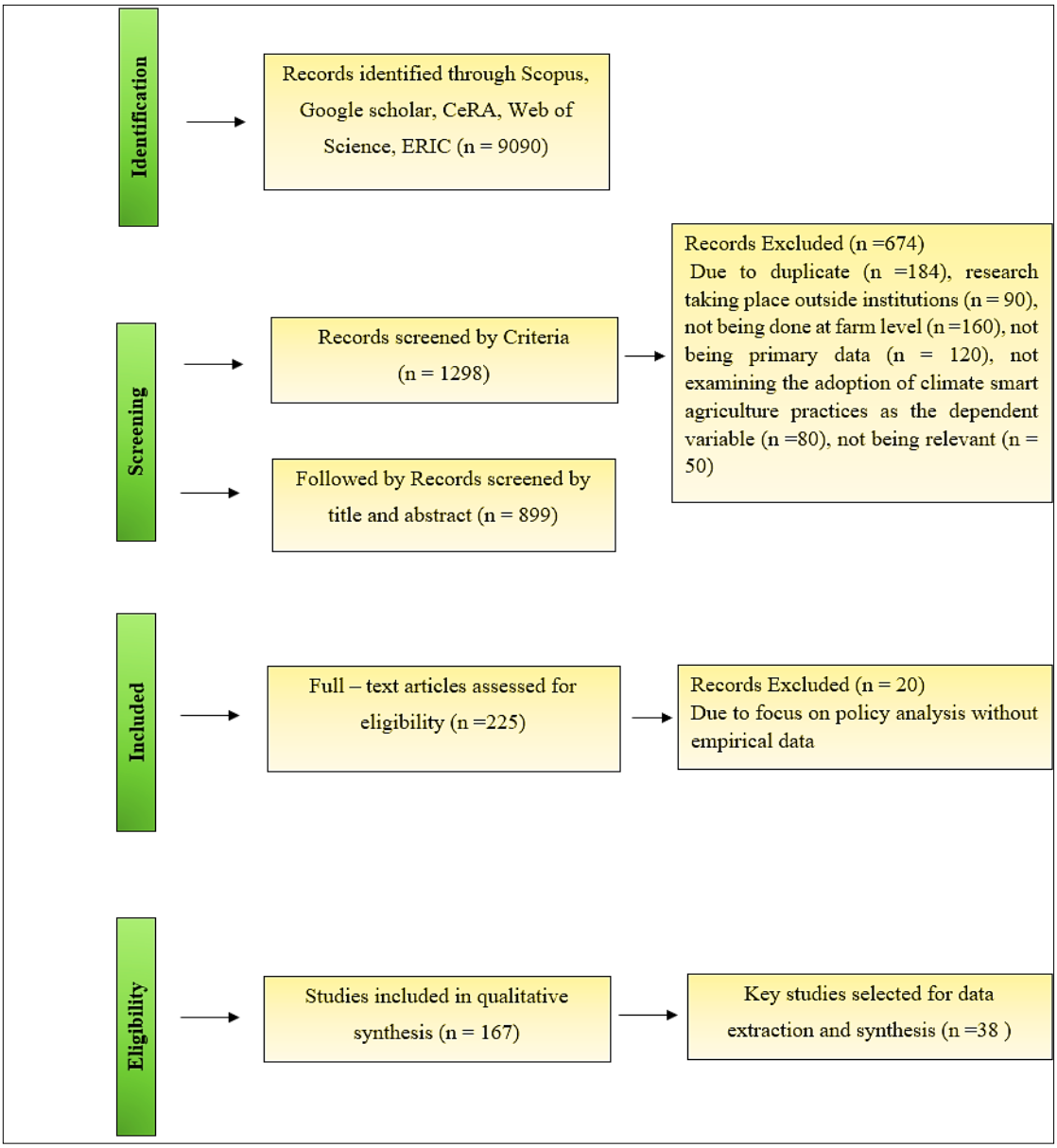

Fig. 1. Prisma flowchart.

("institution" OR "organization" OR "agency") AND ("mitigation" OR "reduce" OR "alleviate" OR "adapt") AND ("climate change" OR "global warming" OR "environmental change" OR "climate adaptation" OR "climate impact" OR "climatic variation" OR "ecological shift")

To further refine the selection, well-defined inclusion and exclusion criteria were applied during the initial screening process, as detailed in Table 1.

Google scholar

To gain deeper insights into the role of institutional partnerships in drought management in Tamil Nadu, a detailed literature review was conducted using google scholar. Relevant studies, including peer-reviewed articles, policy documents and case studies, were identified through targeted searches. The review focusses the collaborative efforts of institutions in addressing drought-related challenges, with a specific focus on agricultural extension services, climate resilience strategies and the effectiveness of institutional frameworks in the region.

As in the previous search, clearly defined inclusion and exclusion criteria were applied during the initial screening process to ensure the relevance and quality of the literature selected, as presented in Table 2.

Results and Discussion

Drought analysis over Tamil Nadu

The average annual rainfall in Tamil Nadu is 945 mm, of which 48 % is received during the northeast monsoon (NEM) and 32 %from the southwest monsoon (SWM). The state experienced its most severe drought in over 140 years during 2016–2017, with the NEM recording a deficit of 62 %. This event affected 3.5 million ha and led to the declaration of drought in over 13300 villages. The economic loss was estimated at USD 3 billion, of which only USD 400 million was insured. Paddy procurement dropped sharply by 84 %, dropping from 8.83 to 1.37 lakh t, prompting the state government to seek ₹39565 crore in central aid. Similarly, the drought in 2002 resulted in crop losses worth ₹1332 crore and cause a reduction of over 13 crore rural workdays across 19 districts. With low storage in the Mettur Dam (12.913 TMC ft vs. its 93 TMC ft capacity), water scarcity was worsened by limited cauvery inflow from Karnataka (21-24).

An analysis of historical droughts in Tamil Nadu using three major indices - the Deviation Index (DI), Palmer Drought Severity Index (PN) and Standardized Precipitation Index (SPI). It reveals significant variation in drought frequency depending on the metric applied. As shown in Table 3, droughts identified by all three indices occurred in about 28 % of the years, indicating substantial overlap among meteorological, hydrological and agricultural drought events. In contrast, the SPI alone detected drought conditions in 47 % of the years, underlining its effectiveness in capturing rainfall deficits. These instances highlight the pressing need for stronger institutional partnerships in drought management (24).

Drought management framework

Fig. 2 illustrates a comprehensive model that underscores the integration of technological, institutional and community-driven approaches. The review highlights the frameworks' alignment with key strategies such as the promotion of drought-tolerant crops, the adoption of micro-irrigation systems and the use of advanced decision-support tools, which enhance adaptive capacity in vulnerable regions. Institutional roles, including Krishi Vigyan Kendras (KVKs) and public-private partnerships, are pivotal in bridging the gap between policy and practice. However, the challenges such as limited funding and policy fragmentation hinder implementation. Addressing these gaps through tailored, region-specific strategies is essential for ensuring sustainable and resilient drought mitigation efforts (24).

State government institutions in drought management

Government responses to drought in India are often reactive, emphasizing coordination and timeliness and typically fall under the broader category of "crisis management" (25). The primary responsibility for managing drought lies with the state governments. However, given the diverse manifestation of drought, each state and its policymakers have adopted different definitions and frameworks for understanding and responding to drought conditions (26). Over the past two decades, India has experienced six major droughts: in 2002, 2004, 2009, 2012, 2013 and 2016, each event posing unique challenges to state's drought management strategies (27).

In Tamil Nadu, recent severe droughts have caused significant agricultural distress, rural hardships and shortages of drinking water and fodder. As a result, the state government declared Tamil Nadu as drought-hit area in 2012-2013 and again in 2016-17 (28). These declarations highlight the recurring nature of drought events and the pressing need for effective drought management responses to mitigate

Table 1. Highlights the inclusion & exclusion criteria by using scopus

Criteria	Inclusion	Exclusion
Time period	2019 - 2024	<2018
Document type	Article	Conference papers, book chapters, review, editorial
Subject area	Environmental science, social science, agricultural and biological science	All other subject area
Keywords	Institution, organization, agency, mitigation, reduce, alleviate, adapt, drought, climate adaptation, drought impact, climatic variation, ecological shift	All other keywords
Source type	Journal	Trade journal
Publication stage	Final	Press
Open access	All open access	Restricted access
Languages	English	Non - english

Table 2. Highlights the Inclusion & exclusion criteria by using google scholar

Process	Key actions
Key concepts	Institutional partnership, drought management, Tamil Nadu, climate-smart agriculture, extension systems, public-private partnerships
Search strings	Use Boolean operators: - "institutional partnership" AND "drought management" AND "Tamil Nadu"- "agricultural extension" AND "climate resilience" - "KVK" AND "drought adaptation" AND "Tamil Nadu"
Apply search filters	Time range: 2018-2024 Language: English Article types: journal articles, reports, theses, working papers
Screening for search results	Reviewed top 200 results per query manually Selected based on relevance of title and abstract
Retrieving for full texts	Accessed via open-access links, institutional subscriptions (CeRA), or direct download Saved using Zotero reference manager
Types of literature collected	Peer-reviewed journal articles Government reports (e.g., from MoA, TNSDMA, TNAU) NGO reports (e.g., MSSRF, DHAN Foundation) Academic theses from Indian universities
Inclusion criteria applied	Focus on institutional mechanisms and partnerships Geographical scope: Tamil Nadu Relevant to drought/climate resilience.
Exclusion criteria applied	Articles with no mention of institutional roles Duplicate or inaccessible texts
Data extraction process	Extracted metadata: authors, year, location, type of institution, type of partnership, drought phase addressed, gender inclusion
Integration with analysis	Organized into thematic categories (e.g., extension roles, PPP models, governance gaps)

their socio-economic impacts.

In response to the growing challenge, several states have made significant progress in formulating Drought Contingency Plans (DCPs), which have become essential tools for minimizing the adverse effects of drought on agricultural output and rural livelihoods (29). However, drought management policies and approaches still vary significantly across states, with each state adopting its own strategies based on local needs and conditions. This variance reflects the complexity of managing droughts as slow-onset disasters that do not have a clearly defined start or end, complicating monitoring and response efforts for governments, policymakers and researchers (30).

There is an urgent need for a comprehensive institutional framework within each state to monitor critical drought indicators such as rainfall patterns, soil moisture levels, crop sowing data and crop loss assessments. This review emphasizes the importance of understanding the mechanisms for monitoring and declaring droughts at the state level and evaluating the effectiveness of these mechanisms in improving drought management (26).

Drought impacts at the regional level often transcend political and jurisdictional boundaries, making it challenging for a single entity, organization, or industry to adequately respond to the risks associated with such large-scale events. Given this complexity, a national drought policy should establish clear guidelines for managing drought and its impacts, with an emphasis on risk management and preparedness (31, 32). Effective drought policies should focus on mitigation actions, particularly through the use of preparedness strategies, in order to reduce vulnerabilities and enhance resilience in drought-prone regions (33).

Table 3. Drought years under the different drought indices (24)

Criteria applied	Years identified as	Years %
All three criteria (DI,	1873, 1875, 1876, 1878,	28 %
Two criteria (DI, SPI)	1871, 1873, 1875, 1876,	45 %
Two criteria (PN, SPI)	1873, 1875, 1876, 1878, 1881, 1889, 1892, 1894,	28 %
SPI alone	1871, 1873, 1875, 1876,	47 %

Although significant progress has been made in establishing state-level drought management frameworks, there remains a critical need for a more integrated and coordinated national approach. Strengthening institutional capacities, improving data collection and analysis and fostering inter-state cooperation will be crucial for enhancing drought preparedness and response across India

Government initiatives and programs to mitigate drought in Tamil Nadu

The government of Tamil Nadu has implemented a range of initiatives and programs aimed at mitigating the impacts of drought (34). These efforts focus on improving water resource management, promoting sustainable agricultural practices and enhancing the resilience of rural communities (35). The twin objectives of water conservation and soil erosion prevention, both fundamental to the agriculture sector are being achieved through various programmes of Tamil Nadu Watershed Development Agency (TAWDEVA) (24).

TAWDEVA established in 2002, is responsible for implementing various watershed development programmes as follows:

•Drought Prone Areas Programme (DPAP)

•Integrated Wasteland Development Programme (IWDP)

•National Watershed Development Project for Rainfed Areas (NWDPRA)

•Watershed Development Fund (WDF)

•Integrated Watershed Management Programme (IWMP)

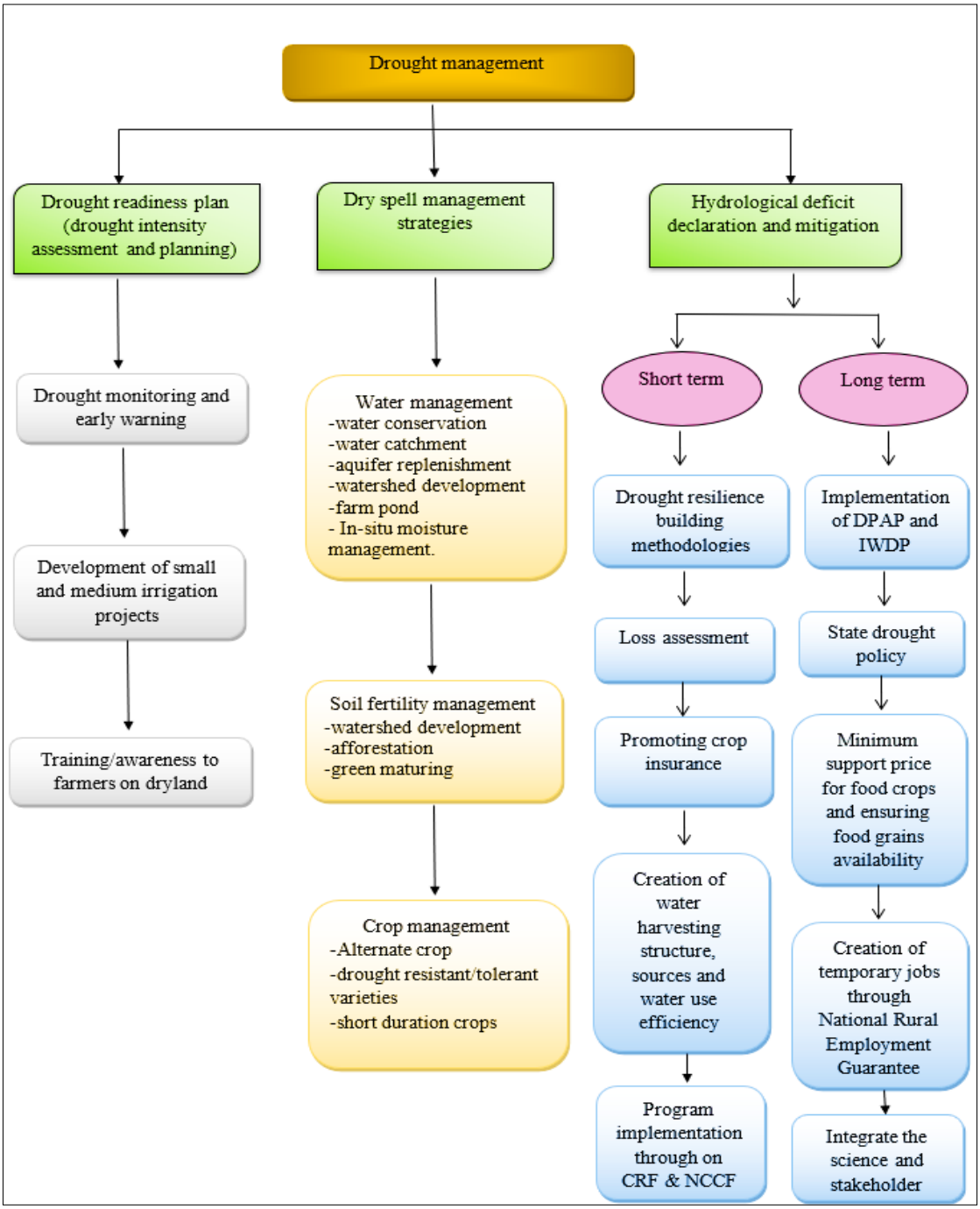

Fig. 2. Drought management framework (24)**.**

Additionally, TAWDEVA serves as the Nodal Agency for various State / Central schemes such as,

•National Agriculture Development Programme (NADP)

•National Food Security Mission (NFSM)

Agriculture Technology Management Agency (ATMA)

•Agriculture Resource Information Systems and Networking (AGRISNET)

•National Project on Management of Soil Health & Fertility

As illustrated in Table 4**,** the success metrics of these watershed development programs include improved water availability, increased agricultural productivity, enhanced groundwater recharge and community participation, indicators that reflect the overall impact and sustainability of the initiatives (24, 36-41).

In addition to state-level initiatives, Tamil Nadu also benefits from several central government programs aimed at improving agricultural productivity and managing water resources. NADP, NFSM, ATMA, AGRISNET, WGDP are among the central programs that complement state efforts. TAWDEVA serves as the nodal agency for coordinating these programs, ensuring their effective implementation across the state (42).

Furthermore, traditional tank irrigation, a vital component of water management in Tamil Nadu, continues to support over 670000 ha of agricultural land, helping to sustain farming activities in drought-prone areas (24).

These policy frameworks have established an institutional structure that facilitates the coordination of multiple actors, including NGOs, the armed forces, paramilitary forces, charities and local communities (43). These groups often serve as first responders during drought crisis and play an important role in providing immediate relief (44). The government's framework offers notable

advantages, such as a unified command structure and clearly defined roles for all stakeholders, which helps prevent confusion during critical field operations. The territorial span of control ensures that there is no overlap in the roles of different organizations, while the three-tier structure-comprising operational, tactical and strategic levels-clearly differentiates the duties and responsibilities of the involved entities (45).

Tamil Nadu has adopted a multifaceted strategy to mitigate drought, combining state and central government programs with community-driven initiatives. This integrated institutional approach, involving clearly defined roles and multi-stakeholder collaboration, has substantially enhanced the state's capacity to manage drought-related challenges. Nevertheless, continued investment in the expansion and coordination of these programs will be crucial for addressing the evolving threats posed by future drought events (46).

As shown in Fig. 3, Tamil Nadu's state-level drought monitoring and management system employs a comprehensive approach that incorporates real-time monitoring technologies, decision-support tools and policy-driven actions. To ensure rapid response and preparedness, the state adopts region-specific strategies that integrate weather data, remote sensing and water resource assessments. Institutions such as the State Agricultural Departments and KVKs play a key role in disseminating relevant information to stakeholders. However, challenges related to coordination, data accessibility and limited adoption of advanced technologies often undermine the effectiveness of these systems. Optimizing drought management at the state level will require enhanced use of technology and strengthened institutional collaboration (31).

Fig. 4 illustrates India's state-level drought relief process, with a particular focus on Tamil Nadu's structured approach to recovery and mitigation. During drought relief operations, coordination between state governments, local organizations and disaster management authorities is vital. Key steps include assessing drought severity, allocating resources and implementing relief measures such as crop compensation, livelihood support and water resource management. Although these efforts provide immediate relief, challenges remain in ensuring equitable distribution and timely execution. Enhancing the effectiveness of the drought relief process will depend on integrating community participation, increasing transparency in resource allocation and reinforcing inter-departmental cooperation (24).

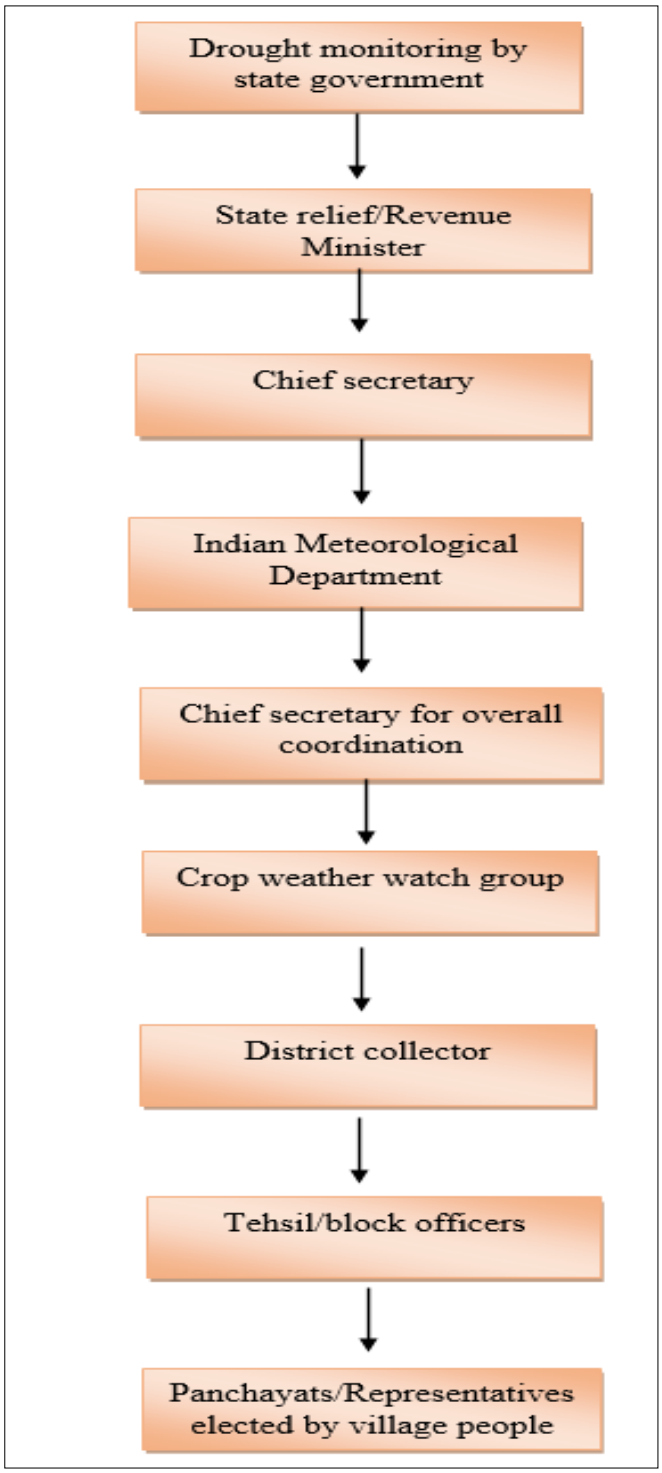

Fig. 3. Drought monitoring and management at the state level in India (Tamil Nadu) (31).

Table 4. Success metrics for watershed development programs (24, 36-41)

Dimension	Sub-dimension	Key metrics
Ecological sustainability	Soil and land quality	-Reduction in soil erosion (sediment yield, land degradation indices)-Increase in vegetative cover (NDVI, canopy cover)
	Water resource indicators	-Rise in groundwater table (pre- and post-monsoon well data)-Number and efficiency of water harvesting structures (check dams, percolation tanks)
Agricultural productivity & livelihoods	Crop and livestock productivity	-Crop diversification index- Livestock productivity and fodder availability
	Income and livelihood diversification	-Increase in household agricultural income (baseline vs. endline) -Reduction in rain-fed agriculture dependence (micro-irrigation adoption)
Social development & community participation	Institutional inclusion	-Formation and activity of watershed committees, SHGs, user groups.
	Human capacity & social capital	-Number of people trained in SWC and sustainable practices.
	Migration and social stability	-Reduction in distress/seasonal migration.
Institutional sustainability & policy integration	Asset and project sustainability	-Maintenance of assets post-project -Functionality of local institutions post-intervention
	Policy convergence	Linkages with other schemes (MGNREGA, NRLM)

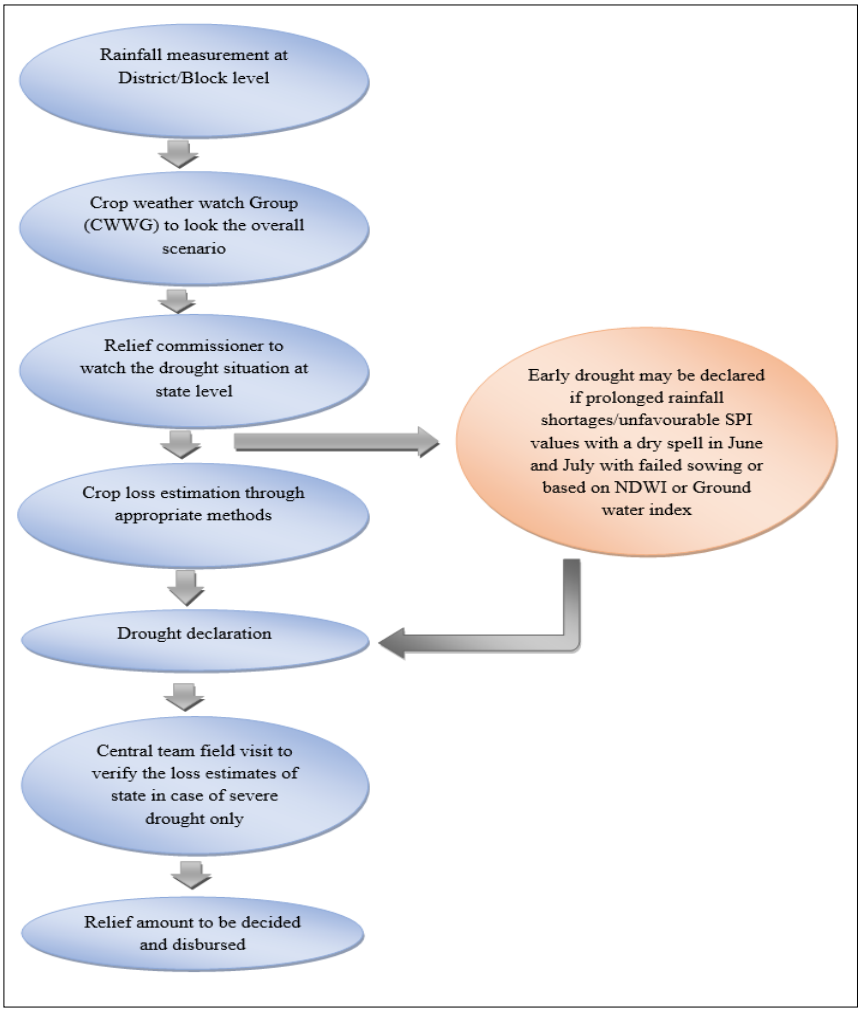

Fig. 4. Drought and relief process at the state level in India (24, 31).

Non-Governmental Organizations (NGOs) in drought management

NGOs are nonprofit, nonpartisan and volunteer-driven entities that address a broad spectrum of social and developmental challenges, often operating independently of direct governmental control (47). In times of crisis, NGOs play a vital role by responding rapidly and efficiently, attempting to minimize the impact of disasters and save lives using the resources available to them. Their capacity for rapid mobilization-unhindered by the bureaucratic delays commonly associated with governmental agencies-enables them to act with significant efficiency during emergencies (48).

NGOs play a particularly important role in mitigating the negative impacts of drought, contributing to disaster response and building long-term resilience. By offering training, raising awareness and establishing clear coordination mechanisms for disaster response, NGOs help reduce the vulnerability of communities affected by drought (49). Their efforts are not limited to immediate relief; rather, they emphasize long-term development strategies that empower communities to cope more effectively with future drought events.

Within the framework of drought management, NGOs engage in a broad range of activities across all three critical phases: pre-disaster preparedness, response during the disaster and post-disaster recovery and rehabilitation (50).

Pre-disaster role

During the pre-disaster phase, NGOs play a crucial role in enhancing resilience and preparedness. There contributions include conducting training and capacity building programs for NGO personnel and local task forces, establishing effective communication network to reach villages and districts, engaging in advocacy efforts and supporting disaster preparedness through strategic planning. NGOs also maintain consistent coordination with local administrative units, such as block control rooms, to ensure a cohesive and collaborative approach to disaster management (51).

During the disaster

When a drought strikes, NGOs activate their early warning dissemination systems to ensure that vital information reaches vulnerable groups in a timely manner. They support block-level administrations in broadcasting these warnings and provide immediate relief, including food, water, medicines and essential supplies. Additionally, NGOs play a crucial role in maintaining sanitation and hygiene during drought crises, as well as offering psychological support and first aid to those affected individuals (52). They also conduct damage assessments to determine the extent of the crisis and help prioritize response measures (50, 51).

Post-disaster role

After the immediate impacts of a drought, NGOs shift their focus to post-disaster rehabilitation and reconstruction. Their efforts include providing technical and material aid to rebuild affected areas, assist in securing financial support for

recovery and engaging in ongoing monitoring and evaluation to ensure the long-term success of recovery initiatives (51). NGO involvement during this phase is crucial in helping communities recover and built resilience to future droughts.

Beyond direct relief and rehabilitation, NGOs are increasingly recognized as effective intermediaries between government agencies and drought-affected communities. Leveraging their grassroots networks and established local presence, NGOs facilitate the bidirectional flow of information, ensuring that community needs are communicated effectively to both governmental and non-governmental stakeholders (52, 53).

In summary, NGOs play an indispensable role in drought management by providing rapid relief, supporting long-term recovery and facilitating communication between the government and affected communities. Their flexibility, local knowledge and community engagement make them a crucial partner in efforts to mitigate the impacts of drought and enhance resilience to future climate challenges.

Case study based on an NGO Initiative: "Drought resilience through traditional tank restoration: A case study of Siruthuli's NGOs work in Sivagangai, Tamil Nadu."

Fig. 5 illustrates the desilting work carried out at Udaikulam Kanmai, led by the Siruthuli NGO, as part of an initiative to enhance water storage capacity and strengthen drought resilience. This initiative was specifically aimed at enhancing the tank's water storage capacity and strengthening drought resilience in the region. Udaikulam Kanmai, an 80-acre traditional irrigation tank in Udaikulam village of Sivagangai district, Tamil Nadu, once played a central role in sustaining agriculture by filling up multiple times a year and supporting local cultivation. Over time, however, the accumulation of silt reduced its storage capacity, limiting water availability during critical periods, especially in summer months when drought conditions were more severe.

In response to growing concern among the farming community, the organization Siruthuli undertook a field survey to understand the extent of degradation. In partnership with AMM Foundation and EID Parry, a restoration initiative was launched with the primary objective of reviving the tank's functionality and enhancing its capacity to support agriculture during water-scarce periods. The project involved removing silt, reinforcing tank bunds and improving inlet and outlet channels to ensure effective water management.

As a result of these efforts, the tank is now capable of storing significantly more rainwater, thereby offering a reliable source of irrigation even during dry spells. Farmers in the region are now better equipped to manage drought conditions, with improved opportunities for cultivating multiple crop cycles. This initiative highlights the effectiveness of restoring traditional water bodies through community engagement and institutional collaboration, offering a sustainable and practical solution for drought management and resilient agriculture in vulnerable rural areas (54, 55).

Case study based on an NGO Initiative: "Drought mitigation through traditional water body restoration: A case study of Nila Oorani by DHAN and HCL foundations"

Fig. 6 illustrates the rejuvenation of Nila Oorani, a traditional pond located within the Madurai Corporation limits in Tamil Nadu, undertaken by the HCL Foundation in collaboration with the DHAN Foundation. Once a vital 1.9-acre water body, Nila Oorani had gradually lost its functional relevance and existed only in official land records. Years of neglect had reduced its water storage capacity to less than 10000 L, rendering it ineffective in addressing the water needs of the surrounding communities, especially during drought conditions.

Recognizing the critical importance of reviving such traditional water resources, the HCL Foundation-under its environmental sustainability initiative, HCL Harit-partnered with the DHAN Foundation, with active support from the Madurai Corporation and the Revenue Department, to implement a comprehensive rejuvenation program. The initiative began with a detailed topographical assessment, which guided an extensive desilting operation. This significantly increased the pond's storage capacity to over 1 million L. The silt removed during the process was strategically used to reinforce the surrounding bunds, thereby enhancing the pond's structural stability and water retention capacity.

To ensure sustainable management, a community-based organization-the Nila Oorani Conservation Association-was established, comprising local residents dedicated to the

Fig. 5. Desilting work at Udaikulam Kanmai led by Siruthuli NGO to enhance water storage and drought resilience (54, 55).

Fig. 6. Drought mitigation through traditional water body restoration: A case study of Nila Oorani by DHAN and HCL foundations (56, 57).

ongoing maintenance and preservation of the pond. This initiative exemplifies the strategic role that non-governmental organizations can play in drought mitigation by reviving traditional water systems through participatory governance and multi-stakeholder collaboration (56, 57).

Public-private partnerships (PPP) in drought management

PPPs are cooperative agreements between public and private sector organizations entities aimed at jointly providing infrastructure or public services (58).These partnerships typically involve shared funding and resource management, drawing on the respective strengths of both sectors to more effectively meet societal needs. The PPP model has gained prominence as a viable approach to harnessing the innovation, efficiency and technical expertise of private enterprises alongside the regulatory authority and social mandate of the public sector (59).

In the context of drought management, PPPs are increasingly recognized as a way to enhance the economic value and effectiveness of infrastructure and service delivery in disaster-prone regions.

The public component of PPP

The "public" aspect of PPPs primarily refers to government-led initiatives aimed at addressing social challenges, such as water scarcity, food insecurity and rural distress during droughts. In rural areas, particularly within the Tahsils (sub-districts), the public sector plays a vital role in mobilizing government resources, ensuring equitable access to water and providing essential services to communities affected by drought. Public sector entities work to formulate policies, regulate water usage and provide necessary infrastructure to manage drought impacts. The government also plays a significant role in coordinating the activities of various stakeholders and ensuring that drought management efforts align with broader national and regional development goals (60).

The private component of PPP

On the other hand, the "private" component involves private business units or companies that engage in the management of drought-related tasks as part of their corporate social responsibility (CSR). Private sector involvement typically includes funding, resource mobilization and technological innovation to address drought impacts. Private companies, through their expertise in infrastructure development, data analysis and service delivery, can support the creation of drought-resilient systems, such as efficient irrigation methods, water conservation technologies and disaster relief mechanisms. The financial aspects of these activities are primarily managed by the private sector, which can bring in investment, efficiency and scalability to drought management projects (61).

The (P3C) public -private-people-community model for drought management

The P3C model represents a comprehensive framework that integrates the public, private and community sectors in drought management. This model emphasizes the critical role of collaboration among all stakeholders-government agencies, private enterprises and local communities to ensure effective and sustainable drought mitigation. The P3C model comprises two core institutional components: the public and private sectors.

In this framework, the private sector contributes by offering tools for data analysis, decision-support systems and strategic drought management interventions. Meanwhile, the public sector is responsible for formulating policies, establishing regulatory frameworks and implementing large-scale infrastructure projects (60). Importantly, the P3C model ensures the active involvement of local communities in the planning, execution and monitoring of drought management activities, thereby promoting context-specific and sustainable solutions.

By integrating scientific data, technological innovations and local knowledge, the P3C model enhances decision-making processes. This collaborative and participatory approach addresses the complex, multifaceted challenges posed by drought, improving both preparedness and resilience in vulnerable regions.

Public-private partnerships, particularly through the P3C model, have emerged as an effective framework for drought management (62). By leveraging the combined strengths of public institutions, private sector innovation and community engagement, this model enables efficient resource allocation, the adoption of innovative solutions and the creation of a collaborative environment essential for long -term drought resilience. As droughts continue to escalate in frequency and severity, especially in vulnerable areas, the role of PPPs in drought mitigation and adaptation is expected to become increasingly pivotal.

The P3C model, as illustrated in Fig. 7, adopts an integrative approach structured around four pillars: policy, process, people and collaboration. The policy component ensures a legal and institutional foundation for drought mitigation; process focuses on the systematic implementation of monitoring and relief strategies. The people dimension highlights the significance of stakeholder engagement and capacity building, while collaboration promotes partnerships among public, private and non-governmental entities. Despite its comprehensive design, the effective implementation of the P3C model remains challenged by fragmented governance structures, limited inter-sectoral coordination and financial constraint (60).

As depicted in the flow diagram (Fig. 8), the P3C model illustrates the dynamic interaction among policy, process, people and collaboration. The model outlines a step-by-step workflow in which policy formulation initiates systematic procedures such as response planning and real-time drought monitoring. These processes actively involve various stakeholders-including farmers, local institutions and community members through participatory approaches and capacity-building initiatives. Effective implementation and resource mobilization are facilitated through coordinated efforts between public and private sectors. Although the model presents a structured and comprehensive framework, its full potential is constrained by challenges such as inconsistent policy enforcement, inadequate stakeholder collaboration and inefficient allocation of resources (60-62).

PPP based case study - "Tirupur water supply and sewerage project - A PPP approach for drought mitigation in Tamil Nadu"

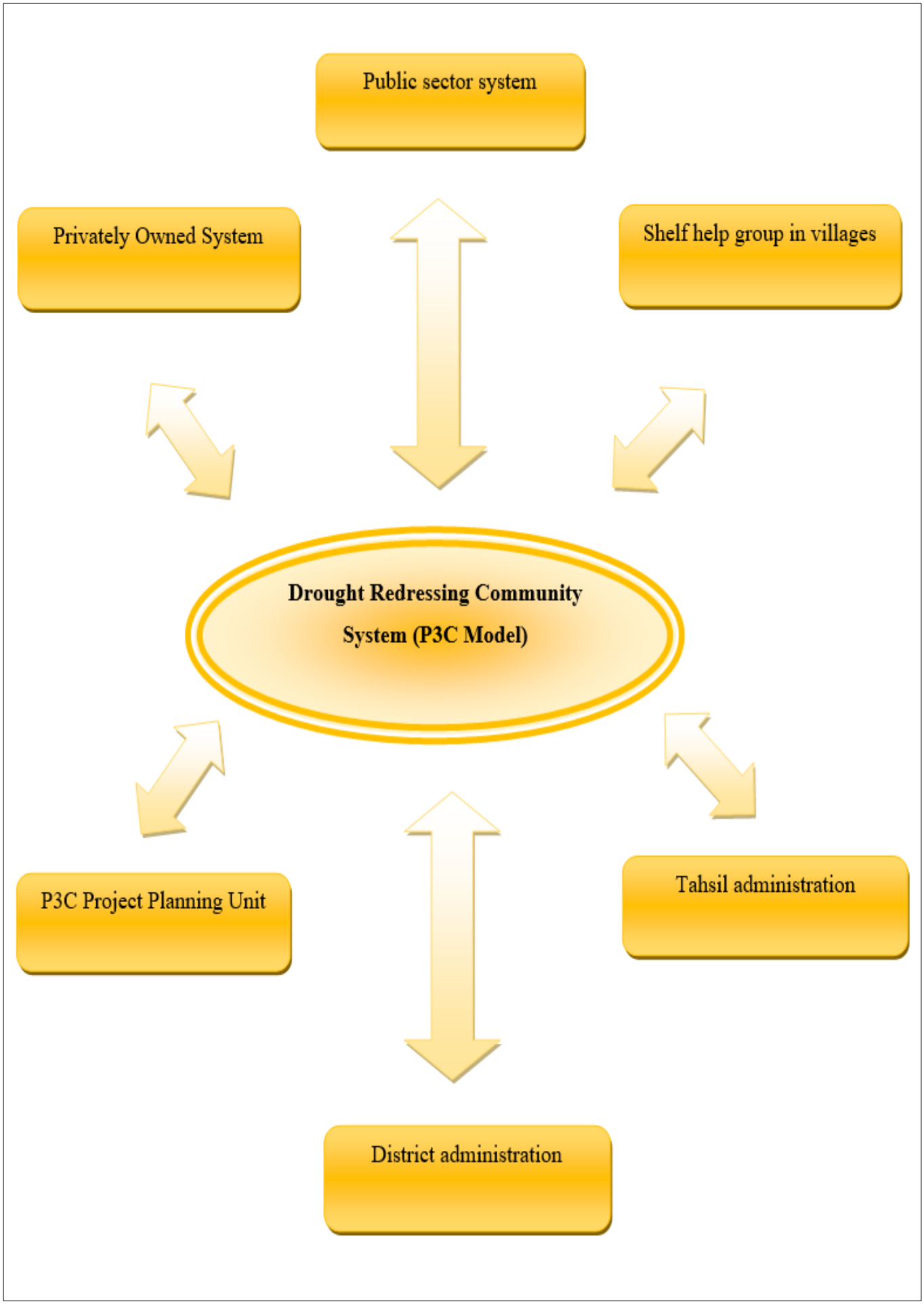

Fig. 7. P3C (Public-Private-People-Community) MODEL (60).

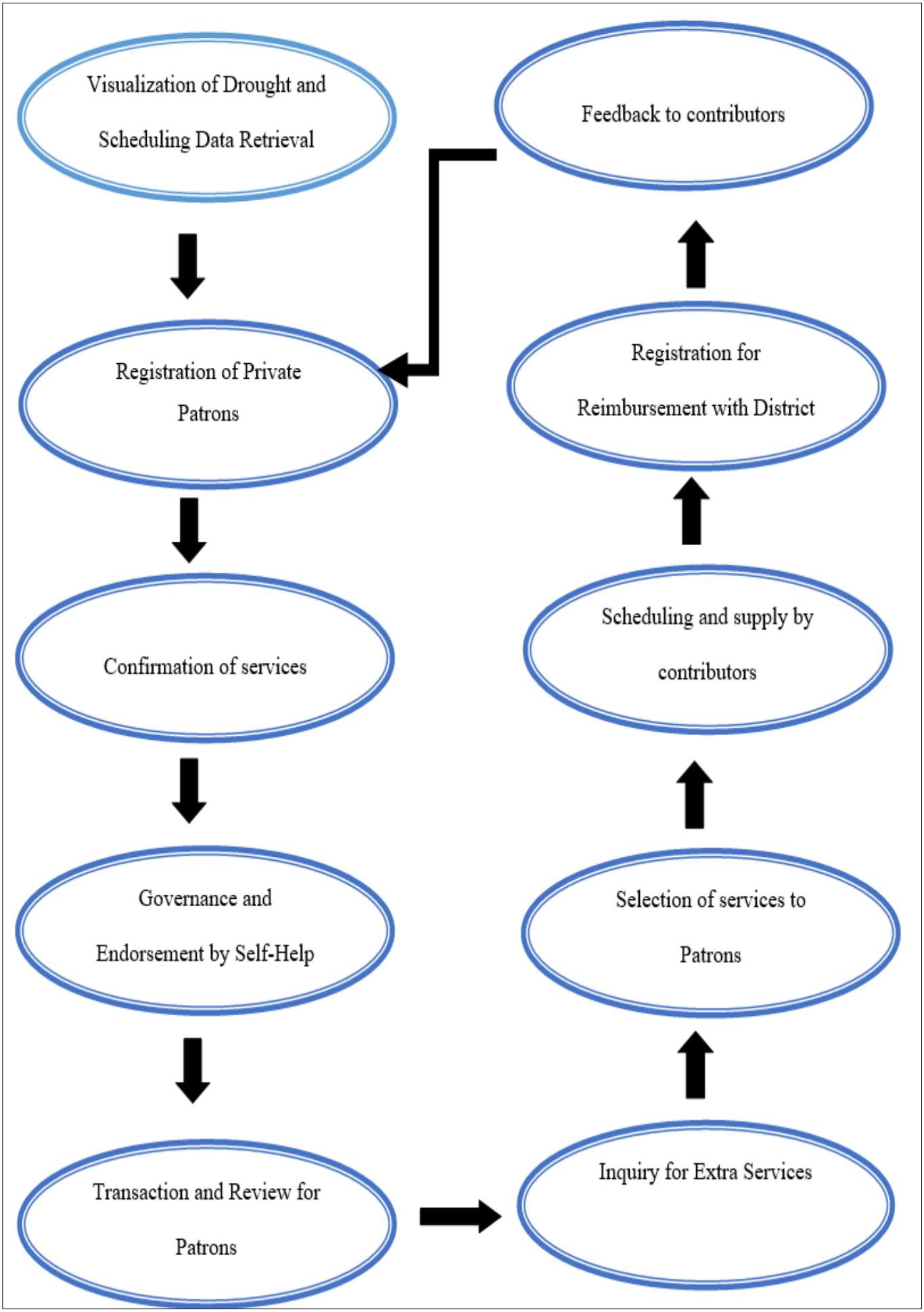

Fig. 8. Working of the P3C model as flow diagram (60-62).

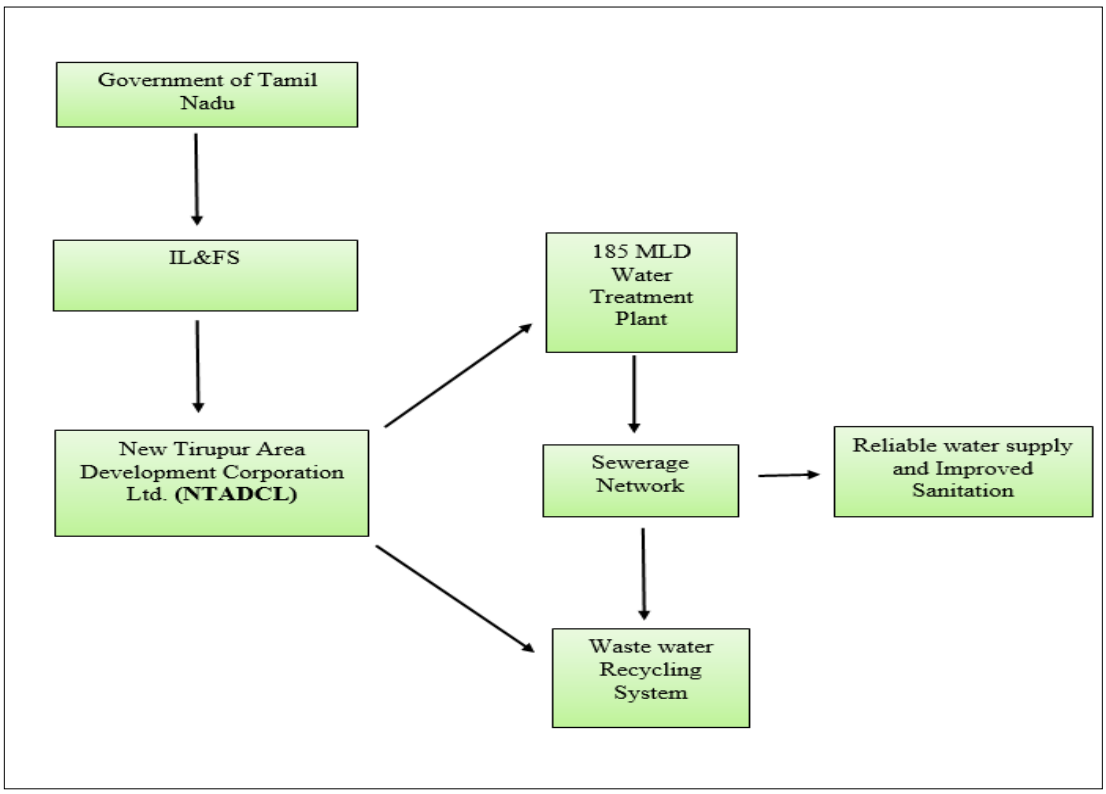

Fig. 9. Tripur water supply and sewerage project (63, 64).

The Tirupur water supply and sewerage project in Tamil Nadu serves as a notable example of a PPP successfully addressing urban-industrial water scarcity exacerbated by recurring drought conditions. Fig. 9 illustrates the operational framework of the Tirupur water supply and sewerage project, implemented under the P3C model. Faced with severely depleted groundwater reserves and increasing water demand from the region's thriving textile industry, the Government of Tamil Nadu launched this ambitious initiative in collaboration with Infrastructure Leasing & Financial Services Ltd. (IL&FS) and the Tirupur Exporters Association (TEA). The project was further supported by a combination of private investors and multilateral agencies. A Special Purpose Vehicle-New Tirupur Area Development Corporation Ltd. (NTADCL)-was established to facilitate the implementation and management of the project. Key components of the initiative included the construction of a 185 million litres per day (MLD) water treatment plant drawing from the Cauvery river, an integrated sewerage network and a wastewater recycling system designed for industrial reuse. These interventions collectively ensured reliable water supply to both industrial and residential consumers, significantly reduced reliance on groundwater and contributed to improved urban sanitation standards (63, 64).

Research and academic institutions in drought management

Institutional research refers to the systematic study conducted within higher education institutions, primarily aimed at gathering data to inform institutional planning, policy development and decision-making (65). Such research is typically carried out within a specific university, college, or academic system and such research plays a vital role in advancing institutional knowledge that can contribute to broader societal challenges, including disaster management and environmental crises such as drought (66). Although institutional research often focuses on understanding the functioning of the institution itself, its findings can extend to improving operational practices, policy frameworks and educational strategies, particularly in areas related to disaster preparedness and response (67).

Role of research and academic institutions in drought management

Research institutions and academic organizations are crucial for developing a strong knowledge base that can support disaster management, particularly in the context of recurring droughts (68). Universities play an integral role in conducting research that not only aids in understanding the causes and impacts of drought but also helps develop mitigation strategies and improve existing policies (69). Their contributions extend to both academic discourse and practical solutions, including the advancement of innovative agricultural techniques, the cultivation of drought-resistant crops, improved water resource management practices and socio-economic interventions aimed at supporting affected communities (70).

A prominent example from Tamil Nadu Agricultural University, a pioneering institution in agricultural research and education in India. Established in 1906 as the Agricultural College and Research Institute in Coimbatore, TNAU has been instrumental in advancing agricultural science, particularly in the domains of drought management, pest control and genetic crop improvement. Over its century-long history, TNAU has evolved into one of India's premier agricultural universities, making significant contributions to both the academic and practical dimensions of drought management in the region (71).

Contributions of TNAU in drought management

TNAU has emerged as a central institution in developing and implementing strategies for effective drought management in Tamil Nadu. The university offers research-based insights into agricultural practices that are more resilient to water

scarcity and climate variability. By prioritizing drought monitoring, data analysis and the promotion of drought-resistant crop varieties, TNAU has firmly established itself as a leading institution in the region's agricultural research landscape. Its contributions to genetic improvement and pest and disease management have significantly enhanced crop productivity and water-use efficiency-both of which are critical during drought conditions (72).

Beyond its academic contributions, TNAU plays an active role in extension services by directly engaging with farmers to disseminate knowledge on water conservation techniques, soil health management and the adoption of climate-resilient farming practices. Its research has effectively bridged the gap between scientific innovation and practical field-level solutions for farmers grappling with drought-related challenges. Moreover, TNAU's involvement extends to policy advocacy, contributing to national discussions on revising and strengthening disaster management frameworks, particularly in the area of drought mitigation (71).

TNAU continues to play a crucial role in managing drought through a combination of applied research, policy advocacy and direct engagement with affected communities (44). Its contributions extend beyond knowledge generation, encompassing the development of innovative solutions and strategies that can be implemented at the grassroots level to mitigate the adverse effects of drought. Such institutions serve as critical centres of expertise and leadership, especially in drought-prone regions like Tamil Nadu. Their sustained engagement is essential for building resilient agricultural systems and enhancing the adaptive capacity of both farmers and policy structures to confront future drought events(73).

TNAU's drought management initiatives: TNAU annual report 2020-2021 findings

Under the Directorate of Crop Management and the Department of Agronomy, TNAU has introduced multiple drought-resistant varieties of millets, pulses and oilseeds including CO 52 rice, VBN 8 black gram and CO 6 pearl millet specifically suited for cultivation in rainfed and water-deficient area.

TNAU has played a leading role in introducing innovative drought mitigation measures Tamil Nadu, especially in semi-arid districts such as Coimbatore, Erode, Dharmapuri and Krishnagiri.

As part of the World Bank-supported TNIAMP, the university has showcased advanced irrigation techniques-such as micro-irrigation systems-to improve water use efficiency in river basin regions.

Under this project, the university has developed water -harvesting infrastructure on its campus, including a 400 m^3 farm pond, a percolation pond, three recharge shafts and fifteen recharge pits, collectively harvesting approximately 4.4 million L of rainwater annually(74, 75).

Fig. 10 demonstrates the vital role played by TNAU in drought management. While the university's capacity building initiatives have empowered stakeholders, there remains a need for enhanced institutional collaboration to increase effectiveness, particularly in light of financial limitations and the challenge of reaching marginal farmers (24).

Table 5 presents the institutional challenges and recommended mitigation measures for improving drought management in Tamil Nadu. It underscores the need to strengthen the TNDMA, given the current limited level of institutional engagement in managing droughts in the state. Effective monitoring, planning and mitigation of drought impacts across sectors require the involvement of diverse stakeholders-including scientists, policymakers and non-governmental organizations-along with adequate financial support and improved interdepartmental coordination (24).

Strategic institutional interventions for drought resilience

Integrated drought information systems

Effective drought preparedness necessitates the integration of meteorological, hydrological and agricultural data. Institutions such as the IMD, TAWDEVA and ATMA must ensure real-time data interoperability through centralized platforms like Tamil Nadu's State Drought Dashboard. This enhances situational awareness and supports timely response planning (76, 77).

Institutional capacity strengthening

Strengthening the capacity of extension personnel and local administrators is vital for efficient drought response. Interventions by the National Innovations on NICRA have improved preparedness in targeted regions (78). NGOs such as Siruthuli have revived traditional water tanks, thereby enhancing irrigation across over 1500 acres. Additionally, Farmer Producer Organizations (FPOs) in Theni district have advanced the adoption of micro-irrigation technologies (79).

Climate-smart technological interventions

The adoption of drought-resilient crop varieties such as CO 51 rice and Vamban 4 blackgram, alongside micro-irrigation technologies under the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), has significantly improved yield stability and water-use efficiency in Tamil Nadu. Mobile applications like *Uzhavan* and *mKisan* have aided nearly 60 % of users in making timely cropping decisions (81-83).

Financial resilience mechanisms

Linking relief funds to Aadhaar-enabled Direct Benefit Transfer (DBT) systems enabled swift compensation of ₹ 2247 crore to 3.1 million farmers following the 2017 drought. Weather-indexed crop insurance under the Pradhan Mantri Fasal Bima Yojana (PMFBY) supported 2.76 million farmers, with over ₹934 crore disbursed in claims during recent drought years (84, 85).

Conceptual framework model for examining institutional linkages in drought management

Table 6 presents a conceptual framework that illustrates institutional linkages for drought management, showcasing a structured, multi-tiered approach that integrates national, state and local institutions. This framework facilitates the coordination of resources, data and action plans across government levels, ensuring timely response and sustained support to affected agricultural communities (Author's own creation).

National level institutions play a foundational role in forecasting and monitoring

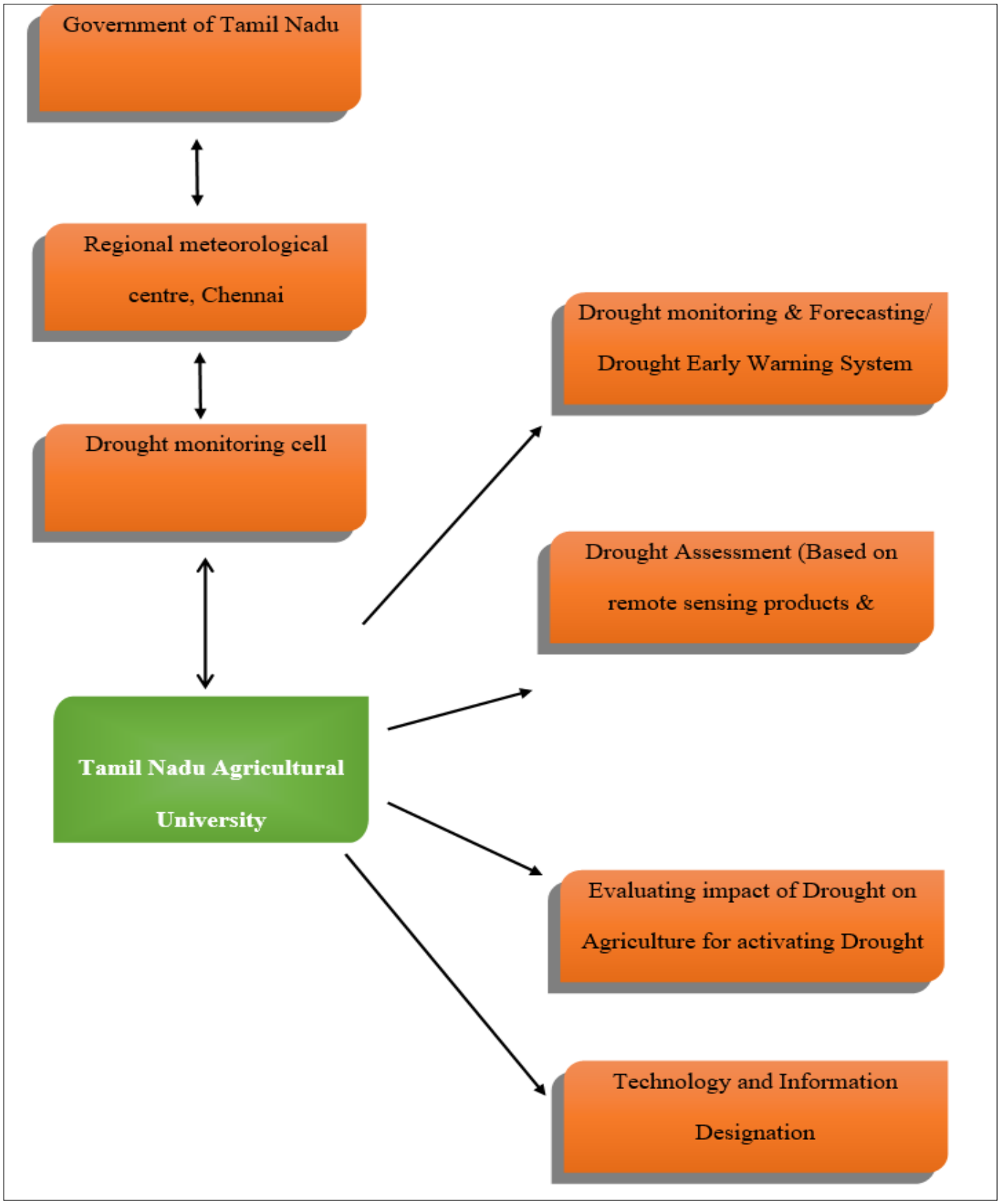

Fig. 10. Research institution (Tamil Nadu Agricultural University, Coimbatore) for drought management (24).

Table 5. Outlines key challenges and proposed mitigative options for enhancing drought management in Tamil Nadu (24)

Component	Challenges	Suggested mitigative options
Institutional	Limited institutional participation in drought management at various levels	Strengthening the state-level institutional framework through the Tamil Nadu Disaster Management Authority (TNDMS), operating under the Department of Environment, Government of Tamil Nadu. The involvement of key stakeholders, including scientists, policymakers from agriculture and public works departments, district-level administrators, NGOs, community-based organizations and farmer representatives, should be prioritized. Additionally, ensuring the allocation of adequate financial resources is critical for effectively monitoring drought onset, progression and its impacts across different sectors.

National-level institutions provide critical support for drought forecasting and monitoring. Key agencies include the IMD, National Centre for Medium Range Weather Forecasting, Department of Space and the National Agricultural Drought Assessment and Monitoring System. Research bodies such as CRIDA, IARI, ICAR and IITM contribute through advanced research initiatives. Disaster response funding is managed by entities like the Relief Commissioner and Drought Task Forces through mechanisms such as the Calamity Relief Fund (CRF) and the National Calamity Contingency Fund (NCCF).

State level institutions

Focusing on Tamil Nadu, state-level institutions adapt national forecasts and datasets to suit local needs. Entities such as the Regional Meteorological Centre in Chennai, the Tamil Nadu Agricultural University's Automated Weather Station (AWS) Network and the State Drought Monitoring Cell analyze and interpret data to inform regional strategies. The State Relief Commissioner and District Collectors coordinate the distribution of relief resources, ensuring that preparedness and response measures are aligned with on-the-ground realities.

Local level institutions

At the grassroots level, local institutions translate state-level plans into actionable measures. Tehsil and Block Development Offices, Gram Panchayats, crop insurance agencies and NGOs collaborate to implement relief efforts, provide financial aid and disseminate drought-related information to farmers. As primary stakeholders, farmers benefit directly from this framework through insurance disbursements, advisory services and access to resources aimed at enhancing drought resilience.

This institutional framework represents a comprehensive model wherein national-level forecasting and assessment inform state-level coordination and planning, which in turn enables effective implementation at the local level. The integration of efforts across all tiers enhances the overall efficiency, responsiveness and impact of drought management strategies, thereby safeguarding agriculture and rural livelihoods. (Source: Author's own creation)

Policy recommendations for enhancing institutional linkages in drought management

A centralized, real-time drought information platform should be developed to integrate data from institution such as the India Meteorological Department (IMD) and the National centre for medium range weather forecasting. This platform would significantly enhance the decision-making ability of state, central and local agencies.

A dedicated task force for drought management should be established, compromising representatives from key national and state agencies, research institutions and NGOs. It is requested that this task force meet regularly to update drought response strategies and share insights.

Increased funding and institutional support should be allocated to state governments and research institutions such as Tamil Nadu Agricultural University, Department of Space. These resources would aid in the development and deployment of advanced remote sensing technologies for early drought detection and impact assessment.

Affordable crop insurance schemes should be encouraged, with government subsidies to ensure timely processing and disbursal of claims during drought period, thereby enhancing financial security for framers.

Mobile-based information dissemination system, such as an expanded version of the *meghdoot* app, should be developed and promoted to provide timely forecasts, early warnings and drought relief updates directly to farmers.

Table 6. Conceptual framework model for examining institutional linkages in drought management

Level	Institutions / Stakeholders	Key roles and responsibilities
Central government	- India Meteorological Department (IMD), New Delhi - National Centre for Medium Range Weather Forecasting (NCMRWF) - Department of Space National Agricultural Drought Assessment and Monitoring System (NADAMS) - National Crop Forecasting Centre (NCFC), CWWG, DAC - Research Institutions (CRIDA, IARI, ICAR, IITM) Relief Commissioner, Drought Task Forces, Calamity Relief Fund (CRF), National Calamity Management Committee	- Drought monitoring and early warning - Remote sensing and weather forecasting - Drought impact assessment - Agricultural research and modelling - Fund allocation through CRF & NCCF - Policy formulation and coordination
Drought monitoring system	- Drought Early Warning System - Drought Assessment (Remote Sensing & Vegetation Index) - Agricultural Impact Evaluation - Calamity Relief Fund (CRF) & NCCF - Preparation & Implementation of Action Plans - Technology and Information Dissemination	- Integrates data and forecasts - Triggers funding and relief mechanisms - Guides state and local actions based on real-time drought indicators
State government (Tamil Nadu)	- Regional Meteorological Centre, Chennai - Drought Monitoring Cell - Tamil Nadu Agricultural University (AWS Network) - State Relief Commissioner - District Collectors	- State-specific drought forecasting and interpretation - Coordination of state response - Monitoring and fund distribution at the district level
Local institutions	- Tehsil / Block Development Office - Gram Panchayats - Crop Insurance Companies - NGOs	- On-ground implementation of relief plans - Information dissemination - Insurance claim processing - Support services to farmers
Beneficiaries	- Farmers	- Receive support through forecasts, insurance, relief funds and capacity -building for drought resilience

Source: (Authors own creation)

Capacity-building programs and climate resilience workshops should be organized for local officials, NGOs and farmer groups to improve preparedness and empower communities to effectively mitigate the impacts of drought using available resources.

The PPP model should be promoted to develop data-driven systems and mobile applications for farmers. Leveraging innovation and expertise through partnerships at all levels can significantly strengthen drought resilience initiatives. Source: Author's own creation

Conclusion

Tamil Nadu's experience in managing drought highlights the critical importance of collaboration among various institutional stakeholders. This review has analyzed the roles played by government programs, NGOs, research institutions like TNAU and PPPs in strengthening drought response efforts. The convergence of these actors has led to improved water resource management, the promotion of drought-resilient crops varieties and support for vulnerable farming communities. The study critically evaluated these institutional arrangements to assess their effectiveness in reducing drought impacts. It was found that while progress has been made, gaps remain in coordination, resource sharing and the use of real-time data for early response.

For long-term drought resilience,

- Farmers should be encouraged to adopt climate-resilient agricultural practices and water-saving technologies.
- Institutions collaborations must be enhanced, especially in the areas of drought monitoring and the dissemination of timely, accurate information.
- Government bodies should prioritize investments in early warning systems and support community-based water conservation.
- This study underscores that sustained collaboration and context-specific solutions will be dynamic in protecting agricultural livelihoods and ensuring sustainable development in drought-prone regions.

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Authors' contributions

PI conceptualized the study, conducted the primary literature review, synthesized the findings and drafted the original manuscript. JP supervised the study, provided guidance in framing the article and critically reviewed the manuscript for intellectual content. PR contributed to idea development, reviewed the manuscript and assisted in securing research grants. GSR assisted with the summarization and revision of the manuscript and provided technical inputs. KS contributed to summarizing the manuscript and assisted in refining the manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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