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ARTIFICIAL TRACER TEST FOR CHARACTERISATION AND CONSERVATION OF KARST WATER IN JONGGRANGAN KARST, JAVA ISLAND, INDONESIA

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Abstract

Anjani, Kiskendo, and Mudal springs are essential in the Jonggrangan Karst region, Java Island, Indonesia, because of their perennial flow as the primary domestic water source for residents living in this region and recharged by the surface flow or underground river. This study aims to describe the underground system connectivity and transport parameters of the three springs through a tracer test and estimate the catchment area using the water balance approach. Besides, proposed conservation actions for each catchment spring are carried out by considering the transport parameters from the tracer test and karstification degree values from previous studies. Tracer test results show that several subsurface flow systems with single-conduit character were found in the study area. The results of the water balance approach show that Anjani Cave has a catchment area of 0.8km^2, while the Kiskendo and Mudal Caves are 3.69 km^2 and 1.71km^2, respectively. Recommended conservation actions include the management of solid and liquid wastes before being discharged, restrictions on upstream land-use conversion and arrangements for the use of pesticides (Anjani catchment). They were also planting pioneer trees and making terraces that effectively prevent erosion (Kiskendo catchment), while in the catchment of Mudal Springs (characterised by diffused-recharge typed), it is necessary to maintain the forest not converting it into rice-field or mixed-garden.

Keywords: *Jonggrangan karst; Tracer test; Transport parameter; Karst catchment conservation*

Introduction

Karst is a term used to refer to a terrain with constituents of limestone or soluble rock, which has a developed secondary porosity characterised by the presence of karren or lapies, close depression, cave systems, scarcity of surface drainage systems, and springs with large discharges [1-3]. *Z. Stevanovic* [4] also revealed that karst aquifers are unique due to the discontinuity of their rock pores and the different distribution of their hydraulic parameters. Consequently, subsurface flow and contaminant transport in karstic aquifers are difficult to predict when compared to those experienced by non-karst aquifers.

C.J.G. Darnault [5] states that there are three types of voids in karst aquifers, namely matrix, fracture, and conduit, which have different characteristics. The matrix measures between µm to mm, have a long travel time and are a laminar flow type. Fracture has a size between 10µm to 10mm, has an average travel time, and the flow follows the Cube Law, which is still classified as laminar flow [6]. Meanwhile, conduits are more than 10 mm in size, have a short travel time, and the flow mechanism follows Darcy-Weisbach's Law; the channel is open

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with the conduit flow type. Based on variations and combinations of these void types, the characterisation of flow in karst aquifers is complicated to predict.

Some methods that can be used to characterise a karst aquifer include spring hydrograph analysis, pumping tests, karst aquifer modelling, and tracer tests [7]. Tracer tests and pumping tests are not suitable for the temporal characterisation of karst aquifer conditions, whereas modelling of karst aquifers requires complex data [8]. Besides, analysis of spring hydrographs, especially in the recession section, is suitable for knowing how karstic aquifers release their flow components [9].

T. Morales et al. [10] revealed that the management of groundwater resources in a karst area requires detailed research and specific methods such as tracer tests to determine subsurface network connectivity. Moreover, the water balance approach is also considered capable of estimating the catchment area of a karst spring [11, 12]. Furthermore, tracer tests combined with geological mapping, geomorphology, speleological investigations, and hydrological monitoring are recommended methods in karst areas to obtain extensive catchment, even in complicated topographic and geological conditions [13-15].

Tracer tests can be divided into two types based on the substances used, namely natural (environmental) tracer and an artificial tracer test [16]. Natural tracers use materials such as microorganisms (plankton, spores) and environmental isotopes (δ18O or δ2H). The main applications of natural tracer are: knowing the origin of water, assessing hydrological processes such as identifying run-off components, subsurface flow mechanisms, lake water balance, and quantitative determination of flow components (for example, to estimate evaporation of open water bodies and determining the transit time of flow water).

Artificial tracers could use materials such as fluorescent dyes (uranine, tinopal, eosin, sulforhodamine B, or pyranine) and salt (sodium, lithium, and potassium). Also, *U. Lauber et al.* [17] revealed that fluorescent dyes could be detected with a fluorometer. Artificial tracer tests with tracer materials such as uranine, tinopal, sulforhodamine B are often used to investigate flow patterns in karstic aquifers. The results of the tracer test can provide precise information related to hydraulic connections, the extent of the catchment area, and transport parameters such as advection, dispersion, dispersivity, and percent recovery.

Tracer tests applied in underground rivers can explain the character of the conduit system, which cannot be accessed directly [18]. In most cases, dye tracers are injected in sinking streams, underground rivers, or potholes, while a monitoring device or fluorometer is usually placed in a spring that is thought to have a connection with the location where the dye tracer is injected. The result of this tracer test is a relationship curve between time from injection and dye concentration called a breakthrough curve (BTC). Transport parameters from tracer test results can be obtained from quantitative analysis and modelling of tracer breakthrough curves [16]. Therefore, all data obtained from BTC will represent information on the nature of water flow between injection sites and monitoring sites. The results of the modelling of BTC are the structure of the aquifer system drainage, the sub-catchment area boundary, and the flow velocity distribution (in the vadose zone; epi-phreatic; and phreatic zone), as well as the estimated volume of water in the conduit network.

Furthermore, *U. Lauber et al.* [17] and *N. Goldscheider et al.* [19] have also conducted a tracer test approach to estimate the distribution of groundwater residence times and to delineate the karst flow boundaries in the Alpine Mountains. In addition, *A. Ender et al.*[20] also carried out tracer tests in Vietnam using the advection-dispersion model (ADM) approach with several transport parameters (dispersion, dispersivity distance, discharge outflow, tracer recovery, maximum concentration, peak time and peak velocity), to determine the spatial distribution of flow and transport parameters that recharge the travel system (vadose and phreatic zone), as well as the influence of seasons on these parameters.

The research area is part of the Jonggrangan Karst region, which is unique in the form of a higher altitude than the surrounding area. This karst area has a basement in the form of old-andesite formation so that there are many contact type springs at high elevation. Consequently, people can easily use it directly. Several springs have large and perennial discharge among the springs, namely the Kiskendo Spring, Anjani, and Mudal. Some hydrological studies that have been conducted in this region include [21] to determine the properties of the release of flow components and predict the karstification degree. *H. Fatoni*, [22] also examined the relationship between discharge variability and karst aquifer memory systems, and *I.A. Kurniawan et al.* [23] applied a time series analysis approach to determine the character of the release components of diffuse flow, fissure, and conduit from karst aquifers.

Research on groundwater connectivity with the tracer test approach, the analysis of transport parameters, and the determination of the catchment area have never been conducted in this region. Research related to these matters will add information and strengthen the results of previous research to reveal the character and development of aquifers in the Jonggrangan karst. Based on these considerations, this study aims to: (i) define a groundwater flow system that affects the Kiskendo Spring, Anjani, and Mudal; (ii) analyse transport parameters of the tracer test results; (iii) estimate the catchment areas of the three springs to formulate their management for conservation.

Materials and Methods

Site Descriptions

The Jonggrangan karst formation is composed of Miocene-Pliocene reef limestone. Physiographically, the Jonggrangan karst is located in the Kulonprogo Mountains, whose formation process has three tectonic phases, namely uplifting accompanied by volcanism, subsidence, and up-doming [24]. The name of this location refers to the Jonggrangan geological formation composed of conglomerates, tuff-marl, and limestone sandstone with lignite inserts at the bottom, while at the top, there are coral limestones [25]. The Jonggrangan Karst has an area of around 17.7km^2 with a maximum width of 3.3km and a maximum length of 6.9km. The elevation of this region varies between 500 to 900m asl. Regionally, the stratigraphy that forms the Jonggrangan karst region and its surroundings is the Nanggulan Formation, Old-Andesite Formation, Jonggrangan Formation, Sentolo Formation, and Alluvial Deposition [25, 26].

E. Haryono [27] explained that some karst morphological features such as the karstic cones and closed basins had been formed at several locations, but with the slope side that has open valleys as a characteristic that the Jonggrangan karst area is still in the early stages of development. Meanwhile, the hydrological characteristic, which is the main characteristic of this region, is that many springs are perennial. Most springs emerge in the contact area between the limestone formations and the harder underlying formations or due to topographic cuts that are affected by fault activity. Some important springs for community use include Mudal (15L/s), Bangki (0.95L/s), Sepenggal (11.2L/s), Kaliterban (0.4L/s), Selangsur (0.14L/s), Anjani (3.44L/s) and Sumitro (30L/s). Besides, the drainage system in Jonggrangan karst is classified as a complex which is reflected by the many foundations in the form of shafts, ponors, caves, sinkholes from allogenic and autogenic rivers, and an underground river that comes out to the surface.

Rain data from the Samigaluh, Girimulyo and Kaligesing rain stations for ten years (2008-2017) shows that the Jonggrangan karst area has an average annual rainfall of 2546mm with the rainy season in October-April and the dry season is May-September. The temperature in November-January has a value of around 23°C, while in February-October, it has an average value of around 24.4°C. The flow system outlet in the Jonggrangan karst area that was chosen as the research site was Anjani, Kiskendo, Mudal springs (Fig. 1). The selection of Anjani, Kiskendo, and Mudal as the focus of this research is because the flow is perennial, has been widely used by the surrounding community, and its accessibility is relatively easy.

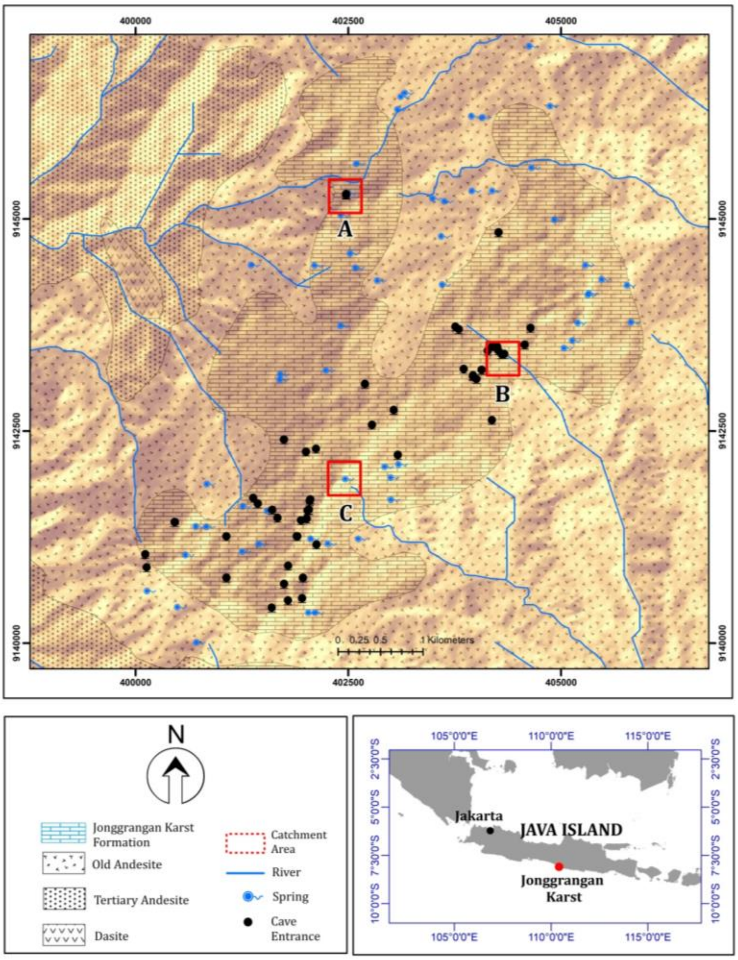


Fig. 1. Jonggrangan Karst area. A: Anjani Cave Stream, B: Kiskendo Cave Stream, C: Mudal Spring

Methods and techniques

Tracer tests

To find out the underground flow connectivity that recharges Anjani Cave, the first two dye tracer injections were conducted into sinking streams, namely Kalicebong and Jumbleng Sawah, on the 28th of April, 2018, until the st of May, 2018. Injection in Kalicebong using uranine and in Jumbleng Sawah using tinopal. The second tracing test was carried out on the 13th to the 15th of April 2019 with the injection site in the Kalisetro Sinking Stream using uranine. A field fluorometer GGUN-FL30 [28] was installed in Anjani Cave on the 28th of April 2018, whereas GGUN FL24 was installed on the 13th of April 2019. In total, five tracer tests (Table 1) were carried out to determine the underground flow system in the Jonggrangan Karst region. Two tracer tests were carried out on the 28th of April, 2018, using uranine and tinopal to determine the underground flow system leading to Anjani Cave (OP-1). Trace agent injection is conducted by pouring uranine in Kalicebong (IP-1) sinking stream and tinopal injection in Jumbleng Sawah (IP-2).

Table 1. Tracer test conducted in the Jonggrangan Karst Area

No	Date	Injection Point	Dye	Quantity (gr)	Observation point	Spring Discharge (l/s)
1	2018/04/28	IP-1	Uranine	400	OP-1	41.94
2	2018/04/28	IP-2	Tinopal	300	OP-1	
3	2019/04/13	IP-3	Tinopal	400	OP-1	45.55
4	2018/06/18	IP-4	Uranine	80	OP-2	107.32
5	2018/06/18	IP-5	Uranine	500	OP-3	128.97

A tracer test to find out the Kiskendo Cave system (OP-2) was carried out by pouring 80 grams of uranine in Semar Cave (IP-4) on the 30^{th} of June 2018. Semar Cave is one of the unmapped systems by [29]. OP-2 has several interconnected network branches between caves (from west to east), including Jumbleng Silodho, Central Jumbleng, Jumbleng Sanyar, Jumbleng Kemejing, Jumbleng Semelong, Upper Kiskendo Cave, Lower Kiskendo Cave, and Soemitro Cave [29]. The tracer test was conducted on the 30^{th} of June 2018 and monitoring with GGUN FL30 was conducted until the 4th of July 2018. For information, IP-4 has a characteristic length of passage reaching 158.2 meters, and there is a sump at the end of the tunnel.

The Mudal spring system (OP-3) was investigated by conducting a tracer test using uranine, which is poured in the Nguwik Cave Stream (IP-5). Uranine injection of 500 grams was carried out on the 16^{th} of July, 2018, which was monitored with an FL30 fluorometer in OP-3, which recorded tracing data until the 31^{st} of July 2018. In order to obtain detailed tracer breakthrough curves, field fluorometers (GGUN-FL 30 and 24; Albillia Sarl, Switzerland) were installed at these observation points. The sampling interval during the tracer tests was 5 minutes.

Furthermore, discharge monitoring was carried out by installing water level data loggers and barometric loggers (HOBO U20L-02) at all three spring locations. Discharge measurements using the current meter are also carried out to create a stage-discharge rating curve at each spring location. Discharge measurements are carried out regularly at various water level conditions. Continuous discharge data from the spring were obtained from the study site and then used for water balance calculations and estimates of the total recovery and water volumes in the subsurface flow system.

Evaluation and modelling of the tracer test results

Quantitative analysis of tracer test results is one of the most reliable methods for constructing and defining solute-transport parameters [30]. All breakthrough curves (BTC) were analytically modelled with a conventional advection-dispersion model (ADM) using Qtracer2 software. Advection is a transfer of material by and with the bulk flow and has unit m/s, while dispersion is turbulent plus diffusive mixing in all directions has unit m/s^2. Then, the general equation of advection-dispersion is shown in the following formula [13]:

$$\frac{\partial c}{\partial t} = D_l \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} \quad \ldots\ldots\ldots\ldots (1)$$

where: c = concentration of the dye tracer; t = time; D_l = longitudinal dispersion coefficient; v = effective flow velocity; and x = longitudinal distance.

Water volumes (V) of the karst conduit system were then approximated by multiplying the mean discharge (Q_{mean}) and the mean transit time of the tracer (t_{mean}) obtained from BTC

[31]. Dispersivity is a measure of the spread of a material due to the tortuosity of the flow path of water through the porous media (m). Mathematically, dispersivity is a ratio between dispersion (m^2/s) and advection (m/s). In addition, percent recovery was estimated by this formula:

$$M_R : \int_{t=0}^{\infty}(Q.c)dt \text{ .... (2)}$$

and total tracer recovery from all down-gradient sampling *points* may be estimated by [32]:

$$T_T = \sum_{i=1}^{n} T_{Ri} \text{ .... (3)}$$

where: c = tracer concentration (kg/L); Q=groundwater discharge (L/sec); T = time of sample collection (sec); T_R = mass of tracer recovered (kg); T_T = total of tracer mass recovered from all sampling point (kg)

If the discharge at the injection site is equal to or near the discharge at the observation location, and when the recovery rate is close to 100%, it can be concluded that there is a direct connection between the two points, without flow divergence and convergence [13]. Tracer mass recovery at an observation point where the discharge was measured during the tracer test allows for a rough estimate of the maximum volume of the karst conduit [33]. If the discharge was measured during the tracer test, then the conduit volume can be calculated using the formula:

$$\int_{t=0}^{tc} Q\, dt \text{ ....(4)}$$

If a single discharge, the conduit volume was calculated by this formula:

$$V= Q \times Tt \text{ ....(5)}$$

where: Q is mean spring discharge (m^3/dt), and V is the volume of individual karst conduits (m^3).

Furthermore, *N. Goldscheider and D. Drew* [34] describe several conduit network configurations in the karst region based on input-output discharges and tracing tests on steady flow, as shown in Table 2.

Catchment area estimation

The catchment area for each spring is estimated using a water balance approach that requires rainfall, evapotranspiration, and spring discharge data, using the equation:

$$Q = P – E + \Delta S \text{ ……….. (6)}$$

where : Q= spring discharge (m^3/detik); P= precipitation (mm/year); E= evapotranspiration (mm/year); ΔS= change in storage (mm/year)

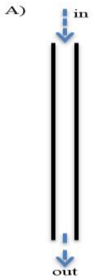
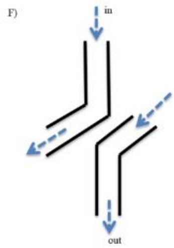
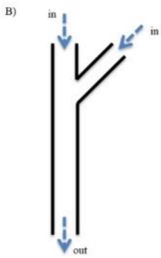
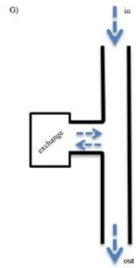
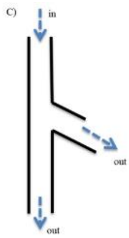
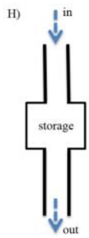
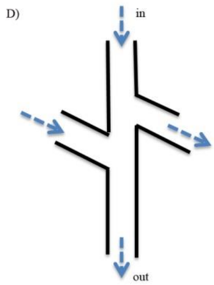
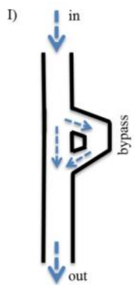
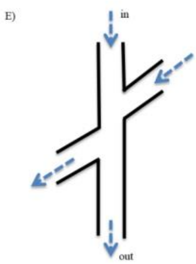
Rainfall data for the calculation of water balance is obtained from the rain station data installed on each spring catchment (November 2017-2018). Flow discharge is obtained from hydrograph data during this period [23].

Meanwhile, potential evapotranspiration is calculated by the Blaney-Criddle method with the formula [35]:

$$PET = \sum Kt \times Kc\ (T \times p /100) \text{ ……..(7)}$$

where : PET= Potential evapotranspiration (inch); Kt = 0,0173t – 0,314; T = Average monthly temperature (°F); Kc = Crop coefficient; p= Percentage of monthly afternoon hours (%)
Furthermore, delineation of the catchment area boundary is carried out using the topographic approach manually, as was conducted by [36].

Table 2. Network configuration for conduit flow under steady flow condition [34]

No	Configuration	Comments	No	Configuration	Comments
1		$Q_{in} = Q_{out}$ $M_{in} = M_{out}$ No dilution No divergence	6		$Q_{in} \neq Q_{out}$ $M_{out} = 0$ Deviation No connection
2		$Q_{in} \leq Q_{out}$ $M_{in} = M_{out}$ Dilution Convergence	7		$Q_{in} = Q_{out}$ $M_{in} = M_{out}$ No dilution No divergence exchange
3		$Q_{in} \geq Q_{out}$ $M_{in} \geq M_{out}$ Divergence No Dilution	8		$Q_{in} = Q_{out}$ $M_{in} = M_{out}$ No dilution No divergence storage
4		$Q_{in} \neq Q_{out}$ $M_{in} \geq M_{out}$ Divergence Convergence dilution	9		$Q_{in} = Q_{out}$ $M_{in} = M_{out}$ No dilution No divergence bypass
5		$Q_{in} \neq Q_{out}$ $M_{in} \geq M_{out}$ Convergence Divergence dilution			

Results and discussion

The complete results of the tracer test in the three locations are provided in Table 3.

Table 3. Results of the tracer test

Injection	Injection code	Unit	IP-1	IP-2	IP-3	IP-4	IP-5
	Dye tracer		Uranine	Tinopal	Tinopal	Uranine	Uranine
	Quantity (gr)		400	300	400	80	500
	Injection point		Cebong river	Jumbleng Sawah	Kalisetro river	Semar Cave	Nguwik Cave
Observation point (OP)	Parameters						
OP-1 (Anjani Cave)	TFD*	min	120	595	245		
	Tp*	min	275	805	375		
	MC*	ppb	221	212.93	1202.5		
	distance	meter	611	853	605		
	Peak velocity	m/min	2.22	1.06	1.61		
	Dispersion	m^2/sec	41.03	9.23	2.6		
	Dispersivity	meter	84.4	40.96	22.03		
	Recovery	%	82	84.8	80		
	Advection	m/hour	1750.7	811.4	422.83		
	CFE*	m^3	269.5	811.74	324.52		
	R^2	-	0.8	0.89	0.88		
OP-2 (Kiskendo Cave)	TFD*	min				255	
	Tp*	min				500	
	MC*	ppb				138.05	
	distance	meter				448	
	Peak velocity	m/min				0.9	
	Dispersion	m^2/sec				22.86	
	Dispersivity	meter				93.9	
	Recovery	%				78.5	
	Advection	m/hour				876.53	
	CVE*	m^3				413.9	
	R^2	-				0.98	
OP-3 (Mudal Spring)	TFD*	min					7140
	Tp*	min					7680
	MC*	ppb					138.82
	distance	meter					584
	Peak velocity	m/min					0.08
	Dispersion	m^2/sec					0.14
	Dispersivity	meter					11.11
	Recovery	%					90
	Advection	m/hour					44.66
	CVE*	m^3					8464.4
	R^2	-					0.95

*Tp = time to peak; MC = maximum concentration; TFD = time of first detection; CVE = conduit volume estimation

To find out the Anjani Cave connectivity system, uranine pouring was carried out at IP-1 (the 28th of April 2018), while tinopal was poured at IP-2 (the 28th of April 2018) and IP-3 (the 13th of April 2019), while the FL30 fluorometer was installed at OP-1. The tracer test results show the flowing connectivity between injection points (IP-1, IP-2, IP-3) and OP-1. The BTC graph shows a single-peak curve, which means that the injection points and OP-1 have a single conduit connection.

In detail, a peak of uranine concentration of 221 ppb was detected on the same date (the 28th of April 2018), at 17.00, while a peak of tinopal concentration was detected on the 29th of April 2018 at 04.00 at 212.93 ppb. The time to peak (Tp) uranine is 155 minutes, while Tp tinopal is 210 minutes. Furthermore, the second tracer test (the 13th of April, 2019) with injection point at IP-3 (Kalisetro) showed a peak of tinopal concentration of 1202.5 ppb at

17:45 or about 375 minutes after tinopal pouring. The results of the BTC tracer test in the Anjani Cave system (OP-1) are shown in figure 2, and the flow connectivity map in the Anjani system is shown in figure 3.

Underground river in Kiskendo Cave (OP-2) has several branch systems of the interconnected void from west to east, covering Jumbleng Silodho, Jumbleng Tengah, Jumbleng Sanyar, Jumbleng Kemejing, Jumbleng Semelong, Upper Kiskendo Cave, Lower Kiskendo Cave, and Soemitro Cave [29] (Fig. 5). The cave-in IP-4 has a hallway length of 158.2 meters. Uranine injection was carried out at IP-4 on the 30th of June 2018 (13.00), and monitoring was carried out until the 4th of July 2018. Tracer tests showed the connectivity between IP-4 and OP-2. The highest peak of uranine concentration in OP-2 was recorded on the 30th of June 2018 (20.05) with a concentration of 138.05 ppb with a reasonably fast time to peak (around 7 hours). As in the Anjani system, the Kiskendo subsurface system also shows a single conduit system (Fig. 4).

Mudal Spring (OP-3) is a perennial spring. Around this spring, several ponors (Jumbleng Sapi Mati, Jumbleng Sigendhol, Jumbleng Sepeti, and Pledangan - Fig. 7) are suspected of having connectivity with Mudal springs. Meanwhile, there is also a watery cave which is Nguwik Cave (IP-5). Uranine injection was carried out in IP-5 sump on the 16th of July, 2018 (10.36), and monitoring with FL30 was carried out until the 31st of July, 2018 (07.15). The results of the tracer test show the connectivity of the flow between IP-5 and OP-3 with the type of single conduit (Fig. 6). The peak of uranine concentration occurred on the 22nd of July 2018 (09.00), amounting to 138.82 ppb, with the appearance of uranine already beginning to be seen, marked by an increase in uranine concentration since the 21st of July 2018 (24.00).

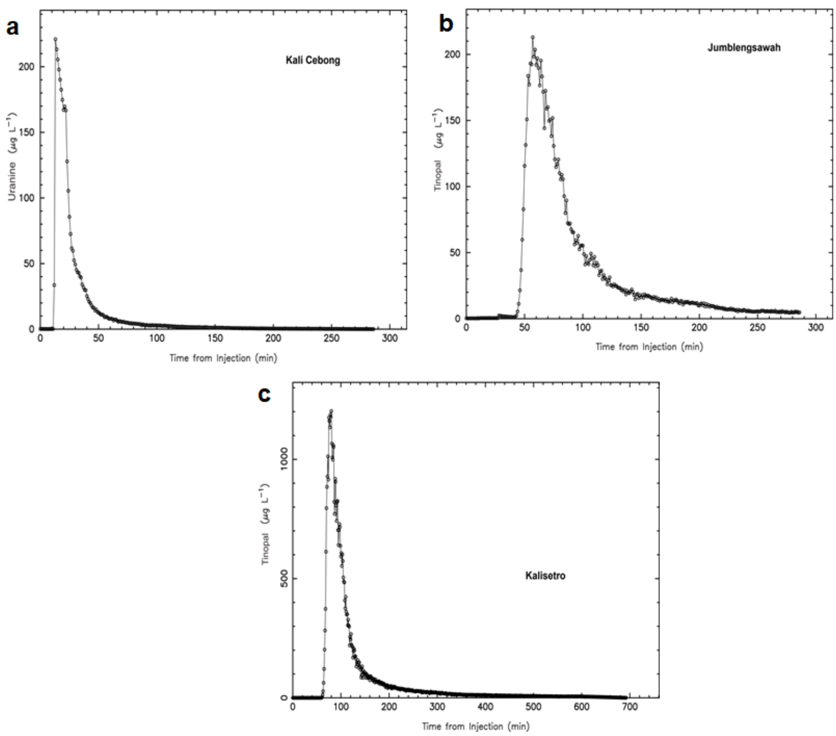


Fig. 2. Breakthrough curves resulting from dye tracer injection in Anjani system:
a – Kali Cebong; b – Jumblengsawah; c - Kalisetro

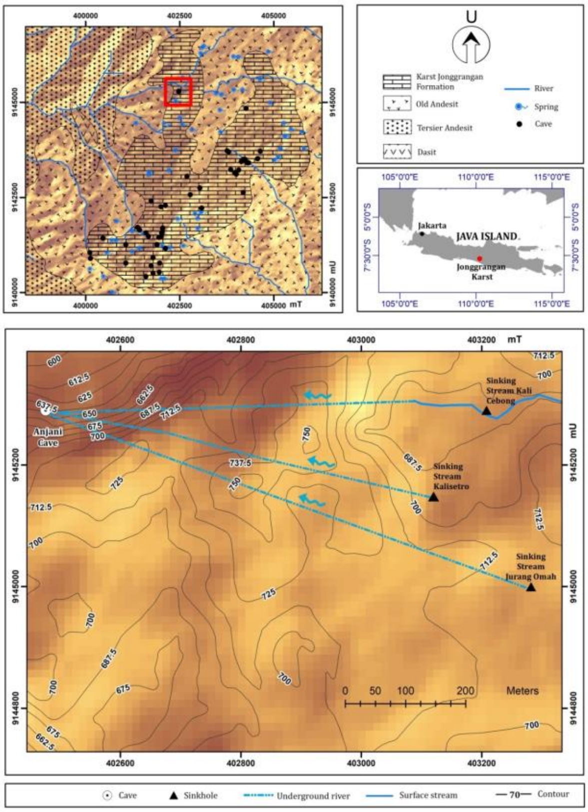


Fig. 3. Connectivity between the injection point and Anjani Cave

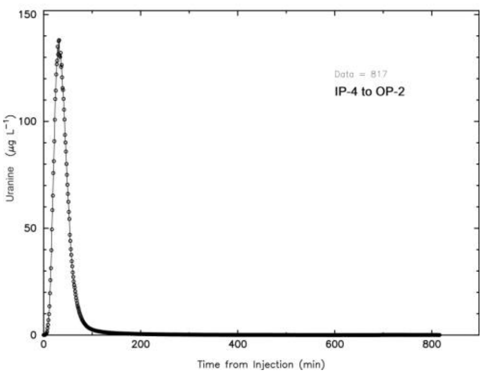


Fig. 4. Breakthrough curves resulting from dye tracer injection in Kiskendo system

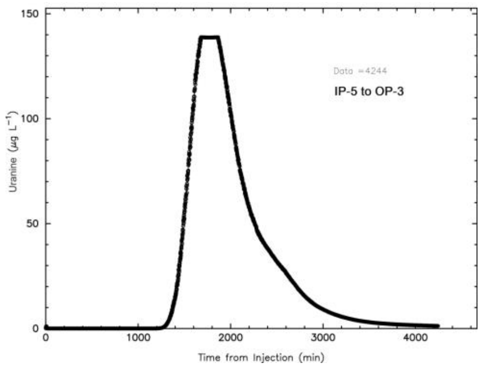


Fig. 5. Breakthrough curves resulting from dye tracer injection in Mudal system

Quantitative analysis of transport parameter

The transport parameter values in this study were analysed with Qtracer2 software rocks [30]. The parameters obtained from breakthrough curves (BTC) in Figures 3, 5, 6 and 7 include the time of first detection (T_0), time to peak (Tp), maximum concentration, and peak velocity, while the quantitative parameters running from Qtracer2 are advection, dispersion, dispersivity, and recovery.

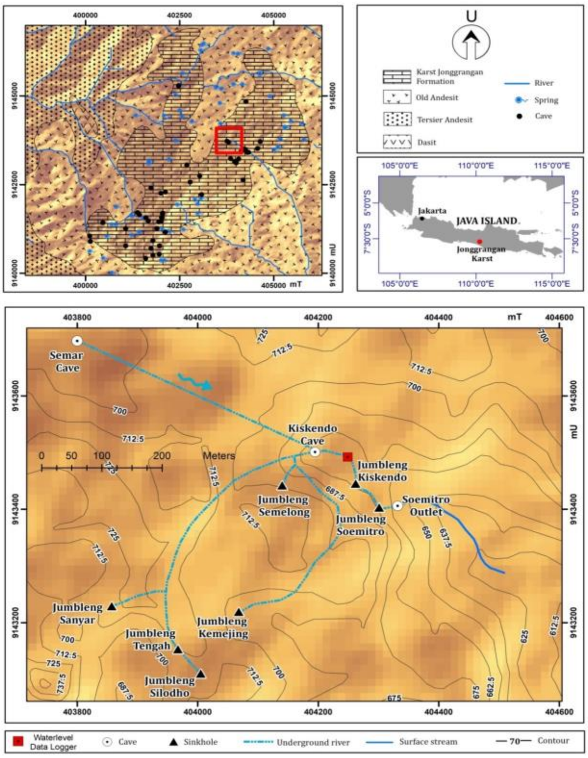


Fig. 6. Connectivity between the injection point and Kiskendo Cave

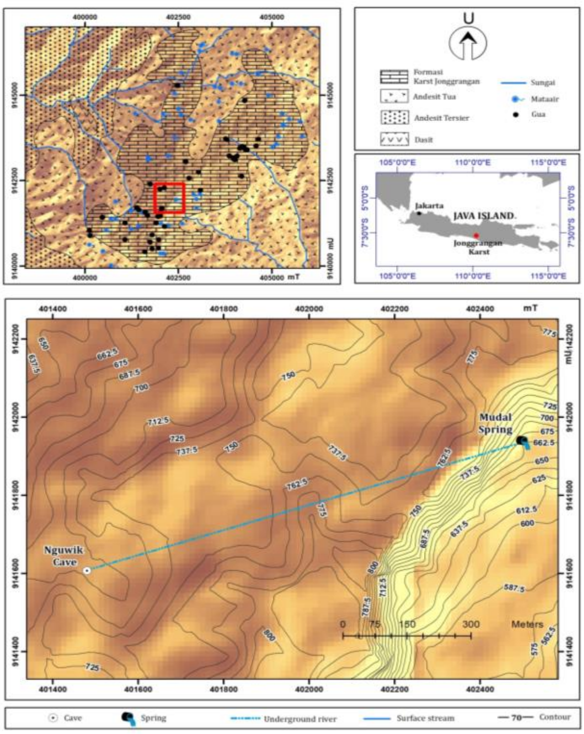


Fig. 7. Connectivity between the injection point Mudal spring

The BTC and quantitative parameters of Qtracer2 are presented in Table 1. First of all, the Advection Dispersion Model (ADM) produced shows gentle curve fitting, with R^2 values greater than 0.8 from all injection points. The fastest advection and time to peak values were found in the Anjani Cave system (1750.7m/hour and 95 minutes, respectively). In more detail, the Tp value of the three injection sites in the Anjani Cave system is 155 minutes (Kali Cebong), 210 minutes (Jumbleng Sawah), and 95 minutes (Kali Setro). The value of Tp in the Anjani Cave system is also classified as the fastest compared to that found in the Kiskendo system and the Mudal spring.

Dispersivity may have units of length, but it is not directly related to the distance of the tracer test. Dispersivity is an empirical factor that quantifies how much contaminants stray away from the path of the groundwater that is carrying it. Mathematically, dispersivity is the quotient between dispersion (m^2/s) and advection (m/s). The smallest dispersivity value is found in the Mudal spring system (injection point: Nguwik Cave), which is relatively small when compared to the dispersivity value in the Anjani system (Kali Cebong - 84.4m; Jumbleng Sawah - 40.96m; Kali Setro - 22.03m) and Kiskendo (93.9m). Meanwhile, the fastest time of first detection (T_0) was found in the Anjani system (120m - Kali Cebong), while the Mudal system had the most extended T_0 value (7140 minutes).

Meanwhile, the dispersion value indicates the distribution of tracer substances in the body of water per unit time. The dispersion value has a unit m^2/s. The smallest dispersion value was found in the Mudal Spring karst aquifer ($0.14m^2/s$), while the highest dispersion value ($41.03m^2/s$) was found in the Kalicebong-Anjani flow system. The recovery value is the mass of the tracer recovered after it has been released. It may be expressed as an actual mass recovered. The highest recovery was found in the Nguwik-Mudal Spring system of 90% of the total 500 grams of uranine injected in the Nguwik Cave, while the smallest recovery value (78.5%) was found in the Semar-Kiskendo system of 80 grams of uranine. A summary of the transport parameters of the tracer test is presented in Table 4.

Tabel 4. Comparison of transport parameters from tracer tests in the three locations

Springs	Transport Parameter	Comparisons	Characteristics
Anjani	Advection	>Kiskendo >Mudal	• the highest karstification degree • recharge in the form of 3 allogenic rivers • the fastest flow release duration of its water storage (0.5 hours)
	Dispersion	<Kiskendo >Mudal	
	Dispersivity	<Kiskendo >Mudal	
	Percent recovery	>Kiskendo <Mudal	
	T_0	<Kiskendo <Mudal	
Kiskendo	Advection	<Anjani >Mudal	• the degree of karstification is lower than Anjani catchment • many sinkholes are found in the Kiskendo system • storage flow release duration ranges from 0.6-25 hours • the most extensive catchment area (3.69 km^2)
	Dispersion	>Anjani >Mudal	
	Dispersivity	>Anjani >Mudal	
	Percent recovery	<Anjani <Mudal	
	T_0	>Anjani >Mudal	
Mudal	Advection	<Anjani <Kiskendo	• the lowest degree of karstification • recharge comes from the underground river system • storage flow release duration is the longest, which ranges from 1.3-12.5 hours
	Dispersion	<Anjani <Kiskendo	
	Dispersivity	<Anjani <Kiskendo	
	Percent recovery	>Anjani >Kiskendo	
	T_0	<Anjani <Kiskendo	

Water balance application to determine the catchment area

A water balance is carried out to determine the catchment area in an input or recharge area system. The parameters used to determine the catchment area with a water balance concept are potential evapotranspiration (PET), average annual spring discharge (Q), and annual precipitation (P). Precipitation (P) is measured directly over one year (December 2017 to November 2018). The results of the precipitation calculation for one year are Kiskendo Cave Springs = 2,495.4mm; Anjani Cave spring = 2,390.5mm; and Mudal Springs = 2,431.3mm.

Spring discharge (Q) for water balance calculation using the average monthly discharge for one year from December 2017 to November 2018. The results of the average annual discharge of the three study springs calculated based on flow hydrograph data are the Anjani Cave spring = 34.9L/sec; Kiskendo Cave spring water = 150.1L/sec, and Mudal springs = 70.1L/sec. Then, potential evapotranspiration (PET) is used to calculate water balance by accumulating the results every month, as presented in Table 5. The three springs at the study site are assumed to have the same PET value because the Jonggrangan Karst area is not significant and has almost uniform land use, meteorological, and topographical conditions. The crop coefficient (Kc) used in PET calculations corresponds to the dominant crops such as cocoa, coffee, and crops that are suitable in areas with a wet climate (Kc = 0.7).

Table 5. The result of the PET calculation

Month	T (˚C)	T (˚F)	Kt	Kc	P (%)	PET (inch)	PET (mm)
2017/12	23.40	74.12	0.97	0.70	8.79	4.42	112.16
2018/01	23.50	74.30	0.97	0.70	8.75	4.42	112.29
2018/02	24.00	75.20	0.99	0.70	7.83	4.07	103.33
2018/03	24.10	75.38	0.99	0.70	8.51	4.45	112.92
2018/04	24.90	76.82	1.01	0.70	8.12	4.43	112.57
2018/05	24.10	75.38	0.99	0.70	8.27	4.32	109.74
2018/06	24.74	76.53	1.01	0.70	7.96	4.31	109.39
2018/07	24.89	76.80	1.01	0.70	8.16	4.45	113.06
2018/08	25.12	77.22	1.02	0.70	8.35	4.61	117.14
2018/09	24.13	75.44	0.99	0.70	8.18	4.28	108.74
2018/10	23.63	74.53	0.98	0.70	8.61	4.38	111.30
2018/11	23.39	74.10	0.97	0.70	8.43	4.23	107.50
						Σ Total	1330.13

Furthermore, the catchment area of the three springs generated from the water balance is conducted as the basis for catchment boundary delineation adjusted to the topographic conditions in the study area. Topographical identification in the catchment area subsequently results in the estimation of catchment boundary, which is done by on-screen digitising through ArcGIS 10.2 software, the extent of which is presented in Table 6 and figure 8.

Table 6. Catchment area as a result of water balance calculation

Spring	PET (mm)	Q (l/sec)	P (mm/year)	Catchment area (km^2)
Kiskendo	1,330.13	150.1	2,495.4	3.69
Anjani	1,330.13	34.9	23,90.5	0.80
Mudal	1,330.13	70.1	2,431.3	1.71

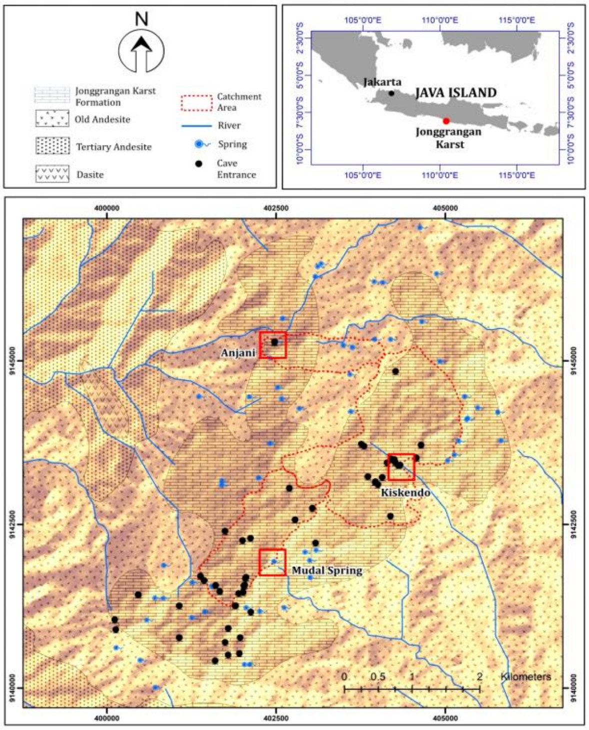


Fig. 8. Catchment area estimation boundary

Recommendations for water resources conservation in each catchment area

Allogenic rivers partially recharge the Anjani and Kiskendo catchment areas. Examples are Kali Setro, Kali Cebong, and Jumbleng Sawah, which dominate the Anjani underground river system (Fig. 8). Meanwhile, the catchment of the Mudal spring is only recharged by autogenic input. In karst groundwater management, catchments that have allogenic recharge have a higher susceptibility to pollution because the flow from allogenic rivers enters directly into the underground river system without being filtered first by the soil [37]. The condition is different from what is experienced by karst catchment, which is influenced by autogenic flow, where most of the water entering the underground system has gone through the filtering and infiltration process (fissure and diffuse systems).

I.A. Kurniawan et al. [23] revealed that the Anjani Cave catchment had the highest degree of karstification (compared to Mudal and Kiskendo). A high degree of karstification indicates the level of development of the most developed voids so that the management of the catchment area is more emphasised to avoid pollutants entering the underground river system. Recession characteristics in Anjani Cave show that there are two turbulent flows, one laminar flow, and three surface flows that recharge Anjani Cave, with the domination of conduit flow so that the release response is relatively fast. *I.A. Kurniawan et al.* [23] also explained that the maximum duration of the release of conduit flow at Anjani was 0.5 hours. The calculation results are also in line with the calculation results of transport parameters in the form of the fastest advection value (994.98m/h) compared to those in Kiskendo and Mudal. Because the Anjani Cave catchment has the fastest advection value and the highest degree of karstification, this has consequences for the location's most vulnerable to pollution. Therefore, the scale of management in the Anjani catchment must be prioritised.

The proposed conservation action for the Anjani Cave catchment is to prohibit the direct disposal of solid and liquid waste into allogenic rivers. In addition, the upstream part of the catchment area is not recommended for anthropogenic activities that have the potential to reduce water reserves that recharge allogenic rivers. Concerning agricultural activities, it is recommended to limit the use of chemical fertilisers because it has the potential to directly enter the Anjani river system (one of which is through the ponor Jumbleng Sawah). Other proposed management actions to address the issue of poultry waste found in the Anjani Cave catchment are the creation of adequate poultry storage and treatment facilities so that it does not seep and pollute karst aquifers, as well as processing poultry waste into biogas.

The void development in the Kiskendo Cave catchment is lower than the Anjani Cave catchment area [23]. The aquifer that recharges the Kiskendo Cave has two laminar flows and one turbulent flow with still dominated by diffuse flow, with a release duration of between 90 to 125 hours. The calculation of transport parameters in the tracer test also indicates that the value of advection in the Kiskendo Cave system is slower than Anjani Cave (876.53m/h). The management actions proposed at the Kiskendo Cave catchment are slightly different from those proposed at the Anjani catchment. In this Kiskendo Cave catchment, many goat farms are found that have considerable waste. In this connection, the disposal of goat farm waste is recommended to be processed first and disposed of in areas far from sinkholes or ponors that are often found in this Kiskendo catchment.

Meanwhile, although the Mudal spring aquifer has a karstification degree that is almost the same as the Kiskendo Cave (5.5) [23], it has a much lower advection value (44.66m/h). This fact shows that the predominant flow in the Mudal system is diffuse flow with a long release time (150 to 166.7h). The recommended management action is to protect the upstream area of Mudal Spring, namely around Nguwik Cave, by not carrying out domestic waste disposal or fertilising activities. In addition, because the recharge of Mudal springs is dominated by diffuse flow, conservation of the forest is needed by not changing it into the land with little vegetation (rice-field and mixed-garden). This condition is closely related to the interception process by vegetation needed to maintain groundwater storage in karst aquifers.

In general, the catchment management of the three springs in the study area is to maintain a thin layer of soil so as not to decrease due to erosion. The suggestion of catchment management related to this is by making a terrace that does not reveal much land. This terrace protects soil loss due to erosion and can increase infiltration capacity so that water has more opportunity to be retained and seep into the soil, which is then stored in the epikarst zone as the main recharge of the aquifer.

Land with a thin solum (almost bare land) is directed to planting pioneer trees, which can quickly grow on rocky lands such as acacia, white albizia, teak, and mahogany. The roots of these plants are strong enough so that in addition to being able to hold the soil due to erosion, they can also make cracks in limestone for rainwater absorption.

In addition, *Suripin* [38] explains that the management of water resources can be realised by: (i) increasing groundwater volume and quality through land management activities and (ii) managing spring discharge to improve the efficiency of its use. Discharge management in the three springs can be said to be quite useful because the discharge has been well utilised and available throughout the year. *Suripin* [38] also added that the basic principle of water resource management is to use water as needed, store it when it is excessive, and use the minimum possible for maximum results. Next, the types of conservation actions proposed at each spring catchment are shown in Table 7.

Table 7. Proposed of water conservation in each catchment

Location	Karstification degree	Catchment area (km²)	BTC quantitative analysis		Problem identification	Proposed management actions
Anjani	8	0.80	Advection	994.98 m/h	Input in the form of three allogenic rivers as sources of contaminants	management of solid and liquid waste that can minimise direct impacts on groundwater
			Dispersion	17.62 m^2/s		management of land use in the catchment upstream
			Dispersivity	49.13 m		restriction/reduction of pesticide use
			Recovery	22.43 %	poultry waste	adequate poultry waste are provided and should be cemented to prevent seepage into the aquifer waste processing into biogas
					waste from fertilising activities	Fertiliser limitation; water quality monitoring
Kiskendo	5.5	3.69	Advection	876.53 m/h	goat farm waste	processing goat farm waste into compost or biogas
			Dispersion	22.86 m^2/s		making an adequate reservoir of goat livestock waste which is impermeable so that no waste seepage occurs into the groundwater
			Dispersivity	93.9 m	the thin layer of soil	planting of pioneer trees such as acacia, albasia, teak and mahogany
			Recovery	52.83 %	erosion	making terraces to prevent soil loss due to erosion
Mudal	5.5	1.71	Advection Dispersion	44.66 m/h 0.14 m^2/s	Groundwater contamination	protecting the upstream area of Mudal Spring, which is around the Nguwik Cave so as not to disposal domestic waste
					Mass tourism	managing the number of tourists, so that visitors' limits must be adjusted to the carrying capacity of the Mudal Spring
			Dispersivity	11.11 m	Domestic waste and fertilising activities	not to dispose of domestic waste around the sinkholes/ponor, as well as monitoring water quality
			Recovery	90%	Condition of recharge area which is dominated by diffuse flow storage	conservation of vegetation (forest) by not turning it into the land that has sparse vegetation (rice-field and mixed-garden)
					Erosion	making terraces to prevent soil loss due to erosion

Conclusion

The tracer tests at Karst Jonggrangan found several subsurface flow systems, namely Kalicebong-Anjani Springs, Jumbleng Sawah-Anjani Kalisetro-Anjani Springs, Semar-Kiskendo Springs, and Nguwik-Mudal Springs. The tracer test results also indicate that all of these systems are single conduits. The water balance approach produces three catchment areas in each spring, namely: (i) Anjani Cave ($0.8km^2$); (ii) Kiskendo Cave ($3.69km^2$); and (iii) Mudal Springs ($1.71km^2$). Furthermore, based on the characteristics of the transport parameters of the tracer test, aquifer karstification degree, and identification of problems encountered in the field, then some recommendations for the management of karst water resources in each catchment are as follows:

- In Anjani catchments that have recharge in the form of three allogenic rivers, with the fastest advection value and the highest karstification degree, the proposed management includes management of solid waste and liquid waste to minimise the direct impact of groundwater contamination. In addition, it is necessary to maintain the condition of upstream vegetation and limit the use of chemical pesticides and fertilisers. Another problem found in the Anjani catchment is the disposal of unprocessed poultry waste so that the proposed management is the provision of adequate reservoirs and processing of poultry farm waste and cemented to prevent seepage that can contaminate groundwater;
- In the Kiskendo catchment, with the issue of goat farm waste, which is still disposed of directly, the proposed action is to handle livestock waste either by composting or processing it into biogas and making a container for cemented livestock manure. Other problems encountered are erosion so that it is necessary to make a terrace and maintain the original vegetation;
- In the catchment of Mudal springs with the most extended advection value and low karstification degree, the proposed management is to limit fertilisation on agricultural land, disposal of domestic waste, as well as to conserve vegetation (forest) in the upstream area by not turning it into a rice-field and mixed-garden.

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