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Integrating Spatial Risk Mapping and Environmental Law for Drought Adaptation in Grobogan, Indonesia

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Abstract

This research investigates drought risk in Grobogan Regency, Central Java Province, by linking spatial evidence, social capacity, and legal frameworks to the advancement of the Sustainable Development Goals (SDGs). A hazard–vulnerability–capacity approach, grounded in Geographic Information Systems (GIS), is combined with surveys, Focus Group Discussions (FGDs), and policy analysis. The study generates a risk map identifying priority subdistricts for intervention. Findings indicate fragmented capacity and institutional arrangements across regions, which undermine the effectiveness of drought response. Regulatory analysis reveals implementation gaps between national legal provisions on water resource and disaster management and their operationalization at the regional and village levels. A Comparative analysis of water resource management practices in Malaysia identifies opportunities to harmonize policies and legal instruments, thereby facilitating the translation of spatial findings into actionable local policies. Policy recommendations include strengthening local regulations (Perda) for emergency water allocation, integrating risk maps into the Regional Medium-Term Development Plan (RPJMD) and village development plans, operationalizing community-based early warning systems (EWS), and establishing hybrid financing mechanisms (APBD–APBDes–grants) for water conservation infrastructure. The primary contribution is the demonstration of integrating spatial analysis and legal studies to inform drought adaptation policies that support SDG indicators, particularly SDG 6 (Clean Water and Sanitation), SDG 2 (Zero Hunger), and SDG 13 (Climate Action). Implementation recommendations encompass measurable monitoring indicators, local capacity-building, periodic evaluations, cross-sector collaboration, and transparent public reporting.

KEYWORDS *Spatial risk mapping, Environmental law, Drought adaptation, Geographic Information System (GIS), Sustainable Development Goals (SDGs)*

Introduction

Alterations in global climate patterns have increased both the frequency and intensity of natural disasters, droughts, and floods, resulting in widespread environmental, economic, and societal impacts that impede regional development.[1]These changes led to new threats and heightened vulnerability in regions whose economies rely heavily on natural resources. Drought, as one of the most extreme natural disasters, has significant socio-economic impacts, including crop failure, water shortages, and potential social conflicts, because water supplies from sources such as

[1] Gumus, Veysel, Oguz Simsek, Yavuz Avsaroglu, and Berivan Agun. "Spatio-temporal trend analysis of drought in the GAP Region, Turkey." *Natural Hazards* 109, no. 2 (2021): 1759-1776.

groundwater, rivers, reservoirs, and aquifers are insufficient to meet human needs and the surrounding ecosystems.[23]

Grobogan Regency in Central Java Province frequently experiences drought, which has significant and measurable impacts on local communities. The agricultural sector, which forms the foundation of the regency's economy, encounters persistent challenges in accessing clean water, thereby threatening both productivity and farmer welfare.[4] Data from the Grobogan Regional Disaster Management Agency indicate that 116 villages across 15 subdistricts are classified as drought-prone, with Gabus, Kradenan, and Kedungjati subdistricts experiencing the most severe drought.[5] In 2020, –there were 107 recorded requests for water assistance in 15 subdistricts, with the highest number in Kradenan .[6] This situation persisted in 2021, when Grobogan was among the three most

[2] Xu, Lei, Nengcheng Chen, Chao Yang, Chong Zhang, and Hongchu Yu. "A parametric multivariate drought index for drought monitoring and assessment under climate change." *Agricultural and Forest Meteorology* 310 (2021): 108657.

[3] Vicente-Serrano, Sergio M., Dhais Peña-Angulo, Santiago Beguería, Fernando Domínguez-Castro, Miquel Tomás-Burguera, Iván Noguera, Luis Gimeno-Sotelo, and Ahmed El Kenawy. "Global drought trends and future projections." *Philosophical Transactions of the Royal Society A* 380, no. 2238 (2022): 20210285.

[4] Pranata, Kukuh Aji, and Ananto Aji. "Analisis Spasial Tingkat Potensi Kekeringan dan Tingkat Kesiapsiagaan Masyarakat dalam Menghadapi Bencana Kekeringan di Kabupaten Grobogan." *Indonesian Journal of Conservation* 10, no. 2 (2021): 90-96.

[5] Sartikasari, Diyah Saputri Ayu, Puji Hardati, and Ananto Aji. "The Preparedness of Tunggak Community Dealing with Drought Disaster, Grobogan Regency."

[6] Dewa, Kusuma Hangga, Mochammad Awaluddin, and Laode M. Sabri. "Analisis Lokasi Rawan Bencana Kekeringan Menggunakan Metode Fuzzy Analitycal Hierarchy Process (FAHP) di Kabup." *Jurnal Geodesi Undip* 12, no. 4 (2023): 445-454.

severely affected areas [7], and in 2023, 71 villages were documented as impacted [8], underscoring the persistent threat of drought in the regency.

Drought arises from multiple interrelated causes. Climate change has intensified - and prolonged heat waves, resulting in increasingly limited water supplies.[9] Beyond climatic influences, anthropogenic activities significantly accelerate drought conditions. Practices such as uncontrolled planting, monoculture cultivation, and inadequate land management diminish the land's capacity to retain water and sustain the hydrological cycle.[10] [11] The interplay of natural and human-induced factors complicates mitigation efforts and necessitates a cross-sectoral strategy.

Drought has cross-sectoral impacts, affecting diverse societal groups and environmental components. Typical consequences include water shortages, reduced crop yields, rising food prices, and deteriorating public health.[12] Reduced water availability for agriculture—directly impacts

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[7] Farah, Ulayya Nisrina, Yudo Prasetyo, and Nurhadi Bashit. "Monitoring Potensi Kekeringan di Kabupaten Grobogan Menggunakan Penginderaan Jauh dan Sistem Informasi Geografis." *Media Komunikasi Geografi* 25, no. 1 (2024): 97-119.

[8] Badan Nasional Penanggulangan Bencana (BNPB), "Kekeringan di Pulau Jawa," *Portal Satu Data Bencana Indonesia*, 2023, accessed January 31, 2025, https://data.bnpb.go.id/pages/kekeringan-pulau-jawa.

[9] Kim, Kyung-Hee, and Byung-Moo Lee. "Effects of climate change and drought tolerance on maize growth." *Plants* 12, no. 20 (2023): 3548.

[10] Van Loon, Anne F., Tom Gleeson, Julian Clark, Albert IJM Van Dijk, Kerstin Stahl, Jamie Hannaford, Giuliano Di Baldassarre et al. "Drought in the Anthropocene." *Nature Geoscience* 9, no. 2 (2016): 89-91.

[11] Gomiero, Tiziano. "Soil degradation, land scarcity and food security: Reviewing a complex challenge." *Sustainability* 8, no. 3 (2016): 281.

[12] Udmale, Parmeshwar, Yutaka Ichikawa, Sujata Manandhar, Hiroshi Ishidaira, and Anthony S. Kiem. "Farmers' perception of drought impacts, local adaptation and administrative mitigation measures in Maharashtra State, India." *International journal of disaster risk reduction* 10 (2014): 250-269.

agricultural growth and productivity.[13] Prolonged droughts may also cause environmental degradation, heighten food insecurity, diminish human well-being, and, under certain circumstances, provoke social unrest.[14][15]

Societal adaptive capacity to drought is frequently constrained by limited access to resources, insufficient management knowledge and skills, and inadequate extension support and policies.[16] Consequently, the implementation of more effective mitigation and adaptation strategies is required, such as spatial risk-mapping and the development of context-specific management models. Spatial analysis using Geographic Information System (GIS) and satellite imagery enables the identification of drought distribution patterns and the most vulnerable regions, thereby enabling more targeted intervention prioritization. This approach is consistent with the disaster risk assessment framework, which integrates hazard, vulnerability, and capacity components to develop risk reduction strategies.[17]

Climate change is altering the global hydrological cycle, resulting in increased frequency and intensity of extreme hydrometeorological events such as droughts, as comprehensively documented in the

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[13] Brás, Teresa Armada, Júlia Seixas, Nuno Carvalhais, and Jonas Jägermeyr. "Severity of drought and heatwave crop losses tripled over the last five decades in Europe." *Environmental Research Letters* 16, no. 6 (2021): 065012.

[14] Malau, L. R. E., and A. T. Darhyati. "The impact of climate change and natural disasters on food security in Indonesia: lessons learned on preserving forests sustainability." In *IOP conference series: Earth and environmental science*, vol. 886, no. 1, p. 012090. IOP Publishing, 2021.

[15] Edossa, Desalegn C., Yali E. Woyessa, and Worku A. Welderufael. "Analysis of droughts in the central region of South Africa and their association with SST anomalies." *International Journal of Atmospheric Sciences* 2014, no. 1 (2014): 508953.

[16] Bahta, Y. T., A. Jordaan, and F. Muyambo. "Communal farmers' perception of drought in South Africa: Policy implication for drought risk reduction." *International Journal of Disaster Risk Reduction* 20 (2016): 39-50.

[17] Badan Nasional Penanggulangan Bencana (BNPB), *Peraturan Kepala Badan Nasional Penanggulangan Bencana (Perka BNPB) Nomor 2 Tahun 2012 tentang Pedoman Umum Pengkajian Risiko Bencana* (Jakarta: Badan Nasional Penanggulangan Bencana, 2012).

Intergovernmental Panel on Climate Change (IPCC) report and recent scientific summaries.[18] These findings establish a robust scientific foundation indicating that regions such as Grobogan face heightened risks of more frequent and severe drought events in the future, underscoring the need to incorporate evidence-based adaptation into regional planning.

The adverse effect of drought on food security and agricultural productivity is well-documented in both global and regional studies. Reports from the Food and Agriculture Organization (FAO) and empirical research demonstrated that drought accounts for a substantial share of agricultural yield losses and intensifies food security risks, especially in rainfed farming systems prevalent across many regions of Indonesia.[19] These findings highlight the importance of prioritizing SDG 2 (Zero Hunger) and SDG 6 (Clean Water and Sanitation) in the development of drought management interventions.

Drought management in Indonesia is governed by several legal and institutional frameworks, including the Disaster Management Law (Law No. 24/2007), the Water Resources Law (Law No. 17/2019), and the Environmental Protection and Management provisions (PPLH; Law No. 32/2009). These laws collectively provide the legal basis for central and regional authorities to undertake planning, resource management, and emergency response to drought events. Nevertheless, studies at the regency and village levels reveal a gap between statutory requirements and operational capacity, as evidenced by insufficient budget allocations, limited cross-sectoral coordination, and a lack of integrated monitoring systems. Therefore, incorporating spatial-analytical findings into subnational policy instruments such as regional regulations (Perda),

[18] Intergovernmental Panel on Climate Change (IPCC), "AR6 Synthesis Report: Climate Change 2023," IPCC, 2023, accessed September 25, 2025, https://www.ipcc.ch/report/sixth-assessment-report-cycle/.

[19] Food and Agriculture Organization of the United Nations (FAO), *The Impact of Disasters and Crises on Agriculture and Food Security* (Rome: FAO, 2021), https://doi.org/10.4060/cb3673en.

regional mid-term development plans (RPJMD), and village development workplans (RKPDes) is critical to ensure that technical interventions are supported by a robust and enforceable legal-regulatory framework.

The Grobogan case offers empirical evidence supporting the need for targeted interventions. Reports from BPBD reports and local academic research indicate a high frequency of water assistance requests, the presence of vulnerable villages, and concentrated impacts within specific sub-districts. This evidence should inform the development of priority zoning, local funding mechanisms, and a legally mandated response standard operating procedure (SOP).[20] Furthermore, linking spatial findings to Sustainable Development Goal (SDG) targets, such as indicators 6.4.1 and 6.4.2 for water-use efficiency and water stress, enables district regions to establish measurable monitoring indicators that are consistent with national and international frameworks.

The adaptation literature demonstrates that effective drought risk reduction requires not only technical solutions, such as reservoirs, soil conservation, and irrigation, but also institutional strengthening, robust local economies through hybrid financing mechanisms, and active community participation via community-based Early Warning Systems (EWS).[21] Accordingly, this research employs spatial analysis as an evidentiary basis for developing concrete policy recommendations and legal-operational mechanisms, enabling its contribution to be assessed in relation to the achievement of the SDGs at the local level.

The research was conducted in Grobogan Regency, Central Java. The study population comprised the physical conditions of the field units and communities in drought-prone areas. A purposive sampling method was

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[20] Dewa, Kusuma Hangga, Mochammad Awaluddin, and Laode M. Sabri. "Analisis Lokasi Rawan Bencana Kekeringan Menggunakan Metode Fuzzy Analityeal Hierarchy Process (FAHP) di Kabup." *Jurnal Geodesi Undip* 12, no. 4 (2023): 445-454.

[21] Liu, Zihao, Aifeng Lv, and Taohui Li. "Intensified Drought Threatens Future Food Security in Major Food-Producing Countries." *Atmosphere* 16, no. 1 (2024): 34.

employed to select 56 households previously affected by drought. The research utilized an observational and descriptive-quantitative design to assess threats (including rainfall, water sources, soil type, groundwater depth, and drought index/NDDI from Landsat imagery), vulnerability (social, physical, economic, and environmental factors), community capacity (institutional structures, risk assessment, knowledge and education, reduction of underlying risk factors, and preparedness), drought management, and regulations relevant regulations and SDGs. Data collection involved secondary sources from BPS, BPBD, and BMKG, as well as maps and Landsat satellite imagery. Primary data were obtained through questionnaire surveys of 56 households, semi-structured interviews with local leaders and policymakers, field observations, and Focus Group Discussions (FGDs) to identify local management practices and needs. The analysis included scoring indicators, determining weights using the Analytic Hierarchy Process (AHP) with stakeholders and experts input, calculating the risk index using the BNPB formula ($R = H \times V / C$), spatial integration and map overlay with ArcGIS to classify risk levels, and a review of regulations to identify implementation gaps between national legal provisions on water resource management and disaster mitigation and operational practices at regional and village levels.

DROUGHT RISK LEVEL IN GROBOGAN REGENCY

Drought disaster risk mapping involves assessing hazards, vulnerability, and community capacities related to drought events.

1. Drought Hazards Levels in Grobogan Regency

The calculation of the drought hazard level utilizes five parameters, including a modified vegetation index. These parameters are rainfall, groundwater depth, soil type, distance from rivers, and the Normalized Difference Drought Index (NDDI). Each parameter is assigned a score based on its values and is subsequently weighted. After the final weighting, the final scores are aggregated and classified into drought categories. The resulting map reflects these parameters and their respective weightings.

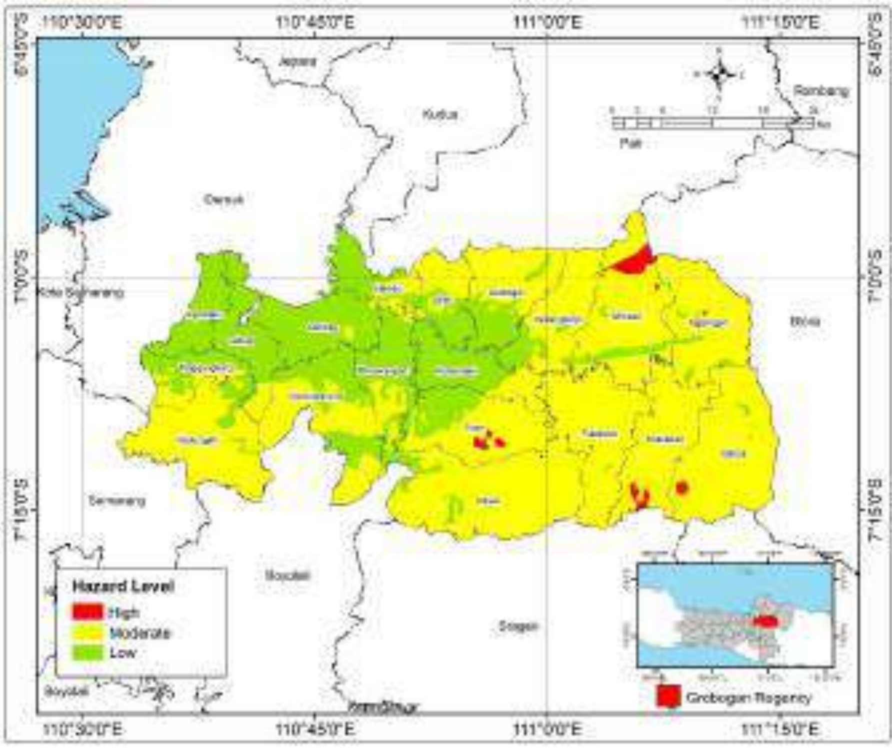

FIGURE 1. Drought Hazard Map of Grobogan Regency

TABLE 1. Drought Hazard Level and Area (Ha) in Grobogan Regency

No.	Hazard Level	Area (Ha)	Percentage
1	Low	61.722,76	30,5
2	Moderate	138.443,4	68,5
3	High	1.904,316	0,9
Total		202.070,5	100

Sources: Analysis Result, 2025

Drought hazard tables and maps for Grobogan Regency indicate that the majority of the area is classified as moderate risk (68.5%), with 30.5%

categorized as low risk and only 0.9% as high. This distribution aligns with previous studies, which reported over 80% of the region in the moderate risk class. High-risk zones are sporadic and are localized, particularly in Toroh and Kradenan, which are known to be drought-prone. The highest concentration of requests for water assistance is observed in Toroh, Kradenan, Geyer, and Pulokulon.[22][23] These findings suggest that mitigation efforts should be implemented at the district scale with moderate vigilance, while water infrastructure policies and investments, such as small reservoirs, dams, and rainwater harvesting systems, should be prioritized in high-risk areas to enhance local resilience.

2. Vulnerability Level of Drought in Grobogan Regency

The drought vulnerability calculation is calculated using the formula from BNPB Regulation No. 02 of 2012 as follows:

$$IKK = (IKS \times 50\%) + (IKE \times 40\%) + (IKL \times 10\%)$$

Where

IKK : *Indeks Kerawanan Kekeringan* (Drought Vulnerability Index)

IKS : *Indeks Kerawanan Sosial* (Social Vulnerability Index)

IKE : *Indeks Kerawanan Ekonomi* (Economic Vulnerability Index)

IKL : *Indeks Kerawanan Lingkungan* (Environmental Vulnerability Index)

Following the completion of calculations, the results were classified using the jerking break method into three categories: low, medium, and high. The results of the vulnerability calculations and their classification are presented below:

[22] S. Anwar, "Atasi kekeringan, 2 desa di Grobogan dibantu alat pemanen air hujan," *Murianews*, 24 Juli 2025, accessed September 25, 2025, https://berita.murianews.com/saiful-anwar/445217/atasi-kekeringan-2-desa-di-grobogan-dibantu-alat-pemanen-air-hujan

[23] Farah, Ulayya Nisrina, Yudo Prasetyo, and Nurhadi Bashit. "Monitoring Potensi Kekeringan di Kabupaten Grobogan Menggunakan Penginderaan Jauh dan Sistem Informasi Geografis." *Media Komunikasi Geografi* 25, no. 1 (2024): 97-119.

TABLE 2. Drought Vulnerability Score in Grobogan Regency

No	Sub-district	Social Vulnerability	Economy Vulnerability	Environment Vulnerability	Drought Vulnerability Score	Vulverability Class
1	Brati	0,46	0,5	0,26	0,457	Moderate
2	Gabus	0,46	0,5	0,26	0,457	Moderate
3	Geyer	0,44	0,5	0,37	0,457	Moderate
4	Godong	0,46	0,5	0,26	0,457	Moderate
5	Grobogan	0,46	0,5	0,26	0,457	Moderate
6	Gubug	0,49	0,5	0,26	0,473	High
7	Karangrayung	0,46	0,5	0,26	0,457	Moderate
8	Kedungjati	0,44	0,5	0,26	0,444	Low
9	Klambu	0,47	0,5	0,26	0,462	High
10	Kradenan	0,46	0,5	0,26	0,457	Moderate
11	Ngaringan	0,46	0,5	0,26	0,457	Moderate
12	Penawangan	0,46	0,5	0,26	0,457	Moderate
13	Pulokulon	0,46	0,5	0,37	0,467	High
14	Purwodadi	0,49	0,5	0,20	0,467	High
15	Tanggungharjo	0,46	0,5	0,26	0,457	Moderate
16	Tawangharjo	0,46	0,5	0,26	0,457	Moderate
17	Tegowanu	0,49	0,5	0,22	0,469	High
18	Toroh	0,49	0,5	0,26	0,473	High
19	Wirosari	0,46	0,5	0,26	0,457	Moderate

Sources: Analysis Result, 2025

Among the 19 subdistricts in Grobogan Regency, eleven are classified as having moderate drought vulnerability, including Brati, Gabus, Godong, Grobogan, and Karangrayung. Six subdistricts, namely Gubug, Klambu, Pulokulon, Purwodadi, Tegowanu, and Toroh, fall into the high vulnerability category. Only Kedungjati is categorized as having low vulnerability, distinguished by a lover social vulnerability score of 0.44, thereby reducing the regency's average vulnerability score. Subdistricts with high vulnerability typically exhibit a social vulnerability score of 0.47 or higher. Environmental factors also play a significant role in these variations; for instance, Pulokulon has an environmental score of

0.37. Economic vulnerability scores are relatively consistent across all subdistricts, averaging approximately 0.5. Consequently, spatial differences in vulnerability are primarily influenced by social and environmental factors. Vulnerability maps for each subdistrict are provided to identify priority intervention locations.

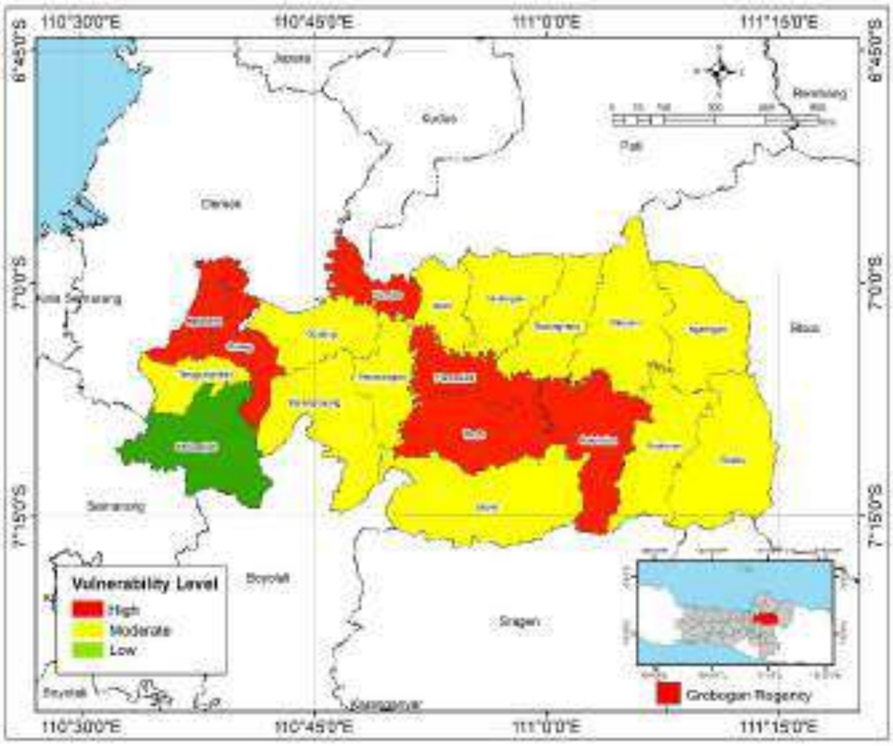

FIGURE 2. Drought Vulnerability Map of Grobogan Regency

3. Assessment of Community Capacity to Address Drought in Grobogan Regency

Questionnaire results from 56 respondents in five sub-districts showed that community capacity to cope with drought was low, with an average of 36%. Pulokulon ranked highest at 53.1% (moderate), as institutions and some operational practices are in place. However, this area still lacks funding, facilities, human resources, and disaster education. Kradenan scored 43.1%, showing strong administrative legitimacy but weaknesses in EWS and literacy; Toroh achieved 34.6% with a relatively complete regulatory structure (78.6%) but minimal support from early warning systems (7.3%) and disaster education (16.1%). Purwodadi, at 25.3%, has regulations in place (62.5%) but limited technical and educational support. Geyer scored lowest, at 24.7%, with critical deficiencies in early warning and crossline preparedness, which are still almost non-existent.

Analysis at the combined sub-district level reveals a pronounced imbalance: while rules and institutions are robust (70.3%), early warning and risk assessment remain very low (17.0%), disaster education is low (20.1%), basic risk reduction is moderate (44.3%), and cross-sectoral preparedness is weak (29.4%). This indicates that the current formal structure does not ensure effective protection, primarily due to insufficient data and studies, inadequate detection systems, limited community literacy, constrained budgets, and a lack of operational training. These deficiencies may result in delayed detection, fragmented response, and low community preparedness during drought events. Recommended priority interventions are as follows: (1) strengthen basic early warning systems and update risk map and studies; (2) implement integrated disaster education programmes in schools and communities to enhance literacy and response behaviour; (3) allocate funding and increase human resources for logistics, training, and emergency budget mechanisms; and (4) initiate pilot projects in Pulokulon or Kradenan to demonstrate effective practices and support scaling up to other sub-districts.

TABLE 3. Percentage of Community Capacity in Facing Drought in Grobogan Regency

No	Sub-district	Disaster management regulations and institutions	Early warning and disaster risk assessment	Disaster education	Reduction of basic risk factors	Building preparedness across all lines	Capacity Level	Category
1	Pulokulon	55,2	45,8	38	60,8	62	53,1	Moderate
2	Purwodadi	62,5	12,5	13,1	19,6	21,9	25,3	Low
3	Toroh	78,6	7,3	16,1	45,5	19,8	34,6	Low
4	Geyer	75,6	1,3	2,5	35,4	3,1	24,7	Low
5	Kradenan	79,2	14,6	26,6	54,9	34,4	43,1	Moderate

Total	70,3	17	20,1	44,3	29,4	36,22	Low

Sources: Analysis Result, 2025

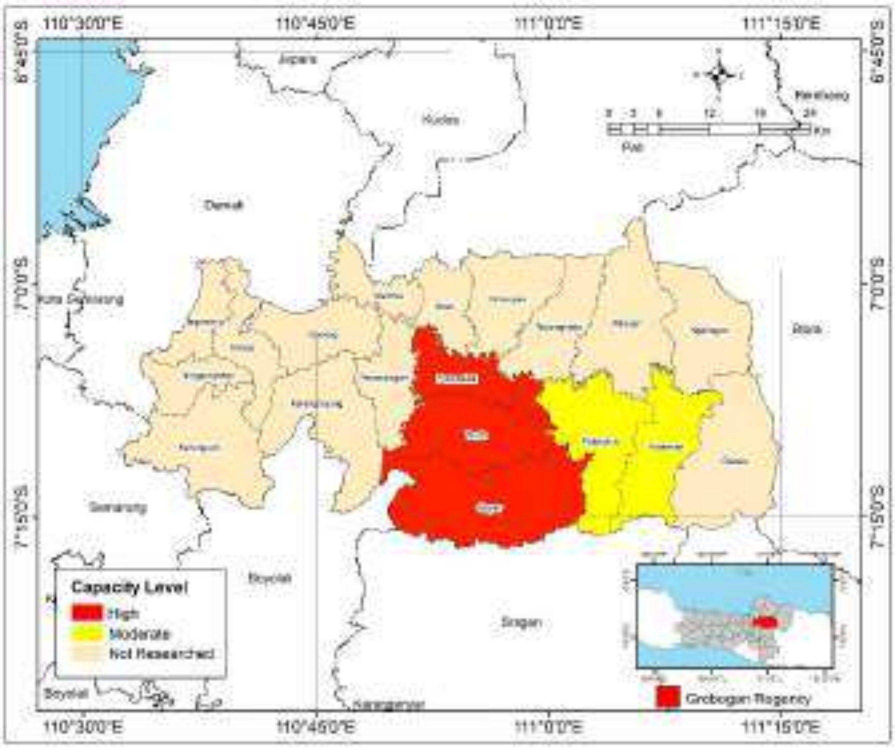

FIGURE 3. Map of Community Capacity in Facing Drought in Grobogan Regency

4. Risk Level of Drought in Grobogan Regency

The overlay analysis covers a total area of 65,746.13 ha, with risk distributed as follows: low, 36,020.14 ha (54.8%); moderate, 19,123.55 ha (29.1%); and high, 10,602.43 ha (16.1%). These results indicate that most of the area is classified as low risk, suggesting relatively greater resilience to drought. Nevertheless, a substantial portion (45% in the combined moderate and high-risk categories) remains vulnerable. Particular attention is warranted for high-risk areas, although smaller in extent, that have the potential to cause significant losses to the agricultural sector and the clean water supply. It is recommended to prioritize interventions in high-risk and adjacent moderate-risk areas through technical mitigation programs, water conservation initiatives, and community capacity building. Regular monitoring and updates to risk maps or studies are also advised to prevent moderate-risk areas from escalating to high risk.

TABLE 4. Drought Risk Level and Area (Ha) in Grobogan Regency

No.	Risk Level	Area (Ha)	Percentage
1	Low	36.020,14	54,8
2	Moderate	19.123,55	29,1
3	High	10.602,43	16,1
		65.746,13	100,0

Sources: Analysis Result, 2025

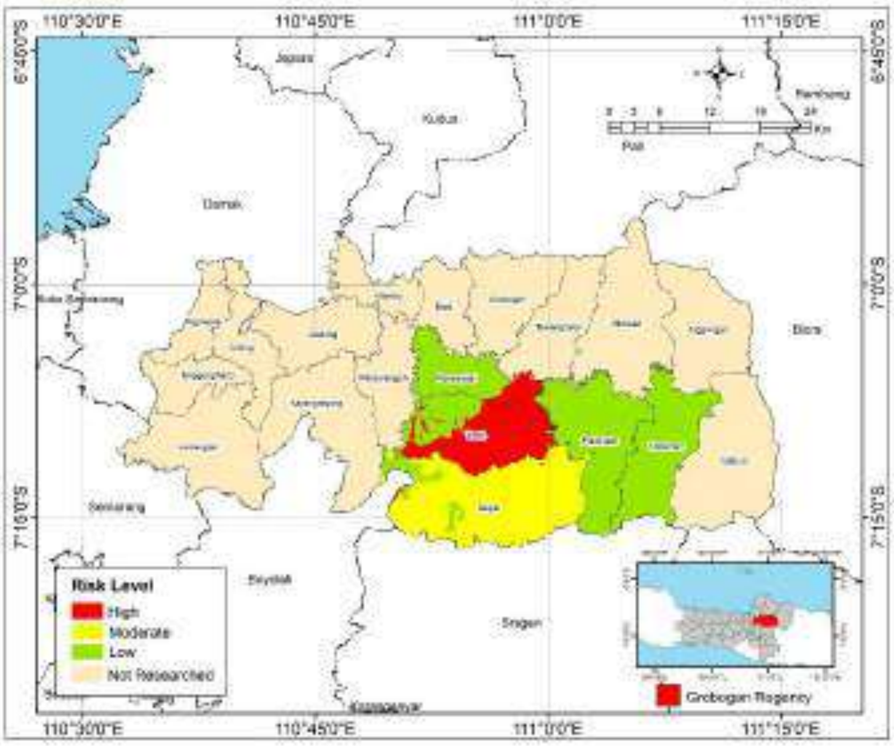

FIGURE 4. Drought Risk Map of Grobogan Regency

Low rainfall, gentle topography, and dry land cover collectively increase drought risk, whereas urban areas and fertile land demonstrate a greater capacity to mitigate such risk. The agricultural sector is particularly affected, as reduced irrigation supply, crop failure, and environmental degradation threaten both livelihoods and socio-economic stability.[24] The literature recommends community-based mitigation strategis, including water conservation infrastructure, diversification of drought-resistant crops, and community participation, alongside integrated spatial risk mapping tailored to local conditions to develop effective adaptation strategies.[25][26] Spatial risk mapping is anticipated to inform regional environmental laws and policies, such as the formulation of region-specific drought adaptation policies in Grobogan and the revision of regional environmental regulations. At the national level, spatial risk mapping is expected to support the integration of national spatial planning policies and the enhancement of environmental instruments within development planning.

IMPLICATIONS OF RISK MAPPING FOR ENVIRONMENTAL LAW AND POLICY

Risk maps that integrate hazard, vulnerability, and capacity elements provide essential spatial evidence for targeting adaptation interventions at priority locations. These maps serve not only as scientific tools for visualizing threats but also as operational instruments for determining budget allocation, EWS design, and adaptation performance monitoring indicators, as demonstrated by methodological literature and

[24] Faizah, Nuraimmatul, and Imam Buchori. "Model Pemetaan Risiko Kekeringan Di Kabupaten Bima, Nusa Tenggara Barat." PhD diss., UNIVERSITAS DIPONEGORO, 2018.

[25] Rahman, Ghani, Min-Kyu Jung, Tae-Woong Kim, and Hyun-Han Kwon. "Drought impact, vulnerability, risk assessment, management and mitigation under climate change: A comprehensive review." *KSCE Journal of Civil Engineering* 29, no. 1 (2025): 100120.

[26] Brill, Fabio, Pedro Henrique Lima Alencar, Huihui Zhang, Friedrich Boeing, Silke Hüttel, and Tobia Lakes. "Exploring drought hazard, vulnerability, and related impacts on agriculture in Brandenburg." *Natural Hazards and Earth System Sciences* 24, no. 12 (2024): 4237-4265.

case studies in drought risk and climate adaptation assessments.[27] However, the experience in Grobogan reflects a pattern observed in other regions of Indonesia: fragmentation between the national legal framework, including the Disaster Management Law, water resource management regulations, and Sendai-aligned Disaster Risk Reduction (DRR) policies, and the implementation capacity at the provincial, district, and village levels. This fragmentation arises when national norms are general and binding but are not translated into local regulations, fiscal mechanisms to ensure program sustainability, or clear operational standard operating procedures (SOPs) for local actors. These findings are consistent with the national DRR status report and legal studies documenting gaps in implementation and emphasize the need to strengthen sub-national legal instruments.[28]

The literature identifies several technical and institutional barriers that significantly hinder the translation of risk maps into policy. First, data interoperability issues arise when maps are compiled by multiple parties without standardized metadata and format requirements, complicating their integration into regional planning systems or decision-making dashboards. Second, fiscal-legal instruments often lack local provisions for allocating mitigation budgets or clear financial mechanisms, such as baseline mitigation budgets and water emergency funds, which impede the conversion of spatial evidence into operational actions. Third, limited legal and technical capacity at the village or sub-district level frequently results in maps remaining as 'academic documents' without legal or budgetary impact. Studies on risk-based budgeting and the integration of disaster risk reduction (DRR) into local spatial planning corroborate these

[27] Mens, Marjolein, Gigi van Rhee, Femke Schasfoort, and Neeltje Kielen. "Integrated drought risk assessment to support adaptive policy making in the Netherlands." Natural Hazards and Earth System Sciences Discussions 2022 (2022): 1-24.

[28] United Nations Office for Disaster Risk Reduction, *UNDRR Annual Report 2020* (Geneva: United Nations Office for Disaster Risk Reduction, 2021), 54.

obstacles.[29]Regarding Early Warning Systems (EWS), legal literature and system evaluations indicate that although national policies recognize the authority and function of EWS, gaps persist in implementation rules at the sub-national level. These include the obligation to share responsibilities, communication protocols among BMKG, BPBD, and communities, and legal mandates for system maintenance and renewal. Such gaps ultimately reduce the effectiveness of community EWS in practice. Legal studies on EWS in Indonesia recommend strengthening the operational mandate through clear local legal instruments.[30]

Regional studies from Malaysia and water resource management literature indicate that integrating monitoring dashboards, enacting water policies that regulate financing for conservation infrastructure, and establishing legal mechanisms to recognize community roles in water management can expedite the application of spatial evidence. Research on hydrological drought in Peninsular Malaysia highlights the significance of data-driven planning, reporting mechanisms, and structured financial support, which are pertinent for formulating local regulations and hybrid financing mechanisms (APBD–APBDes–grants/CSR) in Grobogan.[31]

Additionally, developing fiscal-legal instruments that connect risk maps to diverse financing sources (public, private, philanthropic) enhances the sustainability of adaptation interventions. These findings support the recommendation that spatial evidence should be reinforced by local regulations mandating the integration of risk maps into RPJMD/RKPDes (Regional Medium-Term Development Plans/Village Work Plans),

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[29] Haris, Nurhayati, Andi C. Furqan, Abdul Kahar, and Fikry Karim. "Disaster risk index on disaster management budgeting: Indonesia's national data set." *Jamba-Journal of Disaster Risk Studies* 15, no. 1 (2023): 1365.

[30] Thontowi, Mujiburrahman. "Legal Framework for Multi-Hazard Early Warning System in Indonesia," n.d.

[31] Hasan, Hasrul Hazman, Siti Fatin Mohd Razali, Nur Shazwani Muhammad, and Asmadi Ahmad. "Hydrological drought across Peninsular Malaysia: implication of drought index." *Natural Hazards and Earth System Sciences Discussions* 2021 (2021): 1-28.

explicit allocation of mitigation budget, technical data standards for interoperability, and legal recognition of community EWS to ensure continuity.[32]

Addressing the policy translation gap in Grobogan necessitates a set of integrated actions: (1) legalizing the integration of risk maps, which identify and visualize hazard-prone areas into planning documents through local regulations or decree; (2) establishing fiscal arrangements that include dedicated mitigation budget items for disaster risk reduction and mechanisms for accessing hybrid financing; (3) implementing metadata and interoperability standards to ensure that maps are usable in legislative and reporting processes; and (4) clarifying the operational mandate for community EWS managed by local communities. These measures should be supported by legal-technical capacity-building programs for regional government staff and by public accountability mechanisms to ensure transparency in SDG indicator-based reporting.[33]

INTEGRATION WITH SUSTAINABLE DEVELOPMENT GOALS (SDGS)

The risk map generated in this study serves as both a spatial indicator of local threats and a mechanism for aligning SDG goals, specifically SDG 6 (Clean Water and Sanitation), SDG 2 (Zero Hunger), and SDG 13 (Climate Action), with regional policies and reporting frameworks. Spatial evidence supports the development of localized indicators, including the proportion of villages with risk maps

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[32] Yayasan Humanis dan Inovasi Sosial and Climate Policy Initiative, *Inclusive Climate Finance: Improving Access for Marginalized Populations in Indonesia* (Jakarta: Climate Policy Initiative, 2023), 14.

[33] Haris, Nurhayati, Andi C. Furqan, Abdul Kahar, and Fikry Karim. "Disaster risk index on disaster management budgeting: Indonesia's national data set." *Jamba-Journal of Disaster Risk Studies* 15, no. 1 (2023): 1365.

incorporated into their Regional Medium-Term Development Plan (RPJMD) or Village Work Plan (RKPDes), the number of micro-reservoirs per 1,000 ha, and the average emergency water distribution response time. These indicators facilitate adaptation planning and SDG performance reporting at the sub-national level.[34] In relation to SDG 6, existing literature highlights that reliable water services depend on the integration of governance, monitoring technology, and financing, all of which are advanced through risk mapping.

The mapping process informs the prioritization of investment in conservation infrastructure, such as reservoirs, controlled wells, rainwater harvesting systems, and identifies critical interventions to ensure water availability during dry periods.[35] For SDG 2, the risk map reveals that the high-risk zone predominantly coincides with rain-fed agricultural areas and vulnerable households. Consequently, targeted interventions-including micro-irrigation, emergency water reserves, and drought-resistant agricultural practices can mitigate production losses and sustain local food access.[36] Regarding SDG 13, risk maps function both as tools for identifying vulnerabilities to inform adaptation strategies and as a baseline for evaluating the effectiveness of adaptive measures such as annual reductions in exposure or vulnerability. This approach aligns with

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[34] Rivera, Rayén, Carlos Leal, and Ricardo O. Barra. "Toward Water Security (SDG 6) amidst the Climate and Water Crisis: Lessons from Chile." *Environmental Science & Technology* 57, no. 35 (2023): 12940-12943.

[35] Evaristo, Jaivime, Yusuf Jameel, Cecilia Tortajada, Raymond Yu Wang, James Horne, Howard Neukrug, Carlos Primo David, Angela Maria Fasnacht, Alan D. Ziegler, and Asit Biswas. "Water woes: the institutional challenges in achieving SDG 6." *Sustainable Earth Reviews* 6, no. 1 (2023): 13.

[36] Ansari, Andrianto, Arin Pranesti, Marcli Telaumbanua, Taufan Alam, Rani Agustina Wulandari, and Bayu Dwi Apri Nugroho. "Evaluating the effect of climate change on rice production in Indonesia using multimodelling approach." *Heliyon* 9, no. 9 (2023).

research advocating for the integration of climate adaptation into development planning and the assessment of climate policy performance.[37]

Empirical and methodological evidence strongly support this integration. Studies mapping interactions between SDG targets and those examining geospatial data for SDG monitoring demonstrate that GIS and risk maps enhance local governments' capacity to design targeted policies and quantitatively report progress. Examples include downscaling SDG6 indicators, developing monitoring dashboards, and mapping food insecurity.[38] Nevertheless, many studies indicate that this potential is fully realized only with strengthened governance, improved data interoperability through metadata standards and regular updates, and structured financing. Without fiscal-legal instruments and coordination mechanisms, risk maps often remain technical outputs without sustainable policy impact.[39] Furthermore, recent research on drought policy and risk management underscores the necessity of a comprehensive set of measures. These include monitoring and early warning systems, protection of water sources, socio-economic support for farmers, and hybrid financing mechanisms to maintain the stability of SDG achievements in drought-prone regions.[40]

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[37] Filho, Walter Leal, Tony Wall, Amanda Lange Salvia, Maria Alzira Pimenta Dinis, and Mark Mifsud. "The central role of climate action in achieving the United Nations' Sustainable Development Goals." *Scientific Reports* 13, no. 1 (2023): 20582.

[38] Nilsson, Måns, Elinor Chisholm, David Griggs, Philippa Howden-Chapman, David McCollum, Peter Messerli, Barbara Neumann, Anne-Sophie Stevance, Martin Visbeck, and Mark Stafford-Smith. "Mapping interactions between the sustainable development goals: lessons learned and ways forward." *Sustainability science* 13, no. 6 (2018): 1489-1503.

[39] Koehler, Johanna Karolina Louise. "Not all risks are equal: a risk governance framework for assessing the water SDG." *International Environmental Agreements: Politics, Law and Economics* 23, no. 2 (2023): 179-189.

[40] Masih, Ilyas. "An evaluation of the alignment of drought policy and planning guidelines with the contemporary disaster risk reduction agenda." *Natural Hazards and Earth System Sciences* 25, no. 7 (2025): 2155-2178.

National and regional literature on Indonesia and the Grobogan study area indicates that integrating risk maps into planning documents such as RPJMD and RKPDes, adapting SDG indicators for the sub-district and village levels, and establishing a defined mitigation budget allocation are essential for achieving SDG targets 6, 2, and 13.[41] Recent global research on water scarcity hotspots and heightened extreme risks highlights the urgent need to utilize local spatial evidence in conjunction with adaptive SDG strategies. Consequently, Grobogan should implement risk maps as instruments to align planning, legal frameworks, and financing to secure water services, protect food production, and fulfill climate commitments in a measurable manner.[42]

COMPARISON OF PRACTICES BETWEEN GROBOGAN AND MALAYSIA

The Grobogan study indicates that drought risk in this drought-prone region of Indonesia is shaped by localized spatial vulnerability, differing institutional capacity, and significant dependence on community water initiatives. These factors are evident in both the drought risk mapping study in Grobogan and the evaluation of local community preparedness.[43] Water management at the village and district levels in Indonesia is characterized by pluralistic approaches, including PDAM, national programs such as Pamsimas and PAMDES, BUMDes, mutual assistance initiatives, and rainwater harvesting. However, formal institutions frequently encounter fiscal limitations, technical

[41] Juliannisa, Indri Arrafi, Hania Rahma, Sri Mulatsih, and Akhmad Fauzi. "Regional Vulnerability to Food Insecurity: The Case of Indonesia." *Sustainability* 17, no. 11 (2025): 4800.

[42] Ravinandrasana, V.P., Franzke, C.L.E. The first emergence of unprecedented global water scarcity in the Anthropocene. *Nat Commun* 16, 8281 (2025). https://doi.org/10.1038/s41467-025-63784-6.

[43] Munawaroh, L., and G. P. Pramulatsih. "Drought Sensitivity Modeling in Grobogan Regency, Central Java Indonesia."

standardization issues, and operational capacity challenges, which hinder the sustainability of small-scale infrastructure.[44] Legally and politically, while the national framework-comprising the Disaster Management Law, water resource management regulations, and sustainable development policies- offers a foundational structure, its implementation into enforceable sub-national instruments such as local regulations that allocate mitigation budgets, establish EWS SOPs, and mandate the integration of risk maps into RPJMD/RKPDes remains constrained by challenges identified in studies on DRR implementation and risk-based budgeting in Indonesia.[45] The literature indicates progress in Malaysia regarding regional and state-level water policy integration, the implementation of Integrated Water Resources Management (IWRM) principles in multiple basins, and initiatives to streamline the water legal framework to enhance inter-agency coordination and improve access to funding for water conservation projects.[46] Additionally, Malaysia has developed more structured monitoring systems and planning mechanisms, including dashboards and periodic reporting tools, which facilitate the integration of scientific and spatial evidence into policy decision-making.

The combination of these practices and fiscal policies that facilitate funding for mitigation projects reduces the likelihood that risk maps will remain solely academic outputs.[47] It is important that the Malaysian

[44] Kurniatin, Putri Rut Elok, and Irfan Ridwan Maksum. "Sustainable strategy for community-based drinking water supply (PAMSIMAS) post program in rural Indonesia." *Journal of Governance and Public Policy* 9, no. 3 (2022): 211-224.

[45] Daniel Tsegai and Reza Ardakanian, eds., *Capacity Development to Support National Drought Management Policies for Asia-Pacific Countries*, UNW-DPC Proceedings No. 13 (UN-Water Decade Programme on Capacity Development, January 2015).

[46] Elfithri, Rahmah, and Mazlin Bin Mokhtar. "Integrated water resources management in Malaysia: Some initiatives at the basin level." In *Water Resources Management: Select Proceedings of ICWEES-2016*, pp. 231-244. Singapore: Springer Singapore, 2017.

[47] Fulazzaky, Mohamad Ali, Achmad Syafiuddin, Khalida Muda, Abraham Yazdi Martin, Zulkifli Yusop, and Noor Hisham Ab Ghani. "A review of the management of water resources in Malaysia

context cannot be directly replicated, as significant differences exist in institutional scale, decentralization structure, and fiscal resources. Nonetheless, several actionable lessons emerge: (1) standardizing data interoperability and developing integrated dashboards accelerates the use spatial evidence in planning; (2) establishing legal and financial instruments that ensure transparent funding flows for conservation and water storage infrastructure enhance the sustainability of interventions; and (3) formally recognizing and providing legal frameworks for community roles, such as small water source managers and community EWS operators, supports the continuity of local practices and enables effective scaling.[48]

It is recommended that Grobogan and comparable districts in Indonesia develop comprehensive institutional policies that integrate disaster risk management into district planning and financing. This integration can be accomplished by (a) enacting local regulations or decrees that require the inclusion of risk maps into the RPJMD/RKPDes and the allocation of mitigation budgets ; (b) establishing technical standards for metadata and data interoperability to ensure that maps are accessible to regional planners and finance officials; (c) creating a district-level risk monitoring dashboard with performance indicators including those related to SDGs; and (d) granting legal recognition to community organizations managing water resources or EWS operations, enabling them to receive formal funding and technical support. These are informed by research on Integrated Water Resources Management (IWRM), risk-

facing climate change." *Environmental Science and Pollution Research* 30, no. 58 (2023): 121865-121880.

[48] Hafidh, Rifqi Abdul, Ida Widianingsih, and Achmad Buchari. "The Practice of Community-Based Water Resource Management in Rural Indonesia." *Journal of Governance* 6, no. 2 (2021): 216-230.

based budgeting, and community practices in Indonesia, and relevant lessons from the Malaysian context.[49]

EVIDENCE-BASED, MEASURABLE, AND OPERATIONAL POLICY RECOMMENDATIONS

Transforming spatial and institutional findings in Grobogan into sustainable drought adaptation policies requires a clear, measurable, and spatially evidence-based set of regulatory recommendations. First, the integration of drought risk maps into regional and village planning should be mandated through local regulations (Perda/Perkada) to ensure that priority intervention zones receive appropriate attention. The effectiveness of this approach is supported by GIS and SDG monitoring literature, which demonstrates that the formal use of geospatial technology in planning enhances the accuracy of resource allocation and increases policy transparency.[50]

Second, the allocation of drought mitigation budgets should be secured through local fiscal regulations. Local regulations or decrees need to establish specific mitigation budget items within the regional budget (APBD) and define transfer mechanisms to the village budget (APBDes) for water conservation projects, such as micro reservoirs and controlled wells. In Indonesia, community-based resilience programs frequently encounter funding disruptions in the absence of fixed allocation

[49] Meran, Georg, Markus Siehlow, and Christian von Hirschhausen. "Integrated water resource management: Principles and applications." In *The economics of water: rules and institutions*, pp. 23-121. Cham: Springer International Publishing, 2020.

[50] Qwaider, Sara, Baqer Al-Ramadan, Md Shafiullah, Asif Islam, and Muhammed Y. Worku. "GIS-based progress monitoring of SDGs towards achieving Saudi vision 2030." *Remote Sensing* 15, no. 24 (2023): 5770.

regulations. According to the national literature, project sustainability is ensured only when local regulations mandate mitigation budgets.

Third, the implementation of community EWS requires legal legitimization to establish clear communication SOPs, delineate responsibilities between agencies and communities, and ensure technical support such as tools and training. Reviews of early warning systems indicate that community-based early warning systems (CBEWS) are highly effective in mitigating disaster impacts when supported by institutional legitimacy and a clear, robust regulatory framework.[51] Recent research further highlights the significance of community empowerment and regulatory legitimacy in community EWS to optimize local response efforts.[52]

Fourth, the standardization of metadata and the interoperability of risk map data should be governed by-regional regulations. Such regulations would enable spatial data from mapping activities and periodic updates to be shared, updated, and accessed through portals or dashboards. Existing literature on GIS development capacity for SDG indicators identifies inconsistencies in metadata and data update frequency as primary weaknesses. Therefore, technical regulations that establish standards for metadata, file formats, and update frequency are essential.[53]

Fifth, to ensure legal certainty in the use of water resources and conservation assets such as micro reservoirs, a program of priority land certification and usage permits should be implemented through local

[51] Macherera, Margaret, and Moses J. Chimbari. "A review of studies on community based early warning systems." *Jàmbá: journal of disaster risk studies* 8, no. 1 (2016): 206.

[52] Pham, Thi Dieu My, Annegret H. Thieken, and Philip Bubeck. "Community-based early warning systems in a changing climate: an empirical evaluation from coastal central Vietnam." *Climate and Development* 16, no. 8 (2024): 673-684.

[53] Oxoli, D., S. R. Reyes, S. Peng, M. A. Brovelli, S. Coetzee, I. Ivanova, J. A. Leonardi, D. Rawal, G. Vacca, and S. Zlatanova. "Capacity building for GIS-based SDG indicators analysis with global high-resolution land cover datasets." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 48 (2023): 559-564.

regulations that enable cooperation with the National Land Agency (BPN) or other relevant land agencies. Legal certainty regarding land status is essential, as conservation projects without it are susceptible to disputes and may not be sustainable over time. Several national studies on village water management have identified significant challenges related to legality and land ownership.

Sixth, local monitoring and evaluation (M&E) indicators for SDG achievements should be adapted to the sub-district and village levels. Local regulations should require the establishment of public performance dashboards, annual reporting, and citizen audits. The application of spatial data in monitoring development outcomes is increasing, as demonstrated in the literature on utilizing geospatial information to implement SDGs and monitor their progress, which highlights the use of geospatial data to track development indicators at the local level.[54]

Seventh, strengthening the technical and legal capacity of village and sub-district officials is essential. Local regulations should require data literacy training, the drafting of local legal documents such as village regulations and standard operating procedures, and the maintenance of small water infrastructure. A national study on risk management and decentralization indicates that local capacity remains limited, especially in interpreting maps, technical procedures, and regulations. These deficiencies present significant barriers to the effective implementation of adaptation policies in villages.[55]

This evidence-based policy framework should be translated into local regulations (Perda, Perkada or Perdes) that incorporate operational

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[54] Avtar, Ram, Ridhika Aggarwal, Ali Kharrazi, Pankaj Kumar, and Tonni Agustiono Kurniawan. "Utilizing geospatial information to implement SDGs and monitor their Progress." *Environmental monitoring and assessment* 192, no. 1 (2020): 35.

[55] Ayuningtyas, Dumilah, Sri Windiarti, M. Sapoan Hadi, Ulya Uti Fasrini, and Sandra Barinda. "Disaster preparedness and mitigation in Indonesia: A narrative review." *Iranian journal of public health* 50, no. 8 (2021): 1536.

implementation instruments such as SOPs, budget mechanisms, and public reporting as well as measurement indicators including the percentage of villages integrated into risk maps, the number of active EWS, and the percentage of APBD allocated to mitigation. Implementing-this policy package initially in pilot areas, specifically priority sub-districts, and the evaluation both costs and benefits alongside community feedback will generate an adaptation model suitable for expansion to other areas in Grobogan and comparable districts in Indonesia.

Conclusion

Drought risk mapping in Grobogan Regency demonstrates significant variation between hazard levels and overall risk, despite most of the region exhibiting a moderate hazard level. The intersection of hazard, vulnerability, and capacity results in approximately 45% of the of the area being classified as moderate to high risk, indicating the need for targeted adaptation measures. Spatial analysis further reveals considerable variation in vulnerability among subdistricts, with some exhibiting lower vulnerability. Local capacity remains generally low, particularly regarding early warning systems, disaster literacy, and technical expertise, although formal institutions are comparatively stronger.

The study's findings indicate a persistent gap between the national legal framework and its implementation at the regional and village levels. While national regulations address disasters and water resources, local regulations, mitigation fund allocations, Standard Operating Procedures (SOPs) for Early Warning Systems (EWS), and spatial data standards remain insufficient. As a result, risk maps often serve only as a technical document without influencing policy decisions. In contrast, when risk maps are integrated with a robust legal foundation, such as through the enhancement of Regional Medium-Term Development Plans (RPJMD), Village Management Work Plans (RKPDes), Regional Regulations (Perda), District Regulations (Perkada) mandating map usage, and interoperable metadata standards-these maps become effective tools for prioritizing interventions, monitoring Sustainable Development Goals (SDGs) progress, and identifying location for water conservation investments. Regional Experience further underscores the necessity of sustainable funding mechanisms and the recognition of community roles to ensure the continuity of adaptation measures.

Based on these results, the findings indicate that coordinated efforts are required to integrate spatial evidence, legally binding fiscal instruments, and community capacity building. Such integration is essential to ensure that the risk map effectively drives practical change. Specifically, risk maps should be formally incorporated into regional planning documents, dedicated budget allocations for drought mitigation should be established, and a community Early Warning System (EWS) should be implemented through standard operating procedures (SOPs) and training. Additionally, the development of metadata standards and monitoring dashboard mechanisms is necessary. Implementing these measures concurrently will enhance Grobogan's ability to reduce spatial vulnerability, enable cost-effective interventions, and strengthen water and food security resilience in the face of future droughts.

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