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Nature-based Solutions for Agricultural Drought Adaptation Strategies in the Karst Area of Gunungkidul Regency, Indonesia

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Abstract

Drought significantly impacts agriculture and economies, particularly in karst regions like Gunungkidul Regency, Yogyakarta, Indonesia. This study proposes nature-based solutions (NBS) to address drought challenges, focusing on increasing water retention capacity as the most effective strategy. Identified through the Climate-ADAPT platform and evaluated using multi-criteria analysis (MCA), this strategy scored highest in vulnerability reduction, ecological enhancement, and employment generation. Artificial reservoirs, locally known as "Embung", are recommended for capturing rainfall and runoff in water-scarce areas. These reservoirs provide reliable water sources for agricultural activities during dry seasons, ensuring consistent productivity and reducing the risks of crop failure. Beyond agricultural benefits, reservoirs serve as multifunctional spaces, potentially enhancing local economies through tourism, recreation, and aquaculture. Effective implementation requires tailoring designs to the karst landscape, addressing the unique hydrogeological conditions of the region. Collaboration among stakeholders— including local governments, community groups, and agricultural practitioners— is essential to ensure sustainability and long-term impact. The study emphasizes the importance of integrating stakeholder input in planning and maintenance, fostering a sense of ownership and commitment to these projects. By leveraging nature-based solutions, Gunungkidul Regency can build resilience to climate change, enhance agricultural productivity, and create new socio-economic opportunities. This approach offers a scalable model for other drought-prone regions, highlighting the potential of sustainable, community-centered strategies in addressing complex environmental challenges while achieving broader development goals.

Keywords: agriculture, artificial reservoirs, Climate-ADAPT, karst, water retention

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Agriculture is still a key economic activity for people in rural areas (Nolos et al., 2023). More than two-thirds of rural people depend on agriculture for their livelihood (Adhikari, 2018), like in Gunungkidul Regency. In Gunungkidul Regency, rainfall determines the irrigation needs for rainfed paddy farming, the most widely developed type of paddy farming. Decreased rainfall that triggers a meteorological drought can disrupt rainfed-based agriculture (Putra & Nurjani, 2021). Economic progress in the Karst Mountains of Gunungkidul Regency, particularly in agriculture, faces significant hindrances, primarily due to the scarcity of surface water. The unsuitability of agro-climate and geographical conditions, coupled with natural vulnerabilities, further compounds the challenges of engaging in agricultural economic activities. The meager income levels within the agricultural communities residing in the Karst Mountain area contribute significantly to the elevated levels of poverty experienced in the region (Antriyandarti et al., 2023).

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Droughts may lead to high agricultural losses and endanger global food security. However, the adoption of climate change adaptation strategies as a way to cope with the risks is gaining increased attention. Relevant adaptation strategies are essential to cope with climate change risks and sustain agricultural productivity (Ojo et al., 2021). Adaptation strategies define the procedure for adapting assistance to pursue one of the specified goals of human-centered adaptivity. They establish the method and duration for implementing the assistance adaptation, as well as the information that will shape this decision. They also specify which adaptation targets are influenced by the adaptation (Oestreich et al., 2022).

The most recent and perhaps also most promising approach to adaptation strategies toward climate change is the concept of Nature-Based Solutions (NBS). It is based on the principle that enhancing and protecting natural processes provides multiple benefits for society, thereby ensuring a sustainable delivery of ecosystem services (ES) and buffering the adverse impacts of climate change and natural hazards. The main advantage of NBS over other adaptation strategies is its capability to deliver multiple benefits. They support the resilience of natural processes and help reduce adaptation costs (Martin, Costa, & Máñez, 2020). Furthermore, strategic investments in NBS can potentially reduce the high economic costs associated with extreme drought events. Since the benefits of drought mitigation programs can be approximated as the avoided cost of water shortages, the development of methodologies for quantifying the cost of drought is important (Ciasca et al., 2023). However, the ability of NBS to achieve the desired benefits has not been well evaluated. Concerns about their reliability and cost-effectiveness when compared to constructed alternatives and their resilience to climate change have been raised.

Trade-offs may occur if climate mitigation policy promotes NBS with low biodiversity value, such as afforestation with non-native monocultures. This can lead to maladaptation, particularly in a fast-changing world where biodiversity-based resilience and multifunctional landscapes are critical. As climate policy shifts toward measures like afforestation and greenhouse gas removal, it emphasizes the crucial need for natural and social scientists to collaborate with policymakers. They must ensure that NBS reach their full potential in addressing climate and biodiversity crises while contributing to sustainable development (Seddon et al., 2020). In addition, there are somber but encouraging comments about the path forward. NBS provides appealing options for addressing 21st-century adaptation concerns. However, we must avoid overselling NBS. The term "solutions" may lead to the impression that NBS aims for rapid and neat results. However, these solutions are continual processes that necessitate concerted efforts to evaluate and learn from previous decisions. Deep uncertainty—ecological and social— must be considered. Trade-offs in current and future equity concerns related to sustainability must be identified and examined, as well as the explicit distribution of risks and rewards (Nelson et al., 2020).

Studies on drought disaster adaptation strategies in karst regions, particularly in Gunungkidul Regency, are rare. In addition, some adaptation strategy studies have been conducted in Gunungkidul Regency, but almost all of them only focused on one strategy, such as the use of certain species (Rahayu, Rozaki, & Isdiana, 2022; Srihartanto & Widodo, 2020), without any prior feasibility assessment. This study aims to propose nature-based solutions for drought disaster adaptation strategies in the agricultural sector in Gunungkidul Regency, Indonesia. Adaptation strategies are crucial because they may reduce financial and material losses and help people in other drought-prone areas build coping mechanisms. This study may also help stakeholders increase water availability for the agricultural sector in Gunungkidul Regency.

Materials and Methods

Study Area

The study area is Gunungkidul Regency, Daerah Istimewa Yogyakarta (DIY) Province, Indonesia (Fig. 1). Gunungkidul Regency is known as an area that often experiences drought in Indonesia. Weather and climatic conditions in Indonesia influenced by various global climate dynamics are expected to cause various impacts, including the intensity of meteorological drought events (Putra & Nurjani, 2021). At 1,485.36 km^2 or 46.63% of the DIY Province's total size, Gunungkidul Regency is the southernmost district. The terrain of these parts consists of limestone mountains that run east to west. The topography of the Gunungkidul Regency influences its land use. This region has a per capita income of 3.2 million rupiah and is considered impoverished due to the unfavorable soil conditions and water scarcity. This occurs because small farmers, who make up 70% of the population in Gunungkidul Regency, have a variety of constraints related to capital, technology, and the environment. The carrying capacity of the agricultural land in Gunungkidul Regency significantly influences food insecurity (Iguna, Sudrajat, & Harini, 2021). The karst landscape in Gunungkidul Regency is also one of the factors causing water scarcity (Martias, 2023; Zamroni et al., 2022).

Geologically, the karst landscape causes rainwater to infiltrate underground rivers, creating a water shortage on the surface (Zamroni, Trisnaning, & Widiatmoko, 2023). Karst landscapes are typically considered delicate and susceptible ecosystems. Bare karst land with insufficient soil cover can exacerbate desertification. The underground drainage system can exacerbate drought and flooding issues, while the interconnected surface and subsurface conditions facilitate quickly contaminating pollutants. Karst terrains frequently encounter engineering challenges, including water infiltration in mines or transportation tunnels, reservoir leakage, and failures in building foundations (Guo et al., 2013). The karst landscape, characterized by a confined evaporite aquifer and hypogene karstification, indicates that sinkhole activity will likely intensify during drought. Based on climatic projections, such droughts are projected to increase in frequency (Linares et al., 2017).

Figure 1

The Study Area

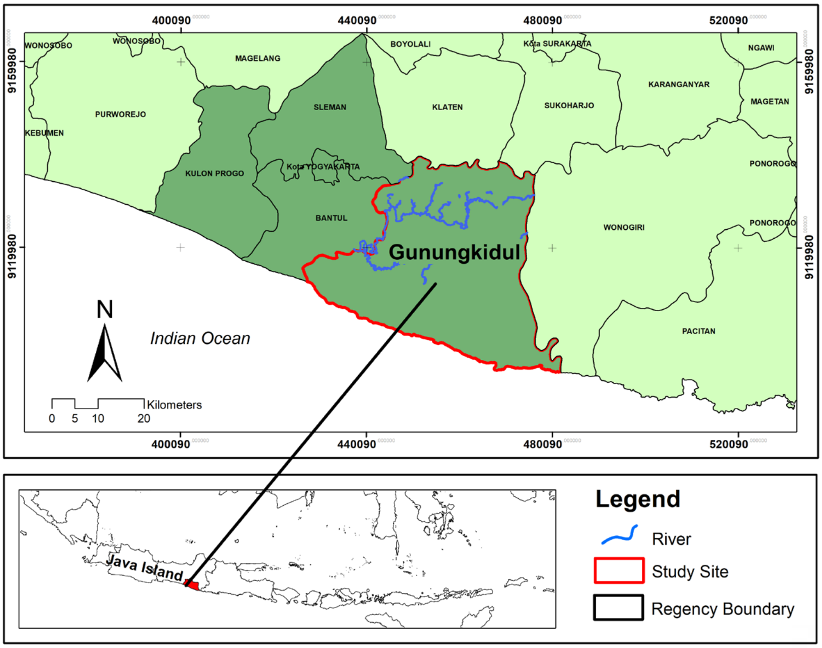


Figure 2

The Flowchart Methodology of the Study

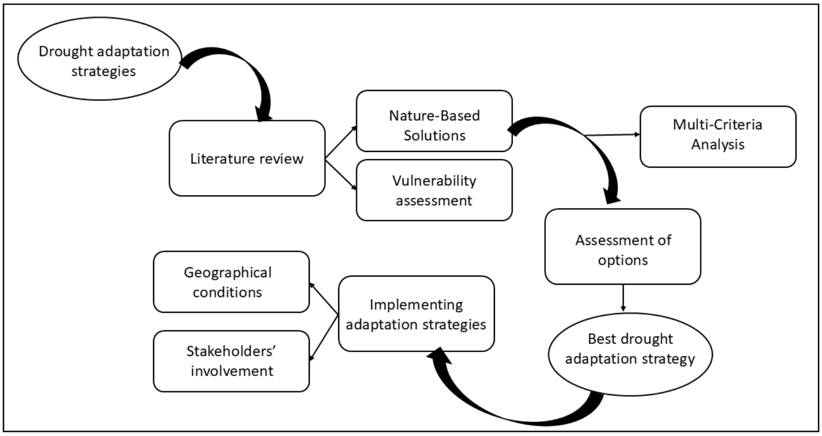


Figure 2 displays the study's flowchart methodology. It includes a literature review, an assessment of options, and implementing adaptation strategies.

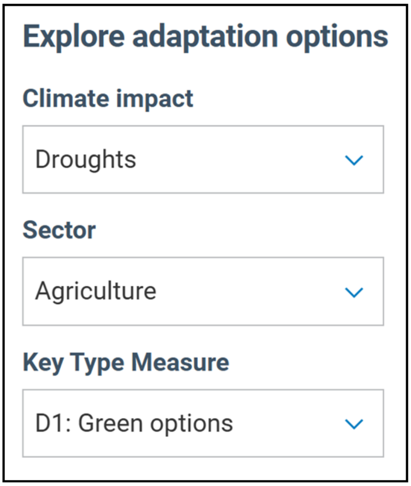
Literature Review

A literature review is an essential component of almost any research project. It serves as the foundation for advancing knowledge, facilitates theory development, closes mature research areas, and uncovers novel research areas. A literature review is a "knowledge map", which analyzes and synthesizes prior literature. Because literature reviews are so prevalent, several comprehensive resources already guide authors through the steps necessary to conduct a literature review (Fisch & Block, 2018). Literature reviews summarize existing research to answer a review question, provide the context for new research, or identify important gaps in the existing body of literature (Hempel, 2020). This study's literature review activities include a review of the NBS and vulnerability assessment.

The NBS study was explored on the Climate-ADAPT platform by selecting the "Explore adaptation options" submenu and then filling in the Climate impact, Sector, and Key Type Measure category tables, respectively, with Droughts, Agriculture, and Green options, as demonstrated in Figure 3. The term "green options" refers to the ecosystem-based (or nature-based) approach and use of the multiple services provided by natural ecosystems to improve resilience and adaptation capacity (Climate-ADAPT, 2023a); this follows the Nature-Based Solutions topic in this study. A more detailed definition of each adaptation strategy was developed by exploring papers from Google Scholar. Google Scholar is a free web search engine that simultaneously indexes full-text scholarly literature across many disciplines and databases. Google Scholar indexes individual academic papers from journals and conference papers, theses and dissertations, pre-prints, academic books, technical reports, abstracts, and other scholarly literature from all broad research areas. Researchers can also access this search engine through a university library, enabling them to link to articles from Google Scholar using library resources (Zientek et al., 2018). A literature review, through Google Scholar and recent news, was also carried out to explore vulnerable sectors to droughts, which focused on the agricultural sector. Vulnerability assessment was considered a critical step towards effective disaster risk reduction. It was multi-dimensional, and its assessment was complicated due to the social, economic, political, and institutional patterns of societies (Roy & Blaschke, 2015). The vulnerability assessment in this study was carried out by reviewing the literature on the impacts of drought on the agricultural sector in Gunungkidul Regency.

Figure 3

Climate-ADAPT platform



Multi-criteria Analysis

The options were assessed by comparing each selected adaptation strategy with specific criteria, such as cost, effectiveness, and social acceptance, both qualitatively and quantitatively. Systematic assessment of technically, economically, and politically feasible options could enable policymakers to make well-informed choices about different adaptation options (de Bruin et al., 2009). The assessment of options in this stage was carried out using Multi-Criteria Analysis (MCA). MCA is a valuable tool for assembling and managing many variables (quantitative as well as qualitative ones) assessed in different ways, thus offering reliable support for decision-making (Stamatakis, Mandalaki, & Tsoutsos, 2016). The MCA aims to find the most favorable solution (Mierzwiak & Calka, 2017). The criteria for assessing each adaptation strategy are vulnerability reduction, costs (direct costs for the implementation and maintenance), enhancement of ecological conditions, public and political acceptance, employment generation, achievement of Sustainable Development Goals (SDG), and institutional and technical capacity. Each criterion was chosen based on its relevance to the specific challenges and objectives of addressing agricultural drought in Gunungkidul Regency, Indonesia, and its alignment with broader sustainable development goals (Haque, 2016).

1. **Vulnerability reduction.** This criterion measures how effectively an adaptation strategy can mitigate the risks and impacts of drought on agriculture. It is a primary goal of climate adaptation, especially in drought-prone regions like Gunungkidul, where water scarcity directly affects agricultural productivity and community livelihoods. Strategies that score high in this criterion contribute significantly to reducing the risks associated with meteorological drought, thereby ensuring food security and resilience (Ojo et al., 2021).

2. **Cost.** This criterion evaluates the financial feasibility of implementing and maintaining an adaptation strategy. Limited financial resources in low-income regions necessitate cost-effective solutions. Rationale: Affordable strategies will likely be adopted and sustained over the long term, ensuring the benefits reach the most vulnerable populations (de Bruin et al., 2009).

3. **Enhancement of Ecological Conditions.** This criterion assesses the strategy's contribution to improving biodiversity, soil health, and overall ecosystem resilience. Gunungkidul's karst landscapes require ecologically sensitive interventions to address water scarcity and soil degradation. Nature-based solutions (NBS) inherently aim to enhance ecological conditions, which provide co-benefits such as carbon sequestration, improved water quality, and habitat restoration (Martin et al., 2020).

4. **Public and Political Acceptance.** This criterion gauges the willingness of stakeholders, including communities and policymakers, to support the strategy. Stakeholders buy-in is essential for the successful implementation of adaptation strategies. High public and political acceptance ensure that strategies are socially and culturally appropriate, facilitating smoother implementation and long-term sustainability (Yeleliere et al., 2022).

5. **Employment Generation.** This criterion evaluates the potential of the strategy to create jobs and improve livelihoods. Employment generation is critical in poverty-stricken regions like Gunungkidul, where many rely on agriculture for their income. Strategies that provide economic opportunities enhance community resilience and incentivize participation in adaptation measures (Ciasca et al., 2023).

6. **Achievement of Sustainable Development Goals (SDGs).** This criterion measures the alignment of the strategy with global sustainability goals. Addressing climate challenges while achieving the SDGs ensures that adaptation strategies deliver multiple societal

benefits. Strategies that align with SDGs, particularly Goal 2 (Zero Hunger) and Goal 13 (Climate Action), contribute to holistic development and resilience (Oraon, Sagar, & Beauty, 2023).

7. **Institutional and Technical Capacity.** This criterion evaluates the level of expertise, infrastructure, and coordination required to implement the strategy. Regions with limited institutional and technical capacity, such as Gunungkidul, need practical and achievable strategies within existing constraints. Strategies with lower technical and institutional requirements reduce the risk of implementation failure and ensure accessibility to local stakeholders (Alvi et al., 2020).

Determination of Weights

The literature review was employed as a method to assess and rank adaptation strategies for combating drought in the agricultural sector. Expert evaluations were central to the process, with each strategy being systematically rated based on multiple criteria associated with Nature-Based Solutions (NBS). The rating system was quantitative, where each of the five adaptation strategies— afforestation and reforestation, establishment and restoration of riparian buffers, rehabilitation and restoration of rivers and floodplains, agroforestry, and increasing water retention capacity— was scored on a scale from 1 to 5. In this scale, 1 represented the lowest score, indicating the least effective or least favorable performance for a given criterion. 5 represented the highest score, denoting the most effective or favorable performance for that criterion. The scores were then used in the calculation using MCA. The strategy that received the highest score is considered the most effective adaptation strategy for the study area.

Overall Assessments and Considerations for Implementation

After the strategies were ranked using MCA, a qualitative description was conducted for each criterion of each adaptation strategy. This step involved a deeper analysis to provide insights into the specific strengths, weaknesses, and contextual relevance of each strategy. The qualitative description aimed to assess not just the numerical rankings but also the practical implications, local context, and the broader environmental, social, and economic factors that might influence the success of each strategy.

In the adaptation strategy implementation stage, two factors must be considered after selecting the best adaptation strategy: (1) the feasibility of geographical conditions and (2) stakeholders' involvement. Geographical conditions play a crucial role in the cost of adaptation strategies, particularly for countries already experiencing high temperatures or more vulnerable to climate change (Alvi et al., 2020). Additionally, geographical conditions are important factors that determine climatic conditions and play a role in ecology and biodiversity conservation, affecting plant growth, development, and distribution (Guo et al., 2014; Singh, 2019).

Stakeholders are individuals or group representatives who either directly impact a decision or have the ability to influence it, as well as those who experience its effects (Sagar, 2017). Decision-making on adaptation strategies to ensure good ecological status involves stakeholders with different interests and perceptions of the most critical problem. Reducing this considerable amount of ambiguity is necessary to achieve a political decision (Refsgaard et al., 2013). In addition, collaborative action involving stakeholders can promote effective action on climate change by fostering consensus and building local ability and expertise to collectively adopt adaptation measures (Nolos et al., 2022b; Yeleliere et al., 2022).

The search for data regarding stakeholders' involvement in drought disaster adaptation strategies in Gunungkidul Regency was carried out using Google Scholar and institutions' websites. Two essential questions were considered: (1) Who are the stakeholders who play a role in implementing the adaptation strategies? (2) What are the roles of each stakeholder in the implementation of adaptation strategies?

Results and Discussion

Adaptation Strategies Options

Climate-ADAPT has suggested five adaptation strategies to combat drought in the agricultural sector: afforestation and reforestation, establishment and restoration of riparian buffers, rehabilitation and restoration of rivers and floodplains, agroforestry, and increasing water retention capacity.

Afforestation and Reforestation (NBS 1)

The establishment of a forest is called "afforestation", especially in areas where there was no prior forest (Oraon et al., 2023). One land use modification project that is becoming more common is afforestation, mainly intended to produce wood, conserve water and soil, increase carbon storage, and mitigate climate change (Hong et al., 2018). Asia is experiencing more frequent and severe droughts, a serious threat to preserving biodiversity and forest ecosystems. Therefore, the best way to adjust to a drier environment would be to choose drought-resistant plants for afforestation projects (Bhusal et al., 2021). Reforestation is the process of replanting trees on recently forested ground, while afforestation involves planting trees on land that has not had any forest cover for at least 50 years (Sheng, Han, & Zhou, 2017). To determine how to reorganize agricultural zones, requiring reforestation is considered. It must measure the effects of past land uses, establishment techniques, species combinations, and interactions with neighboring land uses on reforestation's environmental (especially biodiversity) outcomes. It must also quantify how responses measured at the individual planting level scale up to watersheds and regions. According to Cunningham et al. (2015), models built using this data will support extensive reforestation to sequester carbon and enhance native biodiversity, the nitrogen cycle, and water balance at regional scales. Agrarian development may result in land use changes, such as converting forest land to agricultural land. Increased agricultural efficiency can raise production per unit area of land, which may lessen the pressure on land and increase the likelihood of afforestation and reforestation, thereby enhancing the afforestation and reforestation potential of a country (Sheng et al., 2017).

Establishment and Restoration of Riparian Buffers (NBS 2)

Riparian zones connect and impact ecological processes at the terrestrial and aquatic ecosystems interface. In proportion to their size, their management can have a significant impact on stream water quality as a buffer between land-use activities and waterways (Agarin et al., 2021; Mendoza et al., 2023). Managers sometimes see riparian buffer zones as "the last line of defense" for preventing the degradation of rivers. Several important things vegetated riparian buffers do, such as trap more soluble pollutants in the soil, enable suspended particles to settle in the buffer soil, and catch pollutants in runoff (Nolos et al., 2022a; Senoro et al., 2023). Renouf and Harding (2015) strongly encourage the installation of buffers, which can include fencing to keep livestock out and preserve vegetated streamside margins to protect and clean up agricultural streams. The establishment and restoration of riparian buffers can reduce the effects of drought by enhancing groundwater recharge through increased soil permeability and increased water-soil contact times or by improving microclimatic conditions through the shading effects of trees and shrubs (Climate-ADAPT, 2023b).

Rehabilitation and Restoration of Rivers and Floodplains (NBS 3)

Climate change will likely cause direct river changes. This could have significant, unexpected effects on their shape and the ecosystems that live in them (Zamroni & Faustino-Eslava, 2023). In addition, degraded wetlands cannot replenish groundwater or store water for use during dry spells. Flow control refers to a robust natural plant cover's ability to absorb and store precipitation-related water, minimize surface runoff, and gradually release water to maintain flows throughout the dry season. This ability affects both surface and groundwater. Thus, suitable catchment management techniques can reduce droughts (Mahlaba, 2022). The term "river restoration" encompasses a wide range of actions that have as their primary goals the morphology and hydrology of rivers and actions related to land use and spatial planning. Sets of actions frequently bundle these strategies to achieve self-sufficiency, fostering the various roles and benefits of river systems in supporting landscape development, biodiversity, recreation, and flood control (Muhar et al., 2018). In the meantime, river rehabilitation is a collection of ecological and managerial measures meant to restore a river system's natural conditions to preserve biodiversity, allow for recreational purposes, control flooding, and balance the advancement of the landscape (da Silva et al., 2021). The internal physical, chemical, and biological characteristics of rivers and floodplains have a crucial role in dictating the kinds, quantities, and geographical distribution of the species that live there. However, the environments in which these species exist also influence their behavior. Although vegetation in the riparian zone on both sides of the river can also have an impact, land use and type determine water quality (Senoro et al., 2022). According to Van Andel and Aronson (2012), rivers and floodplains naturally sustain a diverse range of interacting terrestrial and aquatic flora and fauna and play a crucial role in establishing passageways or corridors between other ecosystems, such as woods.

Agroforestry (NBS 4)

Agroforestry is the intentional planting or preservation of trees on farms in order to increase, vary, and maintain output for better social, economic, and environmental outcomes. Vegetation structure, the role of woody perennials in the system, management input levels, environmental factors, and the system's ecological appropriateness can all be used to categorize an agroforestry system (Atangana et al., 2014). Agroforestry species are resistant to droughts due to a few biological traits, including deep root systems that can absorb more water and nutrients from the soil. According to Quandt, Neufeldt, and McCabe (2017), shade trees can create microclimates that moderate temperature swings, which can lower evapotranspiration. Because their livelihood depends on the sustainability of the natural resource base, farmers must monitor the frequency and intensity of droughts to determine whether to implement agroforestry systems. The Standardized Precipitation Index (SPI) frequently describes global droughts in various hydro-meteorological system compartments. To determine what farmers value in agroforestry practices and agricultural production, inspecting how often and how bad droughts occur, what causes them, and the environmental benefits of smallholder farmers adopting agroforestry as a way to adapt is necessary (Mfitumukiza et al., 2017).

Increasing Water Retention Capacity (NBS 5)

Water retention capacity is the ecosystem's ability to hold onto, absorb, and store precipitation, as well as control water flow and the water cycle process (Wang & Xu, 2022). It also describes the water's capacity to hold and release water over time, especially in situations where the nearby land has less moisture available to it (Zhu & Li, 2023). The primary actions should aim to achieve a strategy that increases local water resources and their availability, improves water use efficiency, reduces water needs for crops, and intensifies irrigation of larger surfaces, given the potential increase in water shortages in agriculture due to droughts and unfavorable climate changes. Increasing soil water retention and plant availability, as well as the retention of water resources (in open waters) for agriculture, primarily for irrigation, are crucial to achieving these goals (Łabędzki, 2016).

Vulnerability Assessment

Gunungkidul Regency's agricultural sector is highly susceptible to droughts. Reduced rainfed paddy productivity (Putra & Nurjani, 2021), food insecurity (Antriyandarti et al., 2023), and poverty in the dryland farming community (Antriyandarti et al., 2018) are a few effects of the drought on the agricultural sector in Gunungkidul Regency.

Reduced Rainfed Paddy Productivity

In the Gunungkidul Regency, rainfed paddy fields cover 44,000 ha of the 117,704 ha of dry land. Rice from Gunungkidul's rainfed lowland contributes 21.79% of the grain produced in the DIY province, with an average output of 4,476 kg/ha. With productivity of 4,476 kg/ha for rainfed lowland rice and 6,300 kg/ha for irrigated lowland rice, the productivity yield difference between the two types of lowland rice is highly noticeable at 1,824 kg/ha (Wirasti et al., 2018). Nonetheless, there is a favorable correlation between meteorological drought and rainfed paddy productivity in Gunungkidul Regency. Paddy's productivity fell during the El Niño years and vice versa. La Niña's occurrence will boost productivity. However, the link between paddy productivity and meteorological drought varies throughout sub-districts. Different types of paddy and the development of unique adaptations in each sub-district may cause differences in the relationships in each place (Putra & Nurjani, 2021).

Food Insecurity

Food insecurity is one issue the government is dealing with regarding the significance of agricultural development in bolstering the national economy. Food insecurity occurs when households do not have enough food due to a lack of financial or other resources. Consequently, buying or getting enough nourishing food can be difficult for households experiencing food insecurity (Rizqi & Yulianti, 2023).

Inadequate topographical features, unfavorable agro-climatic conditions, and environmental susceptibility further hinder agricultural economic activities in the Karst Mountains of Gunungkidul Regency. Because of this, dryland farm households are more vulnerable to food insecurity. Several factors heavily influence the degree of food security, closely linking food insecurity in households to poverty. These variables include the level of knowledge among household members, food availability, prevailing economic and sociocultural conditions, and household income. In terms of monthly household income per adult equivalent, the percentage of dryland farmers in the Gunungkidul Regency with incomes less than 500,000 rupiah is approximately 63.55%. For this category, food consumption accounts for 52.14% of their income. These results classify households in the Karst Mountains as having medium food insecurity, as they spend between 50% and 65% of their income on food (Antriyandarti et al., 2023). Due to their inability to purchase productive assets that would raise family income, the impoverished households in Gunungkidul Regency are experiencing food insecurity since the majority of their family income is only sufficient to cover their basic food demands (Rizqi & Yulianti, 2023).

Poverty in the Dryland Farming Community

The Karst Mountains' dryland agricultural community stands for the difficult-to-overcome rural poor. The farming community is distinct in that it produces and consumes food. The relationship between household food insecurity and poverty is linear. The primary barrier to economic development in the Gunungkidul Karst Mountains, particularly for agriculture and animal husbandry, is the lack of surface water. Agroclimate, topography, and natural vulnerabilities make agricultural economic activities unsuitable. The farming community's meager revenue in the karst mountain region results in high poverty. Extreme climate change and the region's extremely variable rainfall can prove disastrous. As a result, Gunungkidul Regency experiences poverty (Antriyandarti, Barokah, & Rahayu, 2022).

Adaptation Strategies Assessment

Table 1 uses a scale of 1 to 5 to score each criterion of adaptation strategy. Table 2 displays the scores of each adaptation strategy multiplied by the weighted criteria. Table 3 describes the qualitative assessment of each adaptation strategy and criteria. Meanwhile, Figure 3 shows how adaptation strategies are prioritized based on the final weighted scores per option.

Table 1

Scoring Each Criterion of the Drought Agricultural Adaptation Strategy

Criteria	Adaptation Strategy				
	Afforestation and reforestation	*Establishment and restoration of riparian buffers*	*Rehabilitation and restoration of rivers and floodplains*	*Agroforestry*	*Increasing water retention capacity*
Vulnerability Reduction	2	2	2	4	5
Cost	3	*3*	3	4	2
Enhancement of Ecological condition	5	***4***	**4**	**3**	**2**
Public and Political Acceptance	3	*3*	3	2	4
Employment Generation	4	*2*	2	3	5
Achievement of SDG	3	*2*	2	3	4
Institutional and Technical Capacity	2	*2*	2	3	4

Table 2

The Score of Each Adaptation Strategy has been Multiplied by the Weighted Criteria

Criteria	Weighted	Adaptation Strategy				
		Afforestation and reforestation	*Establishment and restoration of riparian buffers*	*Rehabilitation and restoration of rivers and floodplains*	*Agroforestry*	*Increasing water retention capacity*
Vulnerability reduction	0.227	0.454	0.454	0.454	0.908	1.135
Cost	0.182	0.546	0.546	0.546	0.728	0.364
Enhancement of ecological condition	0.159	0.795	**0.636**	**0.636**	**0.477**	**0.318**
Public and political acceptance	0.136	0.408	0.408	0.408	0.272	0.544
Employment generation	0.136	0.544	0.272	0.272	0.408	0.68
Achievement of SDG	0.068	0.204	0.136	0.136	0.204	0.272
Institutional and technical capacity	0.091	0.182	0.182	0.182	0.273	0.364
Total Scores		3.133	2.634	2.634	3.27	3.677

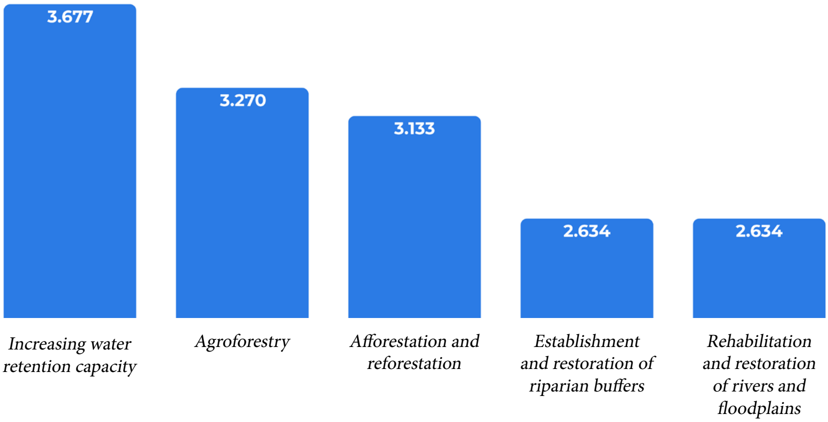
Table 3

The Qualitative Assessment of Each Adaptation Strategy and Criteria

	Adaptation Strategy				
Criteria	*Afforestation and reforestation*	*Establishment and restoration of riparian buffers*	*Rehabilitation and restoration of rivers and floodplains*	*Agroforestry*	*Increasing water retention capacity*
Vulnerability reduction	Forest development in karst areas requires a long time and specific plants	The majority of rivers in karst areas are underground rivers, making it difficult to develop riparian areas	The majority of rivers in karst areas are underground rivers that do not have floodplains and do not have surface water	Increases soil fertility but cannot prevent water from seeping into karst areas	Prevent rainwater from seeping into karst areas and the collected water can be used for agricultural irrigation and daily needs
Cost	The need for land requires quite high funds	The need for land requires quite high funds	The need for land requires quite high funds	The costs are relatively affordable and farmers can get more income	It is expensive to build a water catchment area
Enhancement of ecological condition	Increasing the amount of forest will increase biodiversity	Increasing biodiversity around the riparian buffers	Increasing biodiversity around rivers and floodplains	Improving nutrients and water cycling, but the potential of slash-and-burn agriculture	Catching rainwater may impact underground karst ecosystems that require rainwater
Public and political acceptance	Communities can take advantage of better-quality forests, but they require a lot of land to develop them	Improving river quality, but requires more land to improve riparian areas	Improving river quality, but requiring more land to develop floodplains	Requires more land for agricultural activities	Increase water security, and can be used as a recreation area by developing green open space around the water catchment area
Employment generation	Job opportunities in forest management	There are no economically meaningful employment opportunities	There are no economically meaningful employment opportunities	Opportunities for local communities to develop agroforestry and involve experts	The local community can use it as a tourism destination which can increase job opportunities
Achievement of SDG	In line with the target of achieving the SDGs, there is a risk of socioeconomic impacts	In line with the target of achieving the SDGs, there is a risk of environmental and socioeconomic impacts	In line with the target of achieving the SDGs, there is a risk of environmental and socioeconomic impacts	In line with the target of achieving the SDGs, there is a risk of environmental and socioeconomic impacts	In line with the target of achieving the SDGs, but has a risk of environmental impacts
Institutional and technical capacity	Risk of conflict between stakeholders	Risk of conflict between stakeholders	Risk of conflict between stakeholders	The concerned authorities should work hard in educating farmers	Involvement between stakeholders in water catchment management

Figure 4

The Prioritization of Adaptation Strategies Based on the Final Weighted Scores per Option



Poverty in the Dryland Farming Community

The best adaptation strategy to combat drought in the study area is to increase water retention capacity. In the implementation stage, two factors must be considered: the feasibility of geographical conditions and stakeholders' involvement. Terracing and contour plowing, preserving or reconstructing outdated drainage systems, creating varied water flow patterns, rehabilitating natural water retention areas (ponds, lakes, and reservoirs), installing flood control reservoirs or water impoundments (which usually have a large capacity for storing and controlling high water volumes), and extending, restoring, and adapting floodplains are all ways to improve the landscape's ability to retain water.

Water storage allows farmers to store water on their land during periods of abundance and release it during periods of scarcity. There are three types of small-scale storage: (1) soil moisture storage, which lets more water seep into the ground to increase the amount of rain that reaches soil storage for direct plant use; (2) groundwater storage, which lets water seep beyond the crop's root zone and percolate in aquifers; and (3) surface storage, which uses ponds or tanks that are naturally occurring or man-made (Climate-ADAPT, 2023c). In Indonesia, stakeholders often create artificial reservoirs (Embung) to increase water retention capacity on a large scale in karst areas. Embung is a pond-shaped water conservation structure that can handle runoff, rainfall, and other water sources for cattle, plantations, and agricultural uses, particularly during the dry season. The local community not only manages the reservoir as a water storage facility but also uses it for fishing (Kumalasari et al., 2023). In addition, Embung frequently develops into a tourist destination by transforming the area into a green open space. Gunungkidul Regency's geomorphology is primarily karst. Hydrogeologists all agree that to effectively explore, exploit, manage, and protect karst groundwater resources, they need to use customized strategies that take into account the unique features of karst aquifers, especially the presence of preferential pathways that allow swift flow from the surface to the spring. Artificial recharge must be approached suitably and logically to guarantee the success of managed aquifer recharge in karst aquifers (Daher et al., 2011). When constructing an artificial reservoir in a karst area, consider the following factors:

1. Typically, people regard this kind of measure as promising because its design frequently integrates multiple functions and interests. Landscape feature implementation frequently

incorporates buffer zones and habitat corridors to enhance local biodiversity, landscape connectedness, and soil moisture retention capacity.

2. Thorough site-specific assessments are necessary to reap the anticipated benefits from this option's implementation. When implementing water runoff designs and selecting locations for water storage or ponds, it is critical to consider local weather conditions, crop types, slope, and soil characteristics. The potential for negative impacts occurs if measures are not developed appropriately. Therefore, microdesign— which considers local conditions— is required when deciding where to construct new environmental elements. Flooding and accidental water flows into populated or agricultural regions are among the risks.

3. When designing landscape elements, it is critical to ensure that groundwater storage is placed in a safe location from overflow, leakage, and freezing. Furthermore, improper implementation of the option without careful planning and consideration of other ecosystem components could harm crops, especially in flat or flood-prone locations with higher groundwater tables.

4. Some of the suggested water retention techniques may have an impact on salinity in some situations (such as near the sea or ocean), which could radically alter the soil's quality or render the land unfit for growing particular crops unless irrigation plans are properly adjusted to the new hydro-geological forms. In contrast to the nearby native vegetation and conventional plantings, changes in the hydrological regime may have a notable visual effect from terracing, which decreases runoff and enhances water infiltration.

5. On a larger scale, initiatives need to address not only design and implementation but also land users' changing behavior. Adequate compensation for landowners is also required (Climate-ADAPT, 2023c).

To effectively mitigate a disaster, cooperation among multiple stakeholders is essential (Zamroni, Kurniati, & Prasetya, 2020). Putting these adaptation strategies into practice requires collaboration with a variety of parties. These require interdisciplinary collaborations between the Gunungkidul Regency's Department of Agriculture and Food, local organizations, government policymakers, academic institutions or researchers, and farmer's groups. Local groups should support village meetings and field demonstrations to promote knowledge about agricultural adaptation options, particularly in light of the widespread forecast of droughts in the upcoming decades. Policymakers should strive to enhance and implement the coping mechanisms that they deem essential to provide them with additional options for coping strategies in the future. The Department of Agriculture and Food should consider providing smallholder farmers with tools and education to help them learn more about alternative coping strategies. Farmers who possess greater education and expertise are more likely to weather droughts. As a result, during drought seasons, the government implements a program to help farmers prepare for the drought and make decisions (Muthelo, Owusu-Sekyere, & Ogundeji, 2019; Rachmawati & Zamroni, 2020). The district government is also in charge of developing farmland protection policies.

According to Rahmawati and Lestari (2019), field facilitators selected by the government ought to provide farmers with information on climate change, farming calendars, and pest control field monitoring. Because both public and private parties are typically involved, the complexity of governance and coordination poses a challenge in planning and implementation. Planning for the investment and gaining support from the parties involved could be a constraint. Farmers and other area stakeholders, such as nearby residents, nearby industries, or landowners, must work together and have mutual trust to maintain the area's landscape features and structural changes in land use. If it needs to create larger structural projects like reservoirs or flood pathways, it will need permission from the government or landowners. Water storage options, including regional or municipal investment or collaboration, could potentially benefit local businesses or residents (Climate-ADAPT, 2023c).

Conclusion

This study aimed to propose nature-based solutions (NBS) for drought adaptation strategies in the agricultural sector of Gunungkidul Regency, Yogyakarta, Indonesia. The Climate-ADAPT platform recommended five adaptation strategies: afforestation and deforestation (NBS 1), establishment and restoration of riparian buffers (NBS 2), rehabilitation and restoration of rivers and floodplains (NBS 3), agroforestry (NBS 4), and increasing water retention capacity (NBS 5). Each strategy was evaluated using a multi-criteria analysis (MCA) with seven criteria. The MCA results revealed the following ranking of strategies: NBS 5 > NBS 4 > NBS 1 > NBS 2 > NBS 3. NBS 5 had a total score of 3.677, with the highest score (5) for vulnerability reduction and employment generation. In terms of vulnerability reduction, NBS 5 possesses the greatest potential to stop rainwater from seeping into the karst areas. It can also capture excess water, enabling the use of collected water for agricultural purposes, particularly during the dry season. The local community can use the NBS 5 water reservoir as a tourism destination and fishing grounds for employment generation, increasing job opportunities and positively impacting the region's economy.

The study recommended two (2) considerations in implementing NBS 5: the feasibility of geographical conditions and stakeholders' involvement. Gunungkidul Regency's geomorphology is primarily karst, necessitating the implementation of customized strategies that take into account the unique characteristics of the karst aquifers. Artificial reservoirs may be considered to retain large amounts of water in karst areas. Given the forecasted increase in frequency and length of future droughts, stakeholders' involvement is crucial for the sustainable and long-term implementation of this strategy (NBS 5).

The findings of this study have significant applicability to other drought-prone regions and ecosystems in karst regions, offering a framework for sustainable and adaptable agricultural practices. By leveraging local natural features and resources, NBS can be tailored to various ecosystems— karst landscapes, arid zones, or flood-prone areas. In particular, karst regions globally can adopt artificial reservoirs to counteract the lack of surface water. Arid and semi-arid regions can utilize similar water retention strategies by modifying designs to address soil permeability and high evaporation rates. By customizing the strategies based on ecological, social, and economic conditions, the approach can enhance resilience to drought and other climate challenges, supporting sustainable development across various ecosystems.

This study underscores the potential of NBS for agricultural drought adaptation in the karst region of Gunungkidul Regency. However, it is essential to recognize limitations related to data availability and uncertainties regarding the long-term effectiveness of the proposed strategies across different climate scenarios. Future research must enhance these strategies via longitudinal studies and comprehensive monitoring systems to evaluate their long-term effects on agricultural productivity and ecosystem resilience. We recommend integrating community-based participatory approaches and establishing adaptive management frameworks to enable ongoing evaluation and adjustment of these solutions over time.

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Conflict of Interest Statement

We have no conflict of interest to disclose.

AI Disclosure

We declare that this manuscript was prepared without the assistance of artificial intelligence. Hence, the content of this paper is original.

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