COMMUNITY-BASED SPRINGS MANAGEMENT OF THE SUKOLILO KARST LANDSCAPE AREA TO FULFILL CLEAN WATER NEEDS

Pengelolaan Mata Air Kawasan Bentang Alam Karst Sukolilo Berbasis Masyarakat Untuk Pemenuhan Kebutuhan Air Bersih

DEWI LIESNOOR SETYOWATI[1], PUJI HARDATI[2], ERVANDO TOMMY AL-HANIF[3], JAMHUR[4], RAY GERRALDO S TAMBUNAN[5], FIGO DWI AKBAR[6]

[1,2,3,4,5,6]Program Studi Geografi, Fakultas Ilmu Sosial dan Politik, Universitas Negeri Semarang, Indonesia

*Corresponding author: Ervando Tommy Al-Hanif
Email: ervandotommy@mail.unnes.ac.id

Received: 15 July 2025; Revised: 30 Oct 2025; Accepted: 15 Nov 2025; Published: 08 Dec 2025

To cite this article: Ervando Tommy, A.-H., Dewi Liesnoor Setyowati, Puji Hardati, Jamhur, Ray Gerraldo, S. T., & Figo Dwi Akbar. (2025). Community-Based Springs Management of The Sukolilo Karst Landscape Area to Fulfill Clean Water Needs. *GEOGRAFI*, *13*(2), 33-61. https://doi.org/10.37134/geografi.vol13.2.2.2025

ABSTRACT *The demographic growth rate development is in line with economic dynamics that drive environmental degradation. This occurrence is evident within the KBAK Sukolilo area, which has evolved into a cultivation area despite being designated as a geological cultural heritage site by the Ministry of Energy and Mineral Resources since 2014. The primary issue in the Purwodadi region is the annual occurrence of drought. Ninety-seven villages across 14 districts in Grobogan experience a clean water crisis. The research objectives are: 1) mapping land use distribution and potential water sources in KBAK Sukolilo and 2) analyzing water management for meeting water needs. The research object is the springs located in KBAK Sukolilo, Grobogan District, covering six districts. The research method involves surveying data collection on the potential and quality of springs in KBAK Sukolilo, conducting interviews, and utilizing descriptive analysis and geospatial information analysis techniques. The research findings indicate a dynamic change in land use, with Plantations (22.5%), Fields (13.7%), Settlements (9.4%), Irrigated Rice Fields (34.8%), Rain-fed Rice Fields (12.3%), Bushes (6.9%), and Empty Land (0.4%). The karst area of KBAK Sukolilo, which plays a crucial hydrological role, boasts 28 springs, with the highest potential at the Ngakiman spring, with a discharge of 146.5 liters per second, and the lowest potential of 2 liters per second found in 8 springs in the Sukolilo Karst area in Grobogan.*

Keywords*: Clean Water, Karst Landscape Area, Springs, Karst Sukolilo*

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

1. Introduction

Grobogan Regency is a depression zone (Randublatung zone) situated between the Kendang folding system in the south and the Rembang anticlinorium in the north (Bemmelen, 1949). In the Rembang anticlinorium north of Purwodadi, the Tawun Formation is exposed, consisting of the Tawun Member of the early to middle Miocene period, comprising bioclastic limestone, reef limestone, and the Ngrayong Member of the middle Miocene period, consisting of intercalations of marl, calcareous sandstone, limestone, and napal intercalations, the Bulu Formation of the middle Miocene period, consisting of interbedded limestone, sandy limestone, and marly limestone, and a small outcrop of the Wonocolo Formation of the middle Miocene period, consisting of marl interbedded with calcareous sandstone at the top and limestone plate at the bottom (Sukardi and Budhistira, 1992; Suwarti and Wikarno, 1992; Sapiie *et al.*, 2015). This condition emphasizes that meteorological droughts can develop into socio-economic drought disasters, worsening the living conditions of communities and hindering regional development. The integration between water resource management, conservation knowledge, and infrastructure development is crucial in mitigating the impacts of drought in the Grobogan Regency (Wijaya & Sudaryanto, 2019). Through a multidisciplinary approach, sustainable water resource management can be achieved, reducing the risk of drought disasters and enhancing community welfare. The rapid demographic growth rate and economic dynamics have been two major contributing factors to environmental degradation worldwide. In Indonesia, particularly in the Karst Landscape Area (KBAK) of Sukolilo, population growth and economic expansion have led to significant environmental quality decline, including a decrease in the availability of clean water sources. KBAK Sukolilo, designated as a geological cultural heritage site by the Ministry of Energy and Mineral Resources (ESDM) in 2014, faces serious challenges in maintaining the sustainability of its water resources. This area, dominated by carbonate rocks covering an area of 112.20 km^2, experiences reduced water availability influenced by land use changes and the impacts of global climate change (Kementerian ESDM, 2014). The Purwodadi area, which is part of the KBAK Sukolilo region, experiences drought every year, resulting in a clean water crisis in 97 villages across 14 districts in Grobogan. This crisis highlights the importance of effective and sustainable water resource management (BPS Grobogan, 2020). In facing this challenge, community cooperation and active participation are key to meeting the need for clean water. This research aims to (1) map the distribution of land use and the potential of water sources in KBAK Sukolilo and (2) analyze spring management to meet water needs. In this context, previous studies have shown that environmental degradation, particularly related to water resources, can have negative impacts on the socio- economic livelihoods of communities (Doe & McArthur, 2017). Therefore, this research seeks to provide insights and solutions related to optimizing spring management in karst areas, which are not only important for meeting the need for clean water but also for environmental preservation and the sustainability of the local community's livelihoods.

2. Literature Review

2.1 Karst Area

Karst areas represent unique ecosystems formed by the dissolution of easily soluble rocks such as limestone, dolomite, and gypsum by rainwater containing carbonic acid. This dissolution process creates distinctive geological features such as caves, sinkholes, karst springs, and underground rivers, making karst areas rich in hydrogeological and geomorphological diversity (Wang et al., 2019; Wacana et al., 2011). Karst areas are characterized by topography significantly shaped by the dissolution of carbonate rocks, where groundwater flow plays a crucial role in landscape formation (Aprilia et al., 2021). These characteristics not only provide natural uniqueness but also influence the dynamics of water resources in the area, where karst aquifer systems exhibit high variability in terms of water availability and quality (Hadi et al., 2018). Therefore, a profound understanding of karst hydrogeological characteristics is essential for sustainable water resource management in these regions. Springs in karst areas play a crucial role in supporting ecosystems and the livelihood needs of surrounding communities (Haryono et al., 2022). The unique characteristics of karst areas, formed from soluble carbonate rocks, create complex underground hydrological systems and enable springs to emerge as vital water sources. According to Riyanto et al. (2020), karst hydrological characteristics include significant fluctuations in water volume and quality due to the irregular movement of water through the karst aquifer system. These springs are crucial for the sustainability of local communities, providing clean water for various uses, such as domestic and agricultural, especially in areas where access to other surface water sources is limited (Aji et al., 2019; Hartono, 2020). According to Tolche (2021), mapping the location of springs is crucial information, as several controlling factors of groundwater movement include lithology, slope, land use/land cover (LULC), rainfall, linearity, soil, and drainage density.

2.2 Water Resources Management Approach

The community-based approach to water resources management, as elucidated by Johnson et al. (2019), emphasizes the importance of empowering and directly involving local communities in the water resources management process. Several principles for effective collective management of shared resources include recognition of local rights, regulations tailored to local conditions, community participation in decision-making, monitoring, and enforcement of rules by resource users themselves, as well as fair and prompt conflict resolution mechanisms (Aprilia et al., 2021). In the context of water resources management, this means that local communities are empowered to actively participate in every aspect of water management, from planning to implementation, monitoring, and evaluation.

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

The community-based approach to spring management in Sukolilo can be vital to addressing these challenges. Empowering local communities through education and active participation in water resources management enables the utilization of deep local knowledge about spring characteristics and environmental dynamics (Winarno et al., 2019). Includes the development of sustainable water use practices, monitoring of water quality and quantity, and protection of recharge zones to ensure spring sustainability. This approach also involves the formation of community-level water resource management groups responsible for setting usage rules, conducting monitoring, and managing fair water distribution (Hardati et al., 2022). The implementation of the community-based approach in Sukolilo can be illustrated through projects such as the development of environmentally friendly water management infrastructure, reforestation programs to enhance rainwater infiltration, and environmental awareness campaigns to reduce pollution. By leveraging the synergies between local knowledge and external support, Sukolilo can develop a sustainable and resilient water resources management model, ensuring long-term access to clean water for all its residents (Adiguna & Wahyono, 2021). The community-based approach in Sukolilo offers valuable lessons about the importance of community engagement in natural resource management. By empowering local communities as stewards and protectors of their water resources, Sukolilo not only addresses the unique hydrological challenges of karst regions but also strengthens the socio-economic resilience of its communities to environmental and social changes (Astrawijaya, 2020).

3. Research Area

The focus of this research is on the springs located in the KBAK of Sukolilo, Grobogan District, encompassing six districts. This location was chosen because it is representative of studying the management of spring water resources and land use dynamics in karst areas.

Figure 1. *The Karst Hill Landscape of Sukolilo in Jatipoho Village, Grobogan District*.
Source: Survey, March 2023

4. Research Methodology

4.2 *Research Approach*

This research utilizes both quantitative and qualitative approaches to collect and analyze data. Quantitative research tests previous theories by examining relationships among specific variables. Several research instruments were utilized to analyze the data obtained from these variables, and statistical procedures were used. On the other hand, qualitative research involves exploring and understanding the meanings among a number of individuals or a group of people stemming from social issues (Creswell, 2014; Bauer et al., 2021). The quantitative approach is employed to measure and analyze the distribution of land use and the potential of spring water sources, while the qualitative approach is applied through interviews to understand perceptions and describe community participation in spring water management.

4.3 Data Collection

Data collection in this research is obtained through field surveys and interviews (Bauer et al., 2021; Patton, 2015). Field surveys are conducted to gather data on the potential and quality of spring water. This survey includes measuring the physical data of spring sources, measuring spring discharge, observing spring characteristics, and collecting water samples to test various qualities such as pH, salinity, color, odor, and turbidity.

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

Interviews are conducted involving direct interaction with local communities, government officials, and environmental experts to obtain information about the management and perceptions of spring water. Interviews are conducted semi-structured to allow flexibility in obtaining in-depth information.

4.4 *Data Analysis*

The data analysis in this research employs descriptive data analysis to analyze data from interviews, primarily to assess the level of agreement or disagreement of respondents regarding statements about spring water management. Additionally, spatial analysis is conducted using Geographic Information System (GIS) tools. Spatial analysis is a field related to the analysis, management, and visualization of geographic data. It involves the use of advanced tools and techniques to process, interpret, and understand geographic information (Alphan & Aşur, 2021; Longley, 2015). This analysis is performed to map the distribution of land use and the potential of springwater sources. The use of GIS software enables the visualization of spatial data and the analysis of the relationship between land use and the availability of spring water.

5. Findings and Discussion

5.1 Mapping the Spatial Distribution of Land Use and the Potential of Water Sources

Karst Landscapes (KBAK) represent geomorphologica manifestations typically characterized by closed depressions, limited surface drainage systems, and the presence of caves. This geological formation is primarily shaped through the dissolution process of calcium carbonate rocks, such as limestone. The karst landscape emerges from the intensive interaction between porous calcium carbonate rocks and water, producing unique terrestrial features like conical karst hills. Another characteristic of karst areas is the scarcity of surface water flow, in contrast to the prevalence of subterranean rivers flowing through cave systems. These regions are also distinguished by their unique ecosystems, showcasing distinctiveness in both geophysical aspects and biodiversity. The core zone of KBAK, namely the karst geological protection zone, located in the Holokarst area, has been officially recognized through the Ministerial Decree of Energy and Mineral Resources (ESDM) as an area with optimally developed karst characteristics, where all elements of karst features—including sinkholes, dolines, uvalas, karst domes or towers, caves, and underground rivers—can be identified. This zone is considered a primary protection area aimed at maintaining the integrity of the designated Karst Area with a protective function. Located in Sumber Jatipohon Village, Sedayu, Lebak, and Lebengjemuk in Grobogan District, as well as Sumberagung Village in Ngaringan District, this core zone plays a crucial role in preserving the geological uniqueness, hydrological functions, and ecosystem diversity of the Karst Area. The delineation of the KBAK core zone for both Grobogan and Ngaringan districts was based on the delineation of Karst

Landscapes outlined in the Annex of the Ministerial Decree of ESDM No. 2641 K/40/MEM/2014, dated May 16, 2014. The distribution of the KBAK core zone in the Grobogan and Ngaringan Districts of Grobogan can be seen in Table 1.

Table 1.
The distribution of the core zones of Karst Landscapes (KBAK) within the districts of Grobogan and Ngaringan in Grobogan County.

Zone	Districts	Village	Area (Ha)
Core Zone	Grobogan	Sumber Jatipohon	888,8
	Grobogan	Sedayu	980,2
	Grobogan	Lebak	45,5
	Grobogan	Lebangjemuk	950,3
	Ngaringan	Sumberagung	1.122,9
Total			3.987,7

Source: Interpretation of the Map and Analysis Results for the Year 2021.

The core zones of Karst Landscapes (KBAK) essentially require protection to preserve their natural integrity (Sukmono & Yulianda, 2018). Activities within the protection or buffer zones of KBAK are permitted for community use but are limited and conditional. The utilization of the KBAK buffer zones is directed towards protecting the karst landscape without disrupting the functions of the karst area. In this study, buffer zones are defined as areas that protect the Core Zone. Activities that alter specific geological formations with scientific value, disturb the environmental sustainability of areas with specific geological formations, or adversely impact the protected karst landscape are prohibited in these zones. Agricultural and plantation activities are allowed in this area. The distribution of KBAK buffer zones in the Grobogan and Ngaringan Districts of Grobogan County is presented in Table 2.

Table 2.
The distribution of the buffer zones of Karst Landscapes (KBAK) in the Grobogan and Ngaringan Districts of Grobogan County.

Zone	Area (Ha)	Districts	Village	Percentage Relative to Villages
Buffer Zone	275,9	Grobogan	Sumber Jatipohon	23,7
	647	Grobogan	Sedayu	39,8
	1.422,5	Grobogan	Lebak	96,9
	138,9	Grobogan	Lebengjumuk	12,7
	1.762,6	Ngaringan	Sumberagung	61,1
Total	4.246,6			

Source: Interpretation of the Map and Analysis Results for the Year 2021.

The Development Zone is identified as an area allocated to facilitate the potential development of karst regions, focusing on activities such as sustainable tourism, nature conservation, cultural landscape preservation, and the maintenance of local cultural traditions. Additionally, this area is designated for the placement of essential supporting infrastructure to sustain limited-scale cultivation practices. Land use within this zone includes rural settlements, irrigated agricultural areas, rain-fed paddies, dry land farming, gardens, and shrubland areas. Therefore, this zone is established as a development area with restrictions and conditions. Restrictions refer to the limitations on the scale of development activities, while conditions pertain to the necessity of meeting criteria that support environmental preservation. In the context of this zone, the construction of facilities supporting educational, research, and geological tourism activities is permitted. However, mining activities and the processing of mining products, mainly limestone, are prohibited to maintain the ecological integrity and sustainability of the area. The Development Zone is aimed at being a development area based on the assessment that this zone has minimal impact on the core zone of the Karst Landscapes (KBAK). This area offers opportunities for the development of the trade sector and support services for tourism activities. Furthermore, there are opportunities to enhance educational and scientific research activities within the zone. The delineation of the core zone, buffer zone, and development zone can be observed in Figure 2.

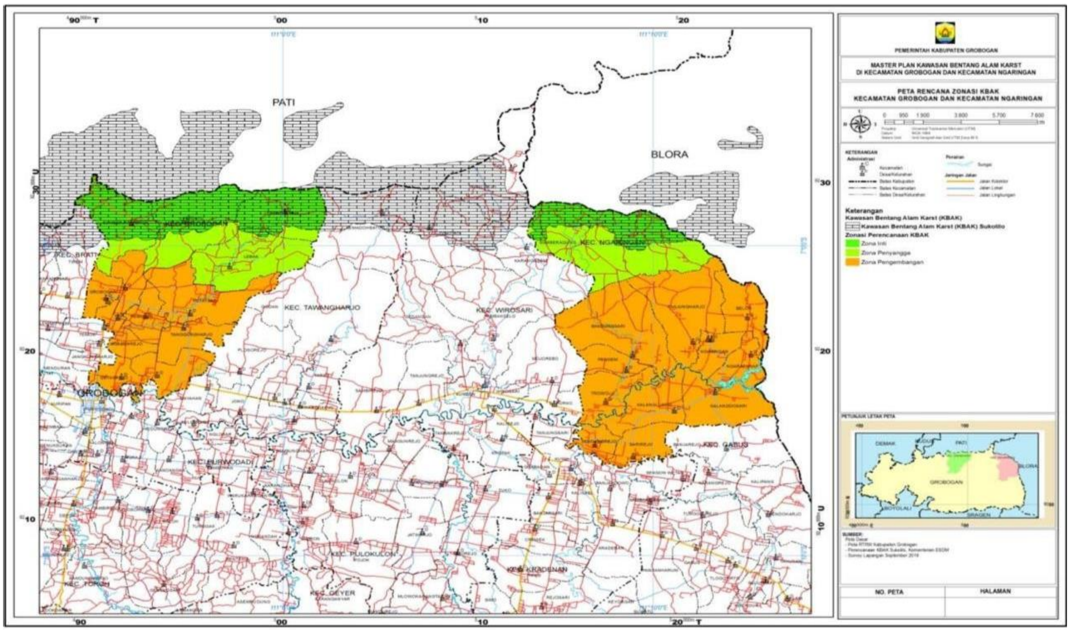

Figure 2. *Map of the Delineation of Core Zone, Buffer Zone, and Development Zone.*
Source: Data Processing of the Research, 2023.

Specifically, Karangasem Village has the potential to function as a southern access gateway to KBAK, affirming its role in facilitating visitor arrivals. Infrastructure development, including improvements to local road networks and environmental roads, is considered essential for enhancing accessibility for residents and supporting ecotourism development.

The increased intensity of land use for rural settlements, in line with population growth, indicates the need for prudent development planning to anticipate future needs. The distribution of the KBAK Development Zone in the Grobogan and Ngaringan Districts of Grobogan County can be seen in Table 3.

Table 3.
The distribution of the KBAK Development Zone in the Grobogan and Ngaringan Districts of Grobogan County.

Zone	Area (Ha)	Districts	Village	Percentage Relative to Villages
Development Zone	460,0	Grobogan	Karangrejo	100
	1.289,5	Grobogan	Putatsari	100
	351,3	Grobogan	Grobogan	100
	483,5	Grobogan	Teguhan	100
	576,9	Grobogan	Ngabenrejo	100
	660,6	Grobogan	Tanggungharjo	100
	406,5	Grobogan	Rejosari	100
	1.689,6	Ngaringan	Getasrejo	100
	715,8	Ngaringan	Tanjungharjo	100
	1.851,8	Ngaringan	Belor	100
	437,5	Ngaringan	Bandungsari	100
	528,2	Ngaringan	Ngaringan	100
	411,7	Ngaringan	Ngaraparap	100
	901,5	Ngaringan	Pendem	100
	725,2	Ngaringan	Kalanglundo	100
	1.035,2	Ngaringan	Trowolu	100
	571,4	Ngaringan	Kalangdosari	100
	343,6	Ngaringan	Sarirejo	100
Total	13.870,7			

Source: Interpretation of the Map and Analysis Results for the Year 2021.

5.1 Land Use

Land use within Karst Landscapes (KBAK) has distinct carrying capacities and resilience compared to other areas due to its significant impact on hydrological systems and inherent vulnerability. Prior to the issuance of the Ministerial Decree of Energy and Mineral Resources (ESDM) No. 2641 K/40/MEM/2014 on May 16, 2014, numerous community activities disrupted the balance of KBAK, such as limestone mining, phosphate extraction, and other minerals, as well as the cultivation of seasonal crops without considering the characteristics of slope and soil type. These activities have a high potential to accelerate the degradation of karst landscapes and compromise the protective functions of the area. The capability of land use is based on seven parameters. The first is elevation, as it defines the characteristic topography of karst areas in determining their use.

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

Second is the slope, interpreted from topographic maps, since land use is often determined or designated based on the steepness of an area. Third is the morphology because the landscape in land use can be discerned from its relief, both coarse and fine, using hill morphology. In contrast, plain morphology depicts conditions dominated by relatively flat areas in karst regions. Fourth is geology, which can reveal physical and environmental aspects. Fifth is groundwater conditions, indicating the distribution of water sources in land used by the surrounding community. Sixth is hydrological conditions, as they describe the flow patterns and characteristics of rivers and their flow rates. Seventh is the land use map, serving as the result to illustrate the digitization of the KBAK area's landscape. In general, Land Use in the Planning Area (Core Zone, Buffer Zone, and Development Zone) appears almost identical. Land use is detailed in Table 4.

Table 4.
The distribution of the KBAK Development Zone within Grobogan and Ngaringan Districts of Grobogan County.

Existing Land Use	Core	Buffer	Development	Area Total (Ha)	% Area
Garden/Plantation	1.504,1	1.752,0	1.725,9	4.982,0	22,5
Dryland Farming	770,5	302,2	1.954,5	3.027,2	13,7
Settlement	265,7	211,4	1.610,7	2.087,8	9,4
Dryland Irrigation	449,0	582,5	6.651,3	7.682,8	34,8
Rainfed Paddy Field	453,4	767,5	1.496,5	2.717,3	12,3
Shrubland	545,0	631,0	347,8	1.523,7	6,9
Vacant Land	-	-	84,0	84,0	0,4
Total	**3.987,7**	**4.246,6**	**13.870,7**	**22.104,9**	**100**

Source: GIS Data Processing, 2021

5.2 Forest Area

The utilization of existing land in the form of gardens or plantations can be interpreted as production forests or community forests. This land allocation is closely related to the planting of perennial plants in a structured arrangement. Visually, both production and community forests generally consist of teak forests, eucalyptus forests, and various intentionally cultivated perennial plants. Production forest areas have been developed into permanent production forest zones, determined based on specific criteria, including slope class, soil type, and rainfall intensity, using a scoring method where the total score is less than 125. Specific criteria for permanent production forest zones include regional physical scoring with scores between 125-175, not included in protected areas with a minimum area of 0.25 Ha based on the accuracy of the 1:10,000 scale map, and the capability to function as a buffer zone.

This area can be developed in existing forests in the Grobogan and Ngaringan Districts, often associated with forests owned by Perhutani. Community forests are defined as forest areas on land that have evidence of land rights, where trees dominate the area within an ecosystem designated by the Regent. The development of community forests aims to support conservation activities to maintain the forest ecosystem. Criteria for community forests include a location at an altitude of more than 1000 meters above sea level, a land slope of 15- 40% or more, and a topsoil layer depth of more than 30 cm or between 60-90 cm. This area can also be developed in the Grobogan and Ngaringan Districts with cooperative management between Perhutani and the local government. The total area of forests and community forests within the planning area reaches 4,982 hectares (22.5%), which, compared to the area of land with slopes above 25% of about 4%, is adequate for slope protection. However, the density of the forest is still considered low, resulting in suboptimal forest functions. The condition of the forest density planted with teak trees can be seen in Figure 3, and the canopy density condition in the production forest planted with eucalyptus can be seen in Figure 4.

Figure 3. *The condition of the density of the production forest planted with teak trees (Photo taken during the peak of the dry season)*
Source: Primary Survey, 2021.

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

Figure 4. *The condition of canopy density in the production forest planted with eucalyptus*
Source: Primary Survey, 2021.

5.3 Agriculture

Wetland agriculture areas are identified as regions supporting agricultural activities through both natural water sources and technical interventions. In the planning area, wetland agriculture is generally located near permanent water sources and irrigation systems that obtain water from local sources or irrigation schemes. In both Ngaringan and Grobogan districts, the condition of wetland agriculture is mostly good, receiving adequate water supply, although there are challenges during prolonged drought periods, such as in Sumberagung Village, Ngaringan District. The management of these agricultural lands aims to maintain cultivation areas, especially for rice production, in an effort to ensure food security stability.

Currently, the total area of wetland agriculture in both districts is 7,682.8 hectares. Development of land for wetland agriculture must include several criteria; among others, land suitability must be the basis for utilization and management of the area; this includes a. variation in cropping patterns including monoculture, intercropping, and mixed sequential cropping, and b. implementation of conservation that includes vegetative and mechanical aspects. Vegetative aspects involve applying year-round planting patterns and planting with sufficient and quality water availability, between 5 – 20 L/second/ha for rice, with water free from pollution, temperatures between 23 – 30ºC, dissolved oxygen 3 – 7 ppm, ammonia maximum 0.1 ppm, and pH 5 – 7. Mechanical aspects include the construction of bunds, terraces, and drainage channels. The development of wetland agriculture is planned on existing wetland agricultural areas in the Grobogan and Ngaringan districts, with a total area of 7,682.8 Ha.

The conservation of existing wetland agriculture areas is not only vital for maintaining food supply but also acts as a green belt supporting the preservation of the karst landscape. The condition in wetland agriculture can be seen in Figure 5.

Figure 5. *The condition of wetland agriculture is currently planted with shallots and rice in Sumber Agung Village (Photo taken during the peak of the dry season).*
Source: Primary Survey, 2021

Dryland agriculture is defined as farming activities conducted in dry areas aimed at cultivating various types of crops. The main challenge in this type of agriculture is the limited availability of water, which necessitates the selection of commodities to match land conditions. The primary commodities in dryland agriculture across four KBAK villages include corn and other secondary crops. The total area of dryland agriculture, encompassing rain-fed paddies and fields, is about 5,744.5 hectares. The development of dryland agricultural areas aims to ensure the sustainability of agricultural cultivation areas that support food crop production. The preservation of existing dryland agricultural areas is not only important for providing food reserves but also acts as a green belt supporting the conservation of the karst landscape. The dryland agricultural areas planned for development are in the Grobogan and Ngaringan Districts. The condition of dryland agriculture can be seen in Figure 6.

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

Figure 6. *The condition of dryland agriculture currently planted with corn and livestock fodder grass (Photo taken during the peak of the dry season).*
Source: Primary Survey, 2021

5.4 Farming

The designated livestock farming area is a zone for the development of livestock enterprises. Generally, it can be classified into two groups: large livestock (cattle, buffalo, goats, sheep, and horses) and various poultry (chickens, ducks, and other types of poultry). For large animal husbandry, it is necessary to have or be close to an area where sufficient livestock feed grows, while poultry farming typically spreads throughout the cultivation area as long as food is adequately provided. To date, livestock farming in the Grobogan and Ngaringan Districts has not been centralized. Livestock activities are still conducted alongside residential areas, and for traditional livestock, pens are attached to the main house building. The existing condition of the designated livestock farming area is not visible, only livestock activities are found, notably large-scale poultry farming encountered during field surveys. Livestock waste management has not been properly implemented. Going forward, the consideration of communal pen management and communal livestock waste management is necessary. The designated livestock farming area has the following criteria: 1) The location refers to the provincial and municipal/city spatial planning (RTRW) and land suitability. 2) Constructed and developed by the government, local government, private sector, and/or community in accordance with biophysical, socio-economic, and environmental aspects. 3) Based on national and regional superior livestock commodities and/or strategic livestock commodities. 4) Development of farmer groups into business groups. 5) Integration with other cultivation areas is possible. 6) Supported by the availability of water sources, feed, technology, institutions, and markets. Locations that can be developed into livestock farming areas are in the Grobogan and Ngaringan Districts, especially in locations close to feed sources.

These locations can be associated or integrated with dryland agriculture. Green feed from dryland agriculture can be utilized as livestock feed. Chicken farming in the Core Zone of KBAK can be seen in Figure 7.

Figure 7. *Chicken Farming in the Core Zone of KBAK.*
Source: Primary Survey, 2021

5.5 Rural Settlements

Rural settlement areas are designated as residential areas that support the life and livelihoods of agrarian communities, encompassing functions of settlement, governmental, social, and economic services, with an emphasis on preserving traditional characteristics. The goal is to provide settlements that meet regulatory standards to fulfill the needs of the population. Criteria for rural settlement development include 1) Allocation of land for new housing ranging from 40% to 60%, adjusted to the characteristics and environmental capacity; 2) Maximum density of 50 houses/ha with adequate public utility facilities; 3) Construction of settlements that are healthy, safe from disasters, and supportive of environmental conservation; 4) Necessary facilities include wastewater disposal systems in accordance with Indonesian National Standards (SNI), efficient drainage systems, adequate clean water supply, and standard waste management systems according to SNI; and 5) Provision of education, health, open space, and commercial facilities according to demographic needs and service standards. The development of rural settlements in the Grobogan and Ngaringan Districts is directed towards existing clusters of rural settlements, with potential for further development into cultural and agrarian tourism destinations. The conditions of rural settlements in the Karst Area can be seen in Figure 8.

Figure 8. *The Conditions of Rural Settlements in Karst Areas*
Source: Primary Survey, 2021

5.6 Industry

Industrial activities within the study area form clusters that are integrated with settlements, such as the Tile Industry Center in Karangasem Village, Wirosari Sub-district, which legally falls within the Core Zone of the Special Agricultural Area (KBAK) outside of this planning area. This industrial center partially relies on raw materials from outside the village (particularly from Sumberagung Village). Small- scale brick and tile industries are also present in Sumberagung Village, Ngaringan Sub-district. Chemically, these industries do not disrupt or contaminate water quality, but they gradually alter the landscape. The condition of the tile industry center in Sumberagung Village can be observed in Figure 9.

Figure 9. *The Conditions of the Tile Industry Center in Sumberagung Village*
Source: Primary Survey, 2021

Figure 10. *Several natural potentials can be utilized for the development of tourism activities.*
Source: Primary Survey, 2021

5.7 Tourism

Natural tourism areas are defined based on their vastness, with natural attractions being the main asset for tourism purposes. They are classified according to facilities, accessibility, tourism potential, socio-cultural interactions, and their relationship with growth centers through corridor development. In the context of this study, natural and religious tourism has flourished, particularly in connection with visits to important local or regional gravesites and the beauty of natural features such as springs and limestone hill landscapes. The aim of developing tourism areas is to conserve the karst area and its culture, utilizing the environment without causing harm. Criteria for development include soil stability, minimizing environmental impacts, less fertile land, accessibility, minimizing traffic disturbances, availability of basic infrastructure, as well as historical and cultural value. The development of tourism potential in the Grobogan and Ngaringan Districts may include religious tourism, nature tourism, ecotourism, and cultural attractions, considering coordination with Perhutani (state-owned forestry enterprise) and local governments. This encompasses development around reservoirs, fruit orchards, and tourist villages, with an emphasis on preserving the karst ecosystem. The natural potential that can be utilized for tourism development activities can be seen in Figure 10.

5.8 Distribution of Springs

Hydrology in karst areas exhibits unique characteristics, resembling a sponge, appearing dry on the surface but harboring vast underground water sources. These characteristics include the presence of underground rivers and caves containing water, attributed to the karst rock formations easily dissolved by rainwater, resulting in specialized topography with caves and underground water systems in rocks such as limestone, marble, and gypsum. Karst, with its topography formed from soluble rock lithology, has distinctive relief and irregular drainage systems, where river flows can suddenly disappear into the ground and reappear elsewhere as large springs. The Sukolilo KBAK karst area plays a vital role in hydrology, with the presence of caves and underground rivers supplying essential groundwater to its surrounding areas. In the Kendeng region facing Pati Regency, such as in Grobogan District, there are 13 springs, while in Ngaringan District, there are 15 springs. In Grobogan, the springs are distributed in Sumber Jatipohon, Sedayu, and Lebengjumuk Villages in the northern part of the karst hills, with a total of 8 springs in Sumber Jatipohon, 3 in Sedayu, and 2 in Lebengjumuk. In Ngaringan, 13 springs are located in Sumberagung Village and 2 in Bandungsari Village, almost all located in the Sukolilo Karst Landscape Area, except for 1 cave in Sumberagung and 2 springs in Bandungsari located outside the karst area.

Table 5.
Distribution of Springs

No	Springs Name	Coordinate				District	Village	Hamlet	Q (l/d	Usage
		LS	BT	Y UTM	X UTM					
1	Mata Air 4	-6,98270	110,94100	9228158	493484	Grobogan	Grobogan	Sumberjatipohon	2	Raw Water
2	Mata Air Gedong Solo	-6,98480	110,93110	9227933	492389	Grobogan	Grobogan	Sumberjatipohon	2	Raw Water
3	Mata Air Njawe	-6,97800	110,92800	9228679	492048	Grobogan	Grobogan	Sumberjatipohon	2	Raw Water
4	Mata Air Sirah	-6,98310	110,93940	9228121	493309	Grobogan	Grobogan	Sumberjatipohon	27	Raw Water, Irrigation
5	Mata Air Belik	-6,98260	110,94020	9228175	493398	Grobogan	Grobogan	Sumberjatipohon	2	Raw Water
6	Sendang Sirah	-6,98360	110,93970	9228064	493340	Grobogan	Grobogan	Sumberjatipohon	27	Raw Water, Irrigation
7	Sendang Belik	-6,98280	110,94080	9228152	493461	Grobogan	Grobogan	Sumberjatipohon	2	Raw Water
8	Mata Air Langensari	-6,98640	110,92940	9227754	492202	Grobogan	Grobogan	Sumberjatipohon	10	Raw Water
9	Sumber Jambon	-6,97660	111,00300	9228833	500331	Grobogan	Grobogan	Lebengjumuk	24	Raw Water, Irrigation
10	Mata Air Pancur	-6,97480	110,99330	9229032	499260	Grobogan	Grobogan	Lebengjumuk	13	Raw Water, Irrigation

continued

11	Mata Air Pucung	-6,97230	110,97040	9229308	496730	Grobogan	Grobogan	Sedayu	13	Raw Water, Irrigation
12	Mata Air Sendang Asem	-6,97210	110,97240	9229330	496951	Grobogan	Grobogan	Sedayu	2	Raw Water, Irrigation
13	Mata Air Suko	-6,98720	110,95410	9227661	494935	Grobogan	Grobogan	Sedayu	27	Raw Water, Irrigation
14	Ketek	-6,99890	111,16110	9226368	517795	Grobogan	Ngaringan	Sumberagung	52	Raw Water, Irrigation
15	Pancur	-6,99520	111,16970	9226773	518741	Grobogan	Ngaringan	Sumberagung	13	Raw Water, Irrigation
16	Pakuwon Kanan	-6,98830	111,14890	9227542	516450	Grobogan	Ngaringan	Sumberagung	32,5	Raw Water, Irrigation
17	Ngrenjah	-6,99410	111,17550	9226896	519382	Grobogan	Ngaringan	Sumberagung	37,7	Raw Water, Irrigation
18	Kembang Kuning	-6,99270	111,16430	9227050	518145	Grobogan	Ngaringan	Sumberagung	32,5	Raw Water, Irrigation
19	Jlono	-6,99880	111,16000	9226379	517667	Grobogan	Ngaringan	Sumberagung	171,6	Raw Water, Irrigation
20	Ngakiman	-6,99470	111,16650	9226829	518388	Grobogan	Ngaringan	Sumberagung	149,5	Raw Water, Irrigation
21	Pakuwon Kiri	-6,99660	111,16500	9226620	518227	Grobogan	Ngaringan	Sumberagung	20	Raw Water, Irrigation
22	Berasan	-6,98870	111,14920	9227499	516477	Grobogan	Ngaringan	Sumberagung	4	Irrigation
23	Sudirwiryo	-6,99550	111,17770	9226745	519623	Grobogan	Ngaringan	Sumberagung	4	Irrigation
24	Sumber Agung	-6,98920	111,15110	9227437	516691	Grobogan	Ngaringan	Sumberagung	2	Raw Water
25	Sendang Gudel	-6,98890	111,15000	9227476	516571	Grobogan	Ngaringan	Sumberagung	6	Raw Water
26	Sendang Budeg	-6,99800	111,15140	9226473	516718	Grobogan	Ngaringan	Sumberagung	2	Raw Water
27	Sendang Mundu 1	-7,02320	111,15480	9223679	517094	Grobogan	Ngaringan	Bandungsari	10	Raw Water, Irrigation
28	Sendang Mendung	-7,02750	111,15580	9223204	517205	Grobogan	Ngaringan	Bandungsari	10	Raw Water, Irrigation

Source: Bappeda Kab. Grobogan, 2023

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

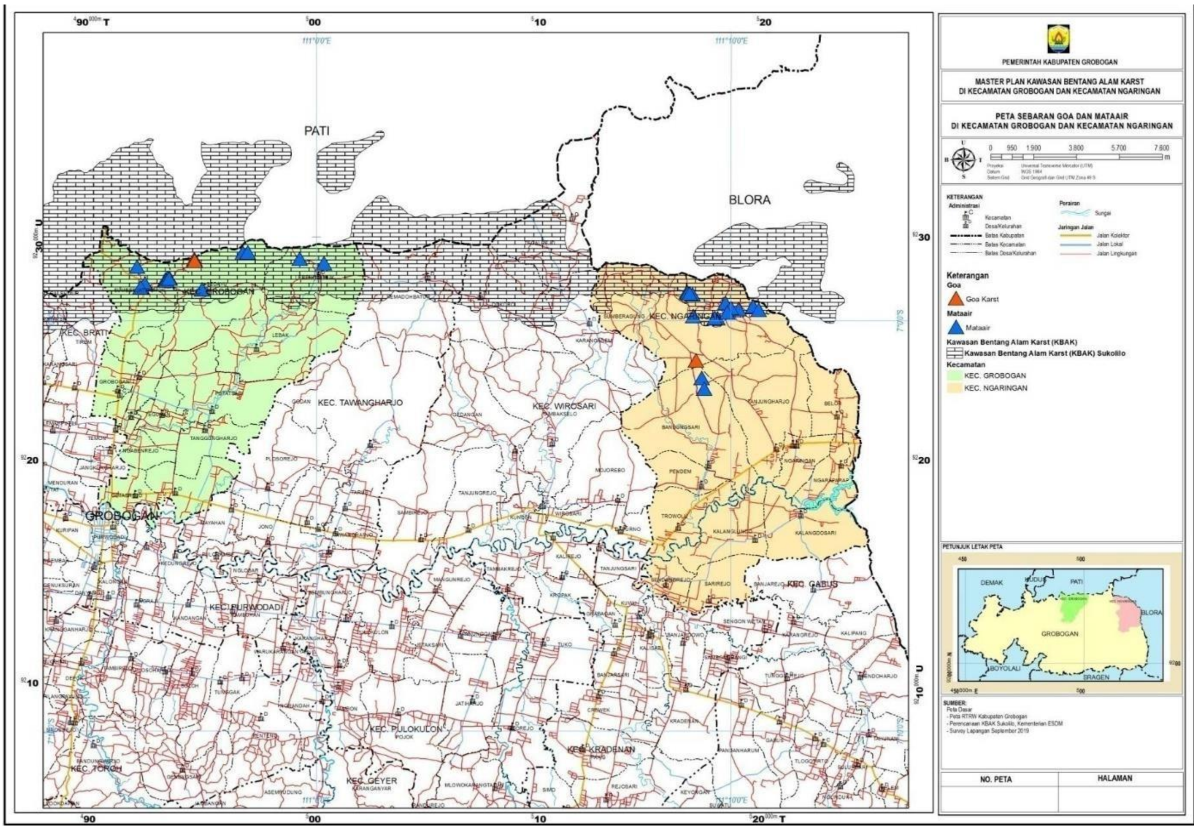

Figure 11. *Map of Cave and Spring Distribution*
Source: Primary Survey, 2021

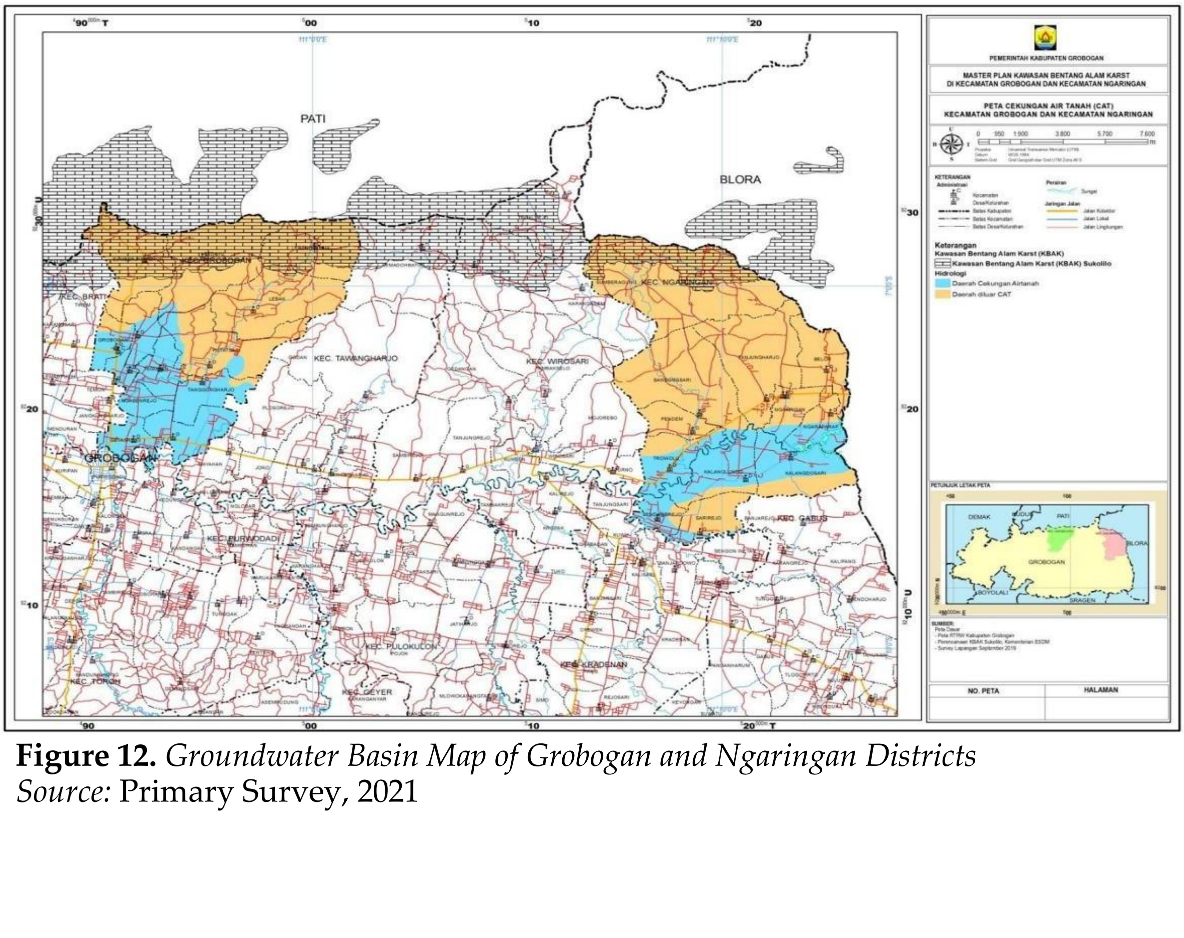

Figure 12. *Groundwater Basin Map of Grobogan and Ngaringan Districts*
Source: Primary Survey, 2021

Research findings reveal the presence of 28 springs in the Sukolilo Karst Landscape Area (KBAK), scattered across various districts and villages. This data includes the spring names, locations (districts and villages), coordinates (latitude and longitude lines), water discharge (in liters per second), and their designated uses (such as raw water or irrigation) in Table 5. The distribution of springs is illustrated in Figure 11. The Map of Cave and Spring Distribution and Figure 12. Groundwater Basin (CAT) Map in Grobogan and Ngaringan Districts. These springs play a vital role in providing water resources for community needs, both for daily consumption and irrigation activities, emphasizing the importance of managing and conserving springs in karst areas to ensure the sustainability of water resources in the future. The springs in karst areas play a crucial role due to their geological characteristics, which allow water to quickly penetrate through the cracks of carbonate rocks, reducing access to surface water. This karstic nature leads to the formation of complex underground aquifer systems, where springs become the primary source of surface water available for ecosystems and human use. The limited availability of surface water, especially during the dry season, makes springs essential for supporting life and agricultural activities in karst regions (Sukmono & Yulianda, 2018). Therefore, the management and conservation of spring sources in karst areas are key to ensuring the sustainability of water resources.

Managing springs in karst areas requires an integrated approach that considers the unique hydrogeological characteristics of karst, including the variability of water flow and vulnerability to contamination. Management strategies include protecting recharge zones, regularly monitoring water quality and quantity, and developing environmentally friendly infrastructure for collecting and distributing water. Community involvement in water resource management is also emphasized to ensure the sustainability and effectiveness of conservation efforts (Martuti et al., 2023).

5.9 Management of Springs for Water Supply

Based on data from the Central Statistics Agency of Grobogan Regency (2020), the population in the planning area until 2018 was 29,745 people. Over the five-year period from 2014 to 2018, there were fluctuations in the population numbers in several villages, which collectively affected the population in the planning area. This data is accompanied by a graph depicting the population growth over the five-year period. The population development in the KBAK Planning Area can be observed in Figure 13. The population growth graph depicts a trend that is nearly linear, but approach the year 2018, the growth rate experienced a decline, indicating that the growth is not entirely linear. Therefore, to project the future population and evaluate its growth rate, the geometric calculation method is applied. The following data presents the tabulation of population growth calculations using the geometric method. The Population Growth Rates in the Planning Area from 2014 to 2018 are detailed by village in Table 6.

According to Hardati et al. (2022), there is a relationship between population growth and dynamics with environmental conditions. In terms of water needs, an increase in the population is accompanied by an increased demand for water to support human life.

Table 6.
The Population Growth Rates in the Planning Area from 2014 to 2018 are detailed by village

No	Village.	Po	Pn	Pn/Po	n	log Pn/Po	(Log Pn /Po)/n atau log 1+r	Anti log (1+r)	r	r (% / th)
		2014	2018							
1	Lebak	9.159	9.272	1,012338	4	0,0053254	0,001331341	1,0030702	0,00307	0,31
2	Lebengjumuk	2.315	2.139	0,923974	4	-0,03434	-0,008585053	0,9804263	-0,01957	-1,96
3	Sedayu	3.712	3.891	1,048222	4	0,0204533	0,005113316	1,0118434	0,011843	1,18
4	Sumber Jatipohon	6.016	5.999	0,997174	4	-0,001229	-0,000307241	0,9992928	-0,00071	-0,07
5	Sumberagung	7.770	8.444	1,086744	16	0,0361272	0,00225795	1,0052127	0,005213	0,52

Source: The Central Statistics Agency of Grobogan Regency, 2020

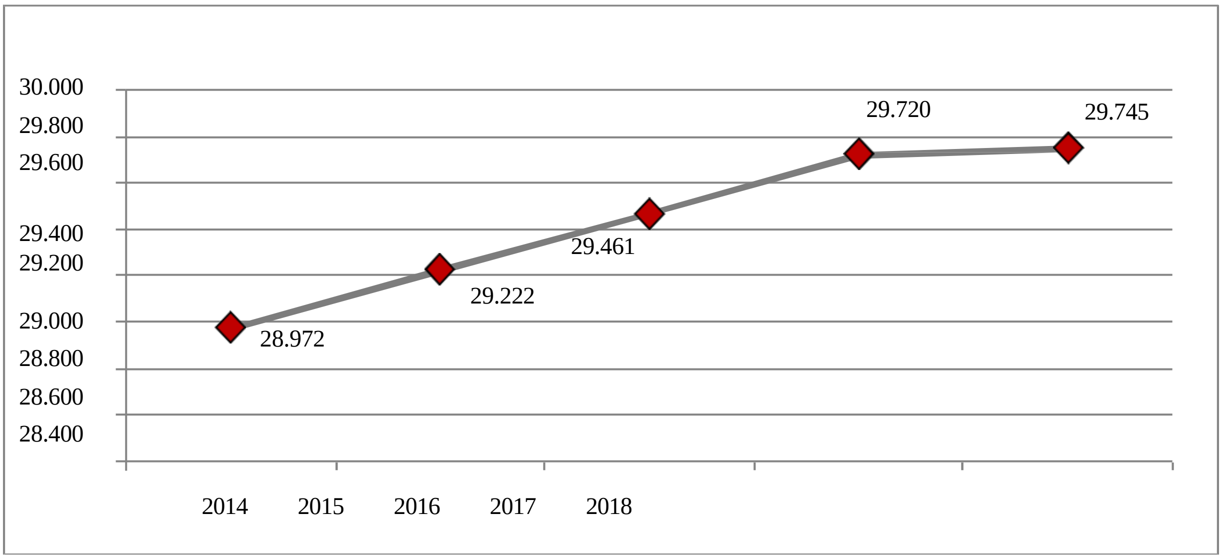

Figure 13. *The Graph of Population Development in the Planning Area from 2014 to 2018*
Source: Data Analysis of the Research, 2023

Statistics from the Central Statistics Agency of Grobogan Regency (BPS, 2020) indicate a negative population growth trend in two villages in the Sukolilo KBAK over the past five years. Overall, five villages recorded population increases from 2014 to 2017, which then slowed down in 2018, although the villages of Lebengjumuk and Sumber Jatipohon experienced declines. This data includes a graph of population growth rates in the Grobogan and Ngaringan Districts from 2014 to 2018. The graph depicting the population development of the Grobogan and Ngaringan Districts from 2011 to 2017 can be seen in Figure 14. Currently, the provision of drinking water or clean water is supported by the Regional Drinking Water Company (PDAM) as well as community-managed water sources, with some households also having private wells, although in limited numbers. There are conflicts over water usage between domestic needs and other activities such as agriculture and livestock farming, especially in recharge areas, where conflicts often arise. Projections of clean water availability indicate that there will be sufficient supply for the next 20 years, provided karst conservation is maintained and there are no extreme climate changes.

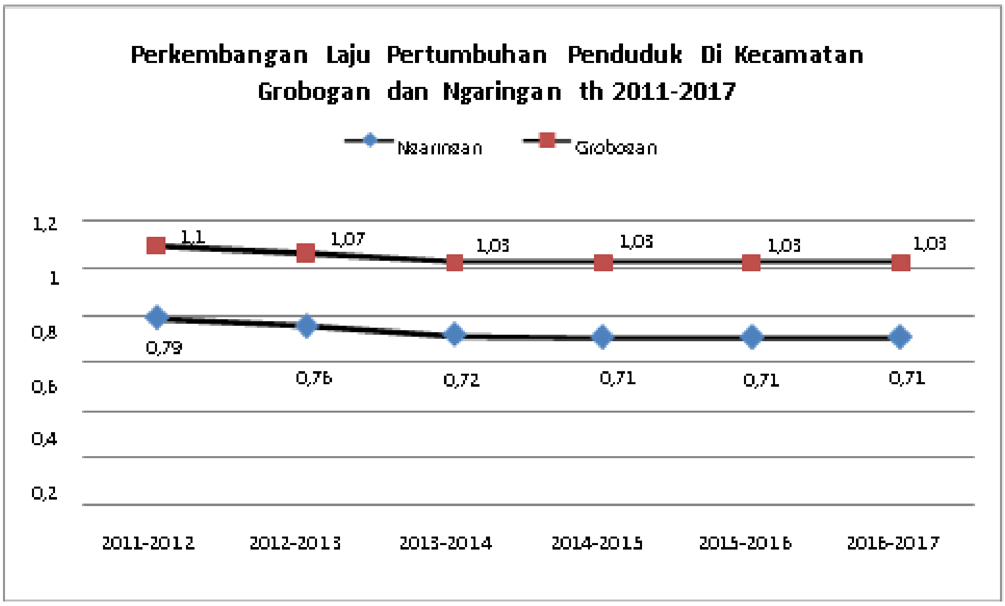

Figure 14. *The graph depicts the population development of Grobogan and Ngaringan Districts in the year 2011-2017.*
Source: The Central Statistics Agency of Grobogan Regency, 2021

However, the high dependence on natural water sources means that a decrease in water supply during the dry season could seriously reduce the availability of clean water, resulting in inadequate fulfillment of basic needs for clean water. The following section will present estimates of clean water requirements until the end of the planning period. The Projection of Clean Water Needs in the Planning Area for the Period 2020-2040 can be seen in Table 7.

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

Table 7.
Projection of Clean Water Requirements in the Planning Area for the Period 2020-2040

Village	Population Projection (Supporting Population) (individuals)	Domestic (120 L/prs/day)	Social & Commercial Facilities (20% domestic)	Firefighting Facilities (Fire Hydrants) 10% of domestic + non- domestic needs	Leaks: 20% of total requirements	Total (Clean Water Requirements)
	2020					
Lebak	9.329	1.119.480	223.896	134.338	295.543	1.773.256
Lebengjumuk	2.056	246.720	49.344	29.606	65.134	390.804
Sedayu	3.984	478.080	95.616	57.370	126.213	757.279
Sumber Jatipohon	5.991	718.920	143.784	86.270	189.795	1.138.769
Sumberagung	8.532	1.023.840	204.768	122.861	270.294	1.621.763
Total	**29.892**	**3.587.040**	**717.408**	**430.445**	**946.979**	**5.681.871**
	2025					
Lebak	**9.473**	**1.136.760**	**227.352**	**136.411**	**300.105**	**1.800.628**
Lebengjumuk	**1.863**	**223.560**	**44.712**	**26.827**	**59.020**	**354.119**
Sedayu	**4.225**	**507.000**	**101.400**	**60.840**	**133.848**	**803.088**
Sumber Jatipohon	**5.969**	**716.280**	**143.256**	**85.954**	**189.098**	**1.134.588**
Sumberagung	**8.757**	**1.050.840**	**210.168**	**126.101**	**277.422**	**1.664.531**
Total	**30.287**	**3.634.440**	**726.888**	**436.133**	**959.492**	**5.756.953**
	2030					
Lebak	**9.619**	**1.154.280**	**230.856**	**138.514**	**304.730**	**1.828.380**
Lebengjumuk	**1.687**	**202.440**	**40.488**	**24.293**	**53.444**	**320.665**
Sedayu	**4.481**	**537.720**	**107.544**	**64.526**	**141.958**	**851.748**
Sumber Jatipohon	**5.948**	**713.760**	**142.752**	**85.651**	**188.433**	**1.130.596**
Sumberagung	**8.988**	**1.078.560**	**215.712**	**129.427**	**284.740**	**1.708.439**
Total	**30.723**	**3.686.760**	**737.352**	**442.411**	**973.305**	**5.839.828**
	2035					
Lebak	**9.768**	**1.172.160**	**234.432**	**140.659**	**309.450**	**1.856.701**
Lebengjumuk	**1.528**	**183.360**	**36.672**	**22.003**	**48.407**	**290.442**
Sedayu	**4.753**	**570.360**	**114.072**	**68.443**	**150.575**	**903.450**
Sumber Jatipohon	**5.927**	**711.240**	**142.248**	**85.349**	**187.767**	**1.126.604**
Sumberagung	**9.224**	**1.106.880**	**221.376**	**132.826**	**292.216**	**1.753.298**
Total	**31.200**	**3.744.000**	**748.800**	**449.280**	**988.416**	**5.930.496**
	2040					
Lebak	**9.919**	**1.190.280**	**238.056**	**142.834**	**314.234**	**1.885.404**
Lebengjumuk	**1.385**	**166.200**	**33.240**	**19.944**	**43.877**	**263.261**
Sedayu	**5.041**	**604.920**	**120.984**	**72.590**	**159.699**	**958.193**
Sumber Jatipohon	**5.906**	**708.720**	**141.744**	**85.046**	**187.102**	**1.122.612**
Sumberagung	**9.467**	**1.136.040**	**227.208**	**136.325**	**299.915**	**1.799.487**
Total	**31.718**	**3.806.160**	**761.232**	**456.739**	**1.004.826**	**6.028.957**

Source: Analysis of Data, 2021

The current provision of clean water relies on the distribution of water from natural springs, which is conveyed through pipelines to storage tanks before being distributed to households. Several challenges arise due to unprotected springs from contamination, such as debris and pollutants, as well as pipeline systems designed without adequate standards, including pipe diameter settings and the placement of pipes and storage tanks. Additionally, the development of large-scale industrial and livestock activities must be carefully managed to prevent future water use conflicts. Specifically, the need for clean water for cottage industries such as sprout production in Sedayu Village is quite significant, exceeding estimates for domestic and non-domestic needs. Although currently fulfilled, it is important to plan for the sustainability of the water supply for the next 20 years, considering the potential water crisis that may occur if the conservation of water recharge areas is not maintained. An overview of the water distribution system in the Planning Area utilizing Natural Springs can be seen in Figure 15.

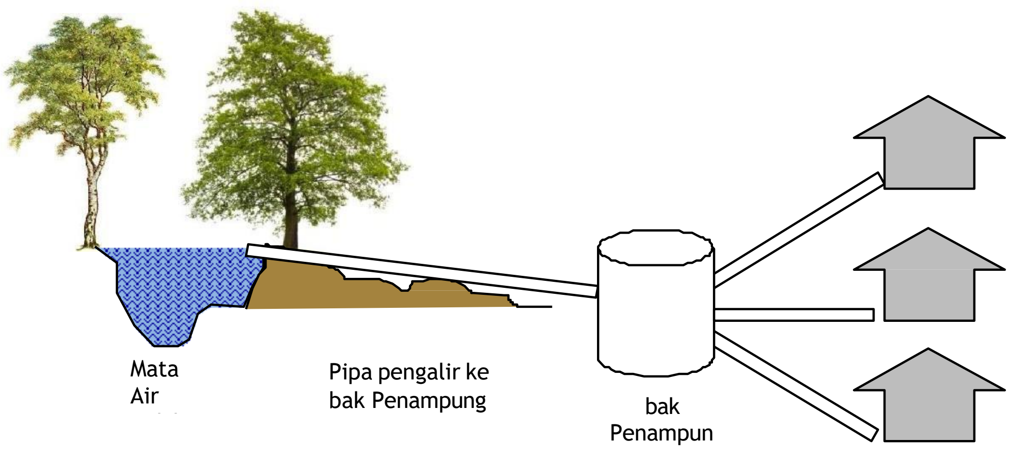

Figure 15. *An overview of the water distribution system in the Planning Area utilizing Natural Springs*
Source: The Plan of the Drafting Team, 2021

Based on information from several residents and village authorities, there has beena decrease in water discharge from several natural springs or wells in recent years, both during the rainy and dry seasons, compared to conditions ten years ago, although the decline is not documented in detail. The decrease in water discharge, combined with the increasing demand for clean water over the next two decades, will pose challenges in providing clean water. The shortage of clean water becomes a major issue that must be addressed. To solve this problem, it is time to initiate planning and implement water conservation strategies, especially in preserving water recharge areas (Wijaya & Sudaryanto, 2019).

Geografi Vol.13 (2), 33-61
ISSN 2289-4470 /eISSN 2462-2400

The plan includes: 1) Development plans for the future should include; 2) Protection of natural spring sources from the effects of drought due to changes in topography and the preservation of critical areas; 3) Physical protection of springs to prevent contamination, especially from plastic waste; 4) Regulation of pipeline systems and more effective tank design; 5) Development of water storage infrastructure such as reservoirs and dams.

6. Conclusion

Based on the results of the research conducted, it can be concluded that the Sukolilo Karst Landscape Area (KBAK Sukolilo) in the Grobogan and Ngaringan Districts is part of the Sukolilo Karst Landscape Area designated by the Minister of Energy and Mineral Resources Regulation No. 2641 K/40/MEM/2014 Regarding the Establishment of the Sukolilo Karst Landscape Area in Grobogan Regency, which includes the Klambu, Brati, Grobogan, Taangharjo, Wirosari, and Ngaringan Districts, comprising core zones, buffer zones, and development zones. Land use in the planning area includes forest areas, agriculture, livestock activities, rural settlements, industry, and tourism. The Sukolilo Karst Landscape Area, which plays a crucial hydrological role, has 28 springs scattered across various districts and villages. The provision of clean water needs in the planning area still shows stability. However, there has been a decrease in water discharge from several springs in recent years. If this is combined with the increasing demand for clean water over the next two decades, it will pose challenges in providing clean water. To solve this problems, it is necessary to start planning and implementing water conservation strategies.

7. Acknowledgement

The authors would like to express their gratitude to the respondents who were willing to participate in this study.

Authors contributions: Dewi liesnoor Setyowati, Puji Hardayati, Ervando Tommy, Jamhur Conceptualisation, methodology, analysis, and writing original draft and Dewi Liesnoor: Review and editing: Figo & Ray Gerraldo

Conflicts of Interest: The authors declare no conflict of interest.

Data Availability Statement: The authors confirm that the data supporting the findings of this study are available within the article.

8. REFERENCES

Adiguna, W. F., & Wahyono, H. (2021). Interaksi Kelembagaan dalam Pengelolaan dan Pemanfaatan Kawasan Ekologis Bentang Alam Karst Sukolilo di Kabupaten Pati. *Journal Of Biology Education,* 4(1), 1-22. https://doi.org/10.21043/jobe.v4i1.10249

Alphan, H., & Aşur, F. (2021). Geospatial analysis of lake scenery as an indicator for the environment: The City of Van (Turkey) and its surroundings. *Environmental and sustainability indicators*, 9, 100091. https://doi.org/10.1016/j.indic.2020.100091

Aprilia, D., Arifiani, K. N., Sani, M. F., Jumari, J., Wijayanti, F., & Setyawan, A. D. (2021). A descriptive study of karst conditions and problems in Indonesia and the role of karst for flora, fauna, and humans. *International Journal of Tropical Drylands*, 5(2). https://doi.org/10.13057/tropdrylands/t050203

Asrawijaya, E. (2020). Gerakan Ekopopulisme komunitas Samin melawan perusahaan semen di pegunungan Kendeng. *Jurnal Sosiologi Pendidikan Humanis,* 5(1). 35-47

Bauer, G. R., Churchill, S. M., Mahendran, M., Walwyn, C., Lizotte, D., & Villa-Rueda, A. A. (2021). Intersectionality in quantitative research: A systematic review of its emergence and applications of theory and methods. *SSM-population health*, 14, 100798. https://doi.org/10.1016/j.ssmph.2021.100798

BMKG. (2023). Laporan Analisis Curah Hujan dan Sifat Hujan. Badan Meteorologi,Klimatologi, dan Geofisika.

BPS Grobogan. (2020). Statistik Daerah Kabupaten Grobogan 2020. Badan Pusat Statistik Kabupaten Grobogan.

Creswell, J. W. (2014). Research Design: Qualitative, Quantitative, and Mixed Methods Approaches. SAGE Publications.

Hadi, S. P., Purnaweni, H., & Prabawani, B. (2018, October). Sustainable use of water resource at North Kendeng Mountain, Central Java, Indonesia. In *IOP Conference Series: Earth and Environmental Science* (Vol. 191, No. 1, p. 012005). IOP Publishing.

Hardati, P., Setyowati, D. L., Arsal, T., Amin, M., & Trihatmoko, E. (2022). The Relationship between Population Dynamic and Garang River Upstream Environment in Central Java, Indonesia. *The Indonesian Journal of Geography*, 54(3), 442-450. https://doi.org/10.22146/ijg.75767

Hartono, D. (2020). Hidrologi Dasar. Yogyakarta: Gadjah Mada University Press.

Haryono, E., Reinhart, H., Hakim, A. A., Sunkar, A., & Setiawan, P. (2022). Linking geodiversity and cultural diversity in geoheritage management: Practice from karst of Sangkulirang-Mangkalihat, Indonesia. *Geo Journal of Tourism and Geosites*, 42, 671-682. https://doi.org/10.30892/gtg.422spl05-876

Johnson, L. E., Smith, K. R., & Jones, D. A. (2019). Evaluating the effectiveness of community management in water conservation efforts. *Journal of Environmental Management,* 245, 342-349. https://doi.org/10.1016/j.jenvman.2016.05.049

Kementerian Energi dan Sumber Daya Mineral (ESDM). (2014). Keputusan Menteri Energi dan Sumber Daya Mineral tentang Penetapan Kawasan Cagar Budaya Geologi. Kementerian Energi dan Sumber Daya Mineral Republik Indonesia.

Klaas, D. K., Imteaz, M. A., Sudiayem, I., Klaas, E. M., & Klaas, E. C. (2020). Assessing climate changes impacts on tropical karst catchment: Implications on groundwater resource sustainability and management strategies. *Journal of Hydrology*, 582, 124426.

Longley, P. A., Goodchild, M. F., Maguire, D. J., & Rhind, D. W. (2015). Geographic Information Science and Systems. John Wiley & Sons.

Martuti, N. K. T., Setyowati, D. L., Rahayuningsih, M., Dewi, N. K., Sidiq, W. A. B. N., & Mutiatari, D. P. (2023). Springs Distribution and Biophysical Mapping as a Strategy to Preserve Water Sources in Semarang City, Indonesia. *Journal of Environmental Management & Tourism*, 14(1), 113-125. https://doi.org/10.14505/jemt.14.1(65).11

Patton, M. Q. (2015). Qualitative Research & Evaluation Methods: Integrating Theory and Practice. SAGE Publications.

Pranata, I. J., Sudarmadji, S., & Raharjo, J. (2021). Pengaruh Perubahan Penggunaan Lahan terhadap Ketersediaan Air di Kabupaten Grobogan. *Jurnal Teknik Pengairan*, 12(1), 34-45. https://doi.org/10.24895/SNG.2018.3-0.994

Riyanto, I. A., Widyastuti, M., Cahyadi, A., Agniy, R. F., & Adji, T. N. (2020). Groundwater management based on vulnerability to contamination in the tropical karst region of Guntur Spring, Gunung sewu Karst, Java Island, Indonesia. *Environmental Processes*, 7(4), 1277-1302. https://doi.org/10.1007/s40710-020-004605

Sukmono, S., & Yulianda, D. (2018). Kajian Karakteristik Geologi dan Hidrogeologi Kawasan Karst di Indonesia: Studi Kasus Kawasan Karst Kendeng, Jawa Tengah. *Jurnal Geologi Indonesia*, 13(3), 177-192.

Tolche, A. D. (2021). Groundwater potential mapping using geospatial techniques: a case study of Dhungeta-Ramis sub-basin, Ethiopia. *Geology, Ecology, and Landscapes*, 5(1), 65-80.

Wacana, P., Rodialfallah, A., Chandra, F., Mesah, D., & Raimon, R. (2011). Study of the Potential of Karst Region in North Kendeng, the Districts of Grobogan and Pati. *In Proceeding of the Asian Trans-Disciplinary Karst Conference* Vol. 1, pp. 169-180).

Wang, K., Zhang, C., Chen, H., Yue, Y., Zhang, W., Zhang, M., & Fu, Z. (2019). Karst landscapes of China: patterns, ecosystem processes and services. Landscape Ecology, 34(12), 2743-2763.

Wijaya, T., & Sudaryanto. (2019). Strategi Adaptasi Masyarakat Terhadap Kekeringan di Kabupaten Grobogan. *Jurnal Penelitian Sosial dan Ekonomi Kehutanan*, 16(2), 123-134.

Winarno, T., Marin, J., Ali, R. K., & Widianto, Y. A. (2019). Geotourism Potential as Information for Infrastructure Planning of the Karst Area, Kayen District, Pati Regency, Central Java. In E3S Web of Conferences (Vol. 125, p. 01013). EDP Sciences.