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CHARACTERIZATION OF UNDERGROUND RIVER PASSAGES CONTROLLED BY ALLOGENIC RECHARGE: INSIGHTS FROM AN ARTIFICIAL TRACER TEST IN THE GUNUNGSEWU KARST AREA, INDONESIA

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Summary. The Ponjong Hydrogeological Subsystem is a part of the Gunungsewu Karst Area on Java Island, Indonesia, and is uniquely influenced by allogenic recharge. This allogenic river system exists because the karst in this subsystem develops over a Tertiary volcanic formation. The contact between the Wonosari Formation limestone and the volcanic rocks, primarily composed of explosive volcanic materials from the Semillir Formation, allows this system forming. In this area, allogenic river catchments are dominated by relatively impermeable volcanic rocks and steep gradients, which often lead to flash floods. This study aimed to determine the characteristics of the cave and conduit networks within the underground river system influenced by allogenic recharge. An artificial tracer test using fluorescent dyes with breakthrough curves recorded by a fluorometer was conducted. Data analysis revealed that large, single conduits predominantly shape the cave networks in the study area. Due to the large discharge and steep gradient of the underground river system, a single conduit is formed instead of a maze-like cave system. The identification of connectivity between the allogenic rivers and the Gremeng Resurgence highlights that the karst drainage basin of the Gremeng Resurgence is not part of the Beton Karst Drainage Basin, as previously suggested by researchers who used methods other than artificial tracer tests. The development of large underground river systems indicates a high vulnerability to groundwater pollution and the ability to release groundwater reserves quickly. This poses a challenge for future environmental management, particularly in relation to water quality and water resource quantity management.

Introduction

The Gunungsewu karst area is located in the south-central part of the island of Java, Indonesia. This karst area is one of the most extensive karst areas in Indonesia with enormous water resource potential. Several underground rivers and springs have been utilized to meet the water needs of the communities in the karst area and also the surrounding areas.

The Gunungsewu Karst Area has six hydrogeological subsystems (Fig. 1) (Haryono et al., 2017). One of which is Ponjong Subsystem (Cahyadi et al., 2018a; Riyanto et al., 2018). This subsystem consists of springs and resurgence with large discharges and a well-developed underground river system (Haryono, 2011).

Ponjong differs from the other subsystems in Gunungsewu in the presence of allogenic recharge (Cahyadi et al., 2018b). Allogenic is a type of water recharge that supplies an underground river or groundwater in karst areas and originate in non-karst areas (Ford & Williams, 2007; Gilli, 2015). In Ponjong Subsystem, the allogenic recharge flows from the north, which is a hilly area with tertiary volcanic rocks (Adji, 2011; 2012). Some experts refer to the catchment area of this subsystem as Panggung Massive (van Bemmelen, 1949).

The allogenic river emerging in Ponjong Subsystem is attributable to the contact between tertiary volcanic rocks and the underlying limestone that forms Gunungsewu Karst Area. These volcanic rocks are part of the four ancient volcanoes, namely Panggung, Manyaran Wonodadi, and Wuryantoro ancient volcano (Fig. 2) (Akmaluddin et al., 2005; Surono, 2008; Bronto et al., 2009). On the 1:100,000 Geologic Map of Surakarta published by the Geological Agency, these volcanic materials are constituents of the Semilir Formation (Tms) and Wonosari Formation (Tmwl) (Surono et al., 1992).

Allogenic recharge in underground rivers/groundwater systems in karst areas is thought to have a considerable influence on the development of cave networks (Palmer, 2007; 2001). Open systems in allogenic rivers allow the entry of water with high concentrations of carbon dioxide into the karst groundwater system, and the dissolution process is thereby more intensive than in areas controlled by autogenic recharge (closed system) (Auler, 2013). Moreover, large amounts of water likely cause highly intensive erosion on the walls of caves and underground rivers, although not throughout the year (White, 1988; Palmer, 2007).

Characterizing dissolution passages and flow connectivity is the first part of defining karst drainage basins. Defining the karst drainage basin (KDB) or catchment area is very important in environmental management (Abdulrazzaq et al., 2022, Imrani et al., 2023). Karst areas with highly developed dissolution passages have very different characteristics from undeveloped karst areas. In addition to the vulnerability to pollution, these conditions are also related to the storage and release properties of karst aquifers, thus determining the condition of water resources in a region.

This study aimed to determine the characteristics of the cave passages and their connectivity within the Ponjong Hydrogeological Subsystem. Understanding the effects of allogenic recharge on the network shape is crucial for managing karst areas in general (Eppelbaum et al., 2014), and particularly those regions affected by allogenic recharge in the future. This paper presents a case study of the Kalimati Sinking Stream - Gremeng Resurgence system, an underground river system at the research site.

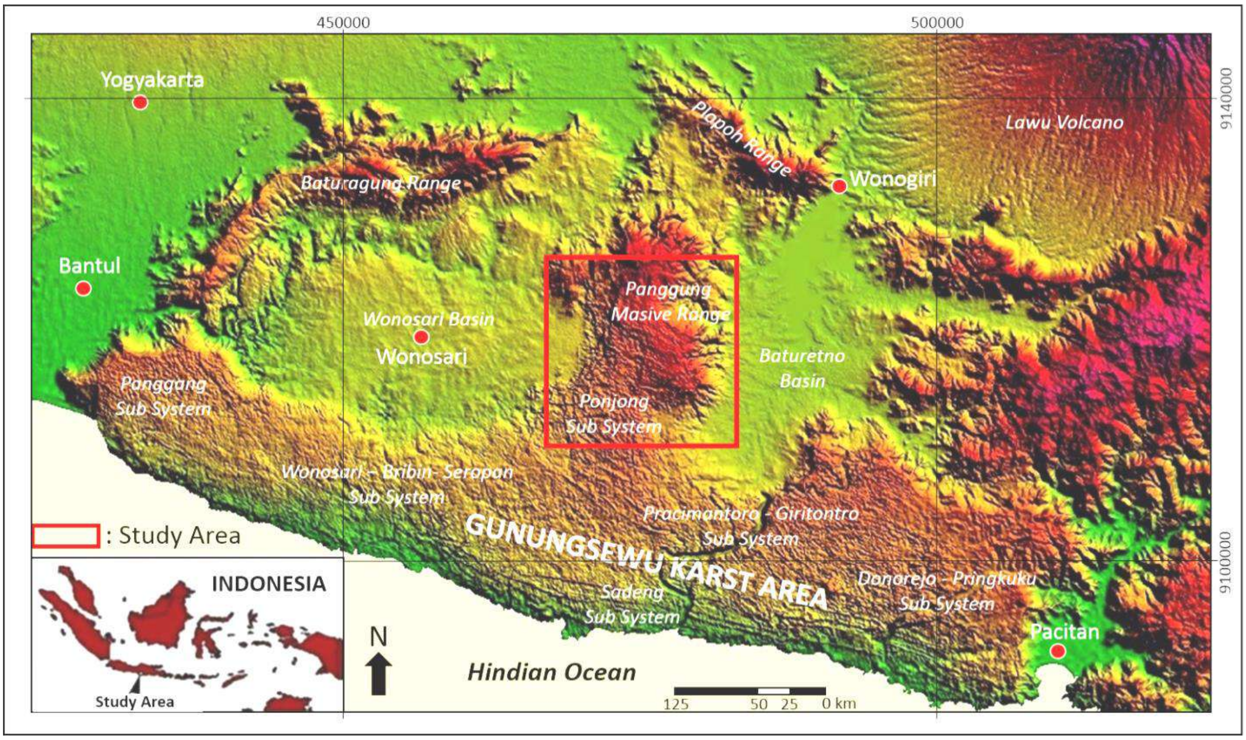

Fig. 1. The Hydrogeological System of Gunungsewu Karst Area
(Sources: Shuttle Radar Topography Mission United States Geological Survey)

Methods

The artificial tracer test resulted in breakthrough curve from which the characteristics of the karst cave networks were identified. Breakthrough curve recording was done with 2 fluorometers placed in Gremeng and Beton Resurgence. Tracer test is a method of tracking or tracing subsurface channels using water tracing agents (Stanley et al., 1980; Käss, 1998; Field, 2003; Field, 2005; Worthington, 2011). This research used two tracing agents or fluorescent dyes, namely uranine and tinopal. Both substances were selected because they are safe to use and easily detected even in minute concentrations (Hess and White, 1989; Behrens et al., 2001; Benischke et al., 2007).

The quantities of dye tracer used in this study are based on the equation proposed by Benischke et al. (2007), as shown in Equation 1. This equation was chosen because it generally does not overestimate the amount of dye tracer needed and does not result in a flat curve in the breakthrough curve (BTC) recording, as it does not exceed the maximum concentration that the fluorometer can detect. M represents the quantity of dye tracer required, in kilograms (kg). L is the distance from the injection point to the observation point, where the fluorometer is installed, measured in kilometres (km). Q is the discharge during artificial tracer tests conducted at the study site, in litres per second (L/s). C is the target peak concentration to be obtained, measured in micrograms per litre (μg/L). The peak concentration refers to the maximum concentration recorded by the fluorometer.

$$M = 1{,}9.10^{-5}(LQC)^{0{,}95} \quad 1)$$

The fluorescent dye was injected into Kalimati Sinking Stream (Fig. 3), and its appearance was observed at Beton and Gremeng Resurgences. This procedure was carried out because underground rivers controlled by allogenic recharge can form maze caves, which are underground passageways with many branches (Palmer, 2007). The observation results were recorded in a fluorometer and analysed based on the shape of the resultant breakthrough curve. Some conduits that are identifiable by the breakthrough curve analysis are shown in Fig. 4.

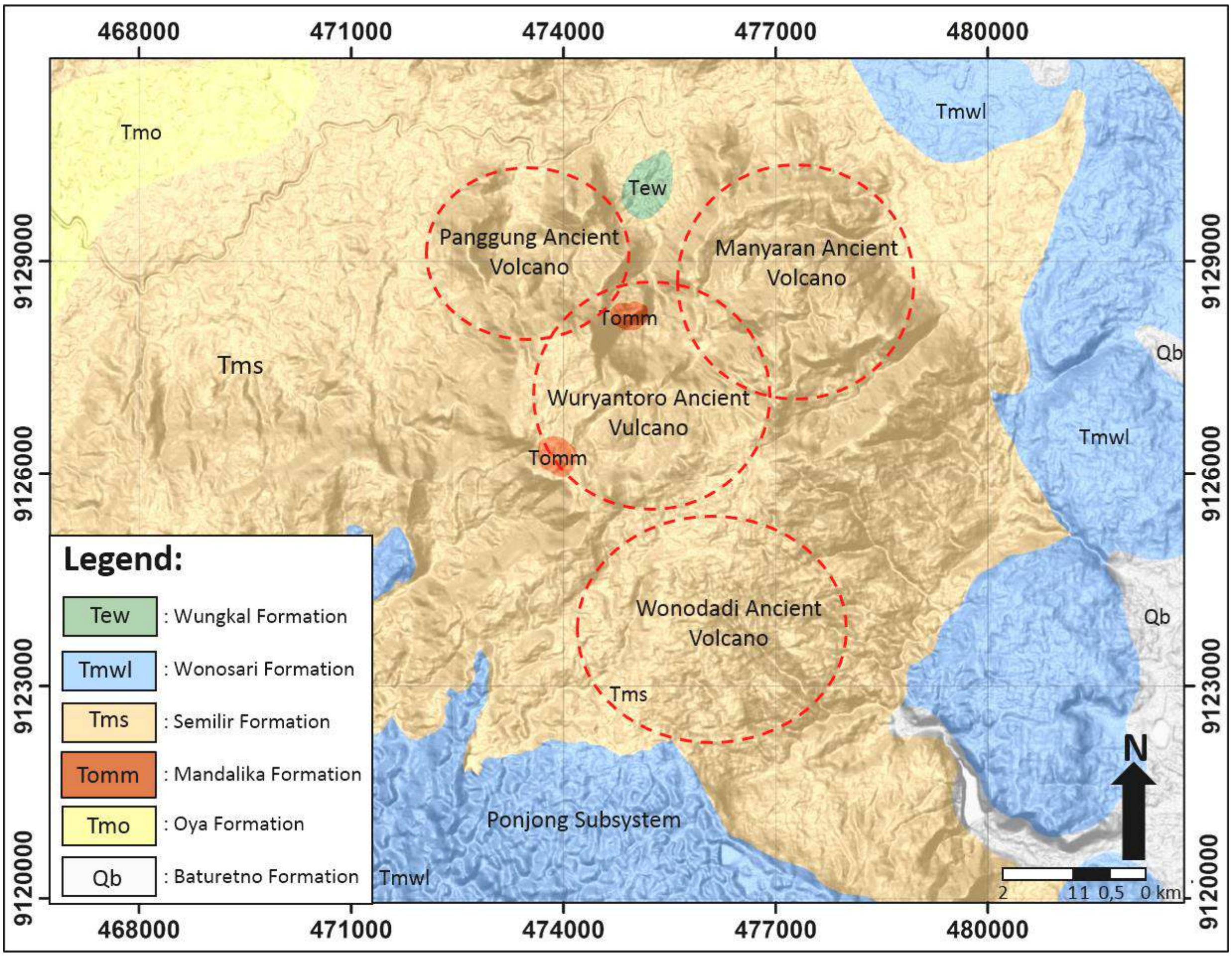

Fig. 2. The Ancient Volcanoes around the Ponjong Hydrogeological Subsystem
(Sources: Geological Map from Geological Agency of Indonesia and DEMNAS from Geospatial Information Agency of Indonesia)

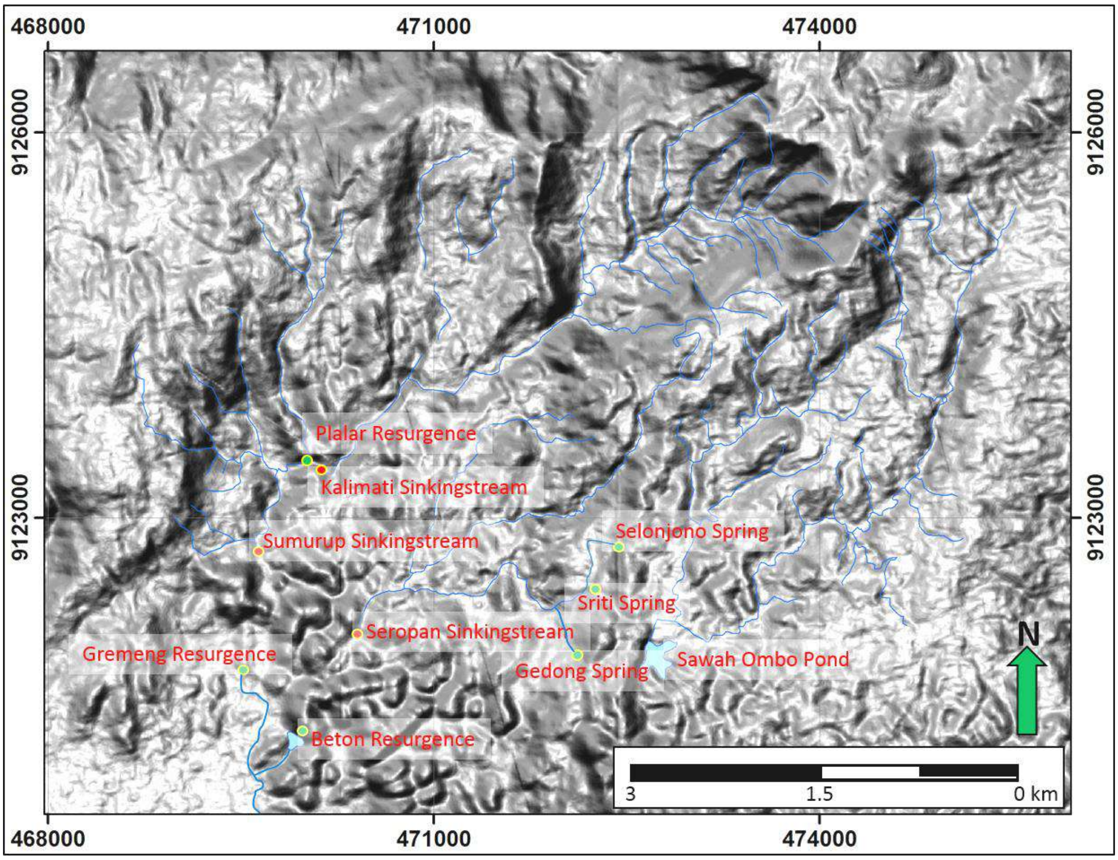

Fig. 3. The Hydrological Conditions of the Karst Area with Ponjong Hydrogeological Subsystem (Sources: Shuttle Radar Topography Mission United States Geological Survey and Field Survey)

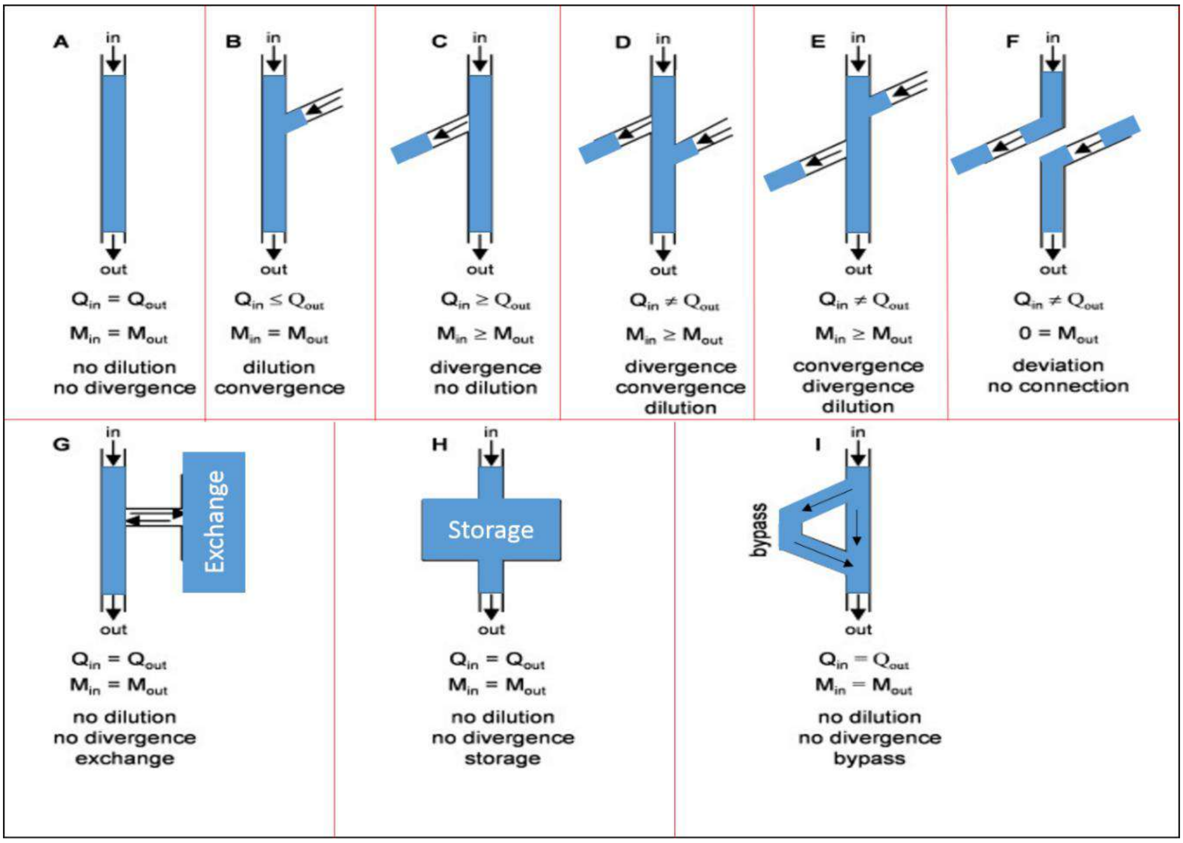

Fig. 4. Several Types of Cave Networks in Karst Underground River (Modification from Goldscheider et al., 2008)

Results and Discussion

The analysis results showed that the fluorescent dye (uranine) injected into Kalimati Sinking Stream appeared in Plalar Resurgence. From this resurgence site, the monitoring detected that the karst water flew through a surface river toward Sumurup Sinking Stream before re-emerging in Gremeng Resurgence. Since the fluorometer at Beton Resurgence did not read the presence of uranine, it implies that the allogenic system of Kalimati is not part of the networks that shape Beton Resurgence. This finding is different from previous studies in the same location because they employed different methods, namely topographic considerations (Budiyanto, Lestari, 2019), topography, cave distribution, and sinking stream (Pratiwi, 2013), and water balance (Lestari et al., 2014). Fig. 5 illustrates the complete connectivity between the sinking streams and resurgences at the research site.

In addition to Kalimati, the tracer dye was injected into Seropan Sinking Stream. Although this dye did not appear at Gremeng Resurgence, it was detected in Beton Resurgence. It indicates that Seropan Sinking Stream and Gremeng Resurgence are from two separate systems. These results are in line with Pratiwi (2013) and Lestari et al. (2014) but contrary to Budiyanto, Lestari (2019) that include Seropan Sinking Stream into the Gremeng Resurgence system.

Recording by fluorometer at Gremeng Resurgence produced a breakthrough curve, as presented in Fig. 6. The breakthrough curve was in a single form, representing a single conduit (Goldscheider et al., 2008; Leibundgut et al., 2009; Gilli, 2015). The steep curve with a short transit time shows that the cave network is well-developed and somewhat large. A single conduit is the characteristic of caves affected by allogenic recharge in addition to maze cave.

The BTC of artificial tracer test results at Kalimati Sinking Stream – Gremeng Resurgence showed that the dye tracer was first detected after 82 minutes. This indicates the rapid flow of water in the underground river, the highly developed dissolution tunnels, and the very high susceptibility to contamination. The dye tracer concentration peaked approximately 22 minutes after injection and was last detected after 223 minutes.

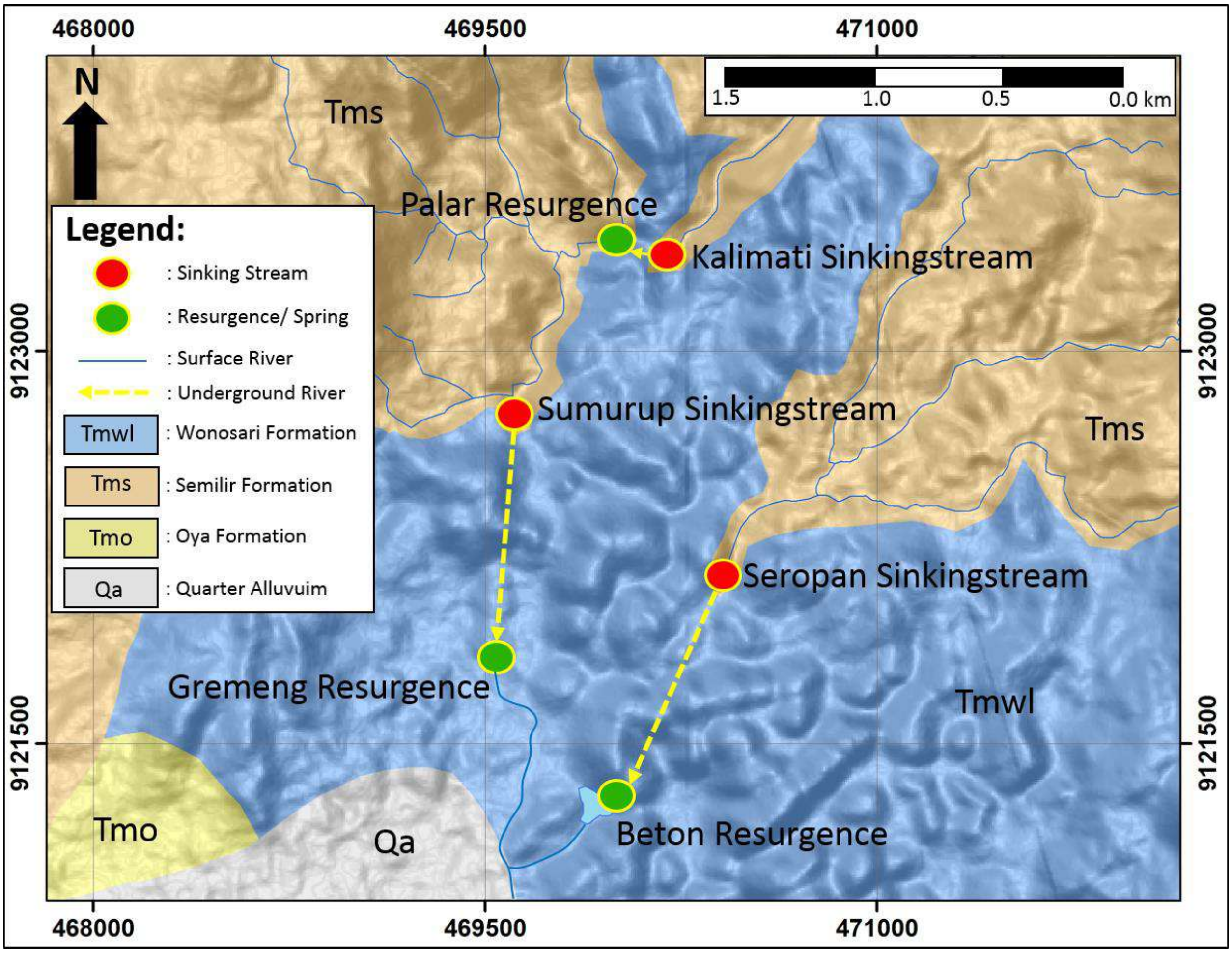

Fig. 5. The Connectivity Between the Sinking Streams and Resurgences in Ponjong Hydrogeological System Based on Tracer Test (Sources: Shuttle Radar Topography Mission United States Geological Survey and Field Survey)

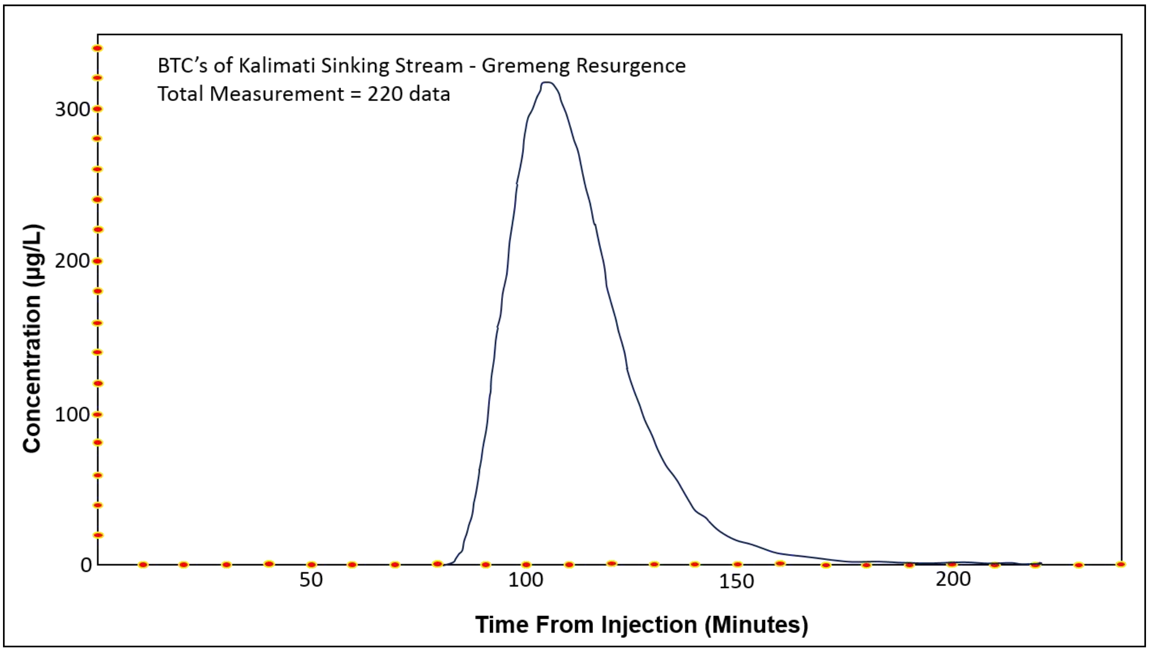

Fig. 6. The Breakthrough Curve at Gremeng Resurgence

Single conduits develop in karst areas controlled by allogenic recharge because the water intermittently flows in a large quantity (for example, flash floods) and at a fast rate as a consequence of underground river flow with high gradient. The high gradient is caused by the vast difference in elevation of sinking stream and resurgence over a short horizontal distance. Cahyadi et al. (2022) mentioned that underground river passages formed in Beton Karst Drainage Basin / KDB (located east of Gremeng KDB) also have single conduit characteristics for all dissolution passages formed (Fig. 7). The BTC recorded at Beton Resurgence shows a shorter time span between the first and last detections compared to the BTC at Gremeng Resurgence. With relatively similar spacing, this suggests a more developed dissolution tunnel in the Beton KDB.

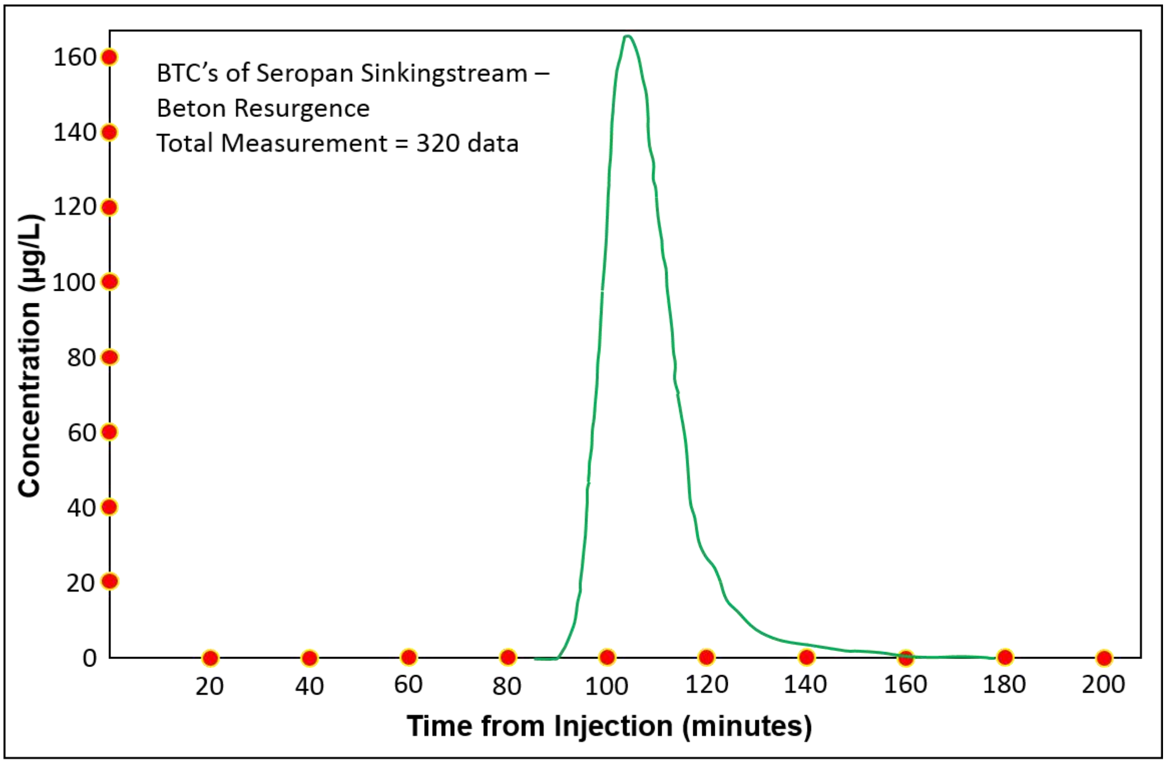

Fig. 7. The Breakthrough Curve at Beton Resurgence

The catchment area of the allogenic river system that enters Gremeng Resurgence is 13.25 km^2 (Cahyadi et al., 2018b). It is mostly composed of volcanic rocks like basaltic-andesitic lava, tuff, volcanic breccia, and agglomerates. Because these rocks poorly absorb water, the rain falling on them transform to high amounts of runoff. Also, the elevations of Sumurup Sinking Stream and Gremeng Resurgence differ by 60 m with a horizontal distance of 800 m, creating a high gradient. Area of watershed of allogenic river, the geological character of the catchment, and high gradient are the factors that form a single conduit system. Unlike this network system, Pindul – an underground river system in Wonosari Basin – has multiple conduit networks and a slightly sloping breakthrough curve (Cahyadi, Agniy, 2016). Despite its broader catchment area, Pindul has a low gradient that allows the development of these networks.

The development of advanced dissolution tunnels with large single conduits allows for rapid flow of underground rivers. This will certainly lead to rapid release of water from the aquifer. This causes the water that enters the underground river to be discharged quickly. On the other hand, the connectivity of the Gremeng Resurgence with the allogenic rivers at the ground surface causes the vulnerability to pollution from the Gremeng Resurgence to be very high. Protection of the karst drainage basin in Gremeng Resurgence requires management of the area outside the karst area which is an allogenic watershed. It is an integral part of the karst area that feeds the Gremeng Resurgence through autogenic recharge.

Conclusions

The breakthrough curve represents the development of an extensive, single conduit cave network in the Ponjong Hydrogeological Subsystem. Also, the absence of fluorescent dye emerging at springs or other resurgences indicates that maze cave does not form in the study area. Single conduits are the result of intermittent allogenic recharge with a substantial quantity. Kalimati Sinking Stream is located at a significantly different elevation than Gremeng Resurgence, results in high gradient and rapid flow of water in the underground river system. Consequently, instead of a maze cave, a single conduit dominates this system.

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ОСОБЕННОСТИ ПОДЗЕМНОГО СТОКА РЕК С АЛЛОГЕННЫМИ ВОДАМИ, ВЫЯВЛЕННЫЕ МЕТОДОМ ИСКУССТВЕННОГО ТРАССИРОВАНИЯ В КАРСТОВОМ РЕГИОНЕ ГУНУНГСЕВУ (ИНДОНЕЗИЯ)

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Резюме. Гидрогеологическая подсистема Понджонг является частью карстовой области Гунунгсеву на острове Ява, Индонезия и находится под уникальным влиянием аллогенного питания. Эта аллогенная речная система существует потому, что карст в этой подсистеме развивается над третичной вулканической формацией. Контакт между известняками формации Воносари и вулканическими породами, состоящими в основном из эксплозивных вулканических материалов формации Семиллир, позволяет сформироваться этой системе. Было установлено, что в этом районе в водосборах аллогенных рек преобладают относительно непроницаемые вулканические породы и крутые уклоны, что часто приводит к неожиданным паводкам. Целью данного исследования было определить характеристики карстовой системы подземных каналов под влиянием аллогенного питания. Был проведен искусственный индикаторный тест с использованием флуоресцентных красителей, кривые прорыва регистрировались флуориметром. Погружающийся ручей Калимати расположен на существенно отличающейся высоте, нежели Гременгский источник, что приводит к высокому уклону и быстрому течению воды в подземной речной системе. Анализ данных показал, что пещерные сети в районе исследования формируются преимущественно крупными одиночными каналами. Из-за большого расхода и крутого уклона подземной речной системы вместо лабиринтообразной пещерной системы образуется одиночный канал. Выявление связи между аллогенными реками и Гременгским источником подчеркивает, что карстовый водосборный бассейн Гременгского источника не является частью Бетонского карстового водосборного бассейна, как предполагали ранее исследователи, использовавшие при исследовании иные, кроме искусственных индикаторных тестов, методы.

Ключевые слова: *аллогенная река, искусственный индикаторный тест, размывание пещерного прохода, флуоресцентные индикаторы*

QUNUNQSEVU KARST REGİONUNDA (İNDONEZİYA) SÜNİ İZLƏMƏ ÜSULU İLƏ TƏDQİQ EDİLMİŞ ALLOGEN SULARLA QİDALANAN ÇAYLARIN YERALTI AXIN XÜSUSİYYƏTLƏRİ

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Xülasə. Ponjong hidrogeoloji alt sistemi İndoneziyanın Yava adasında yerləşən Qununqsevu karst bölgəsinin bir hissəsidir və allogen qidalanmanın özünəməxsus (unikal) təsiri altındadır. Bu allogenik çay sistemi, karstın üçüncü dövr vulkanik süxurları üzərində inkişaf etməsi nəticəsində mövcuddur. Bu bölgədə Vonosari formasiyasına aid əhəngdaşı süxurları ilə əsasən Semilir formasıyasına mənsub, partlayış mənşəli vulkanik süxurlardan ibarət piroklastik qatlar arasında müşahidə olunan litoloji kontakt bu sistemin formalaşmasına şərait yaradır. Aparılmış tədqiqatlar nəticəsində müəyyən edilmişdir ki, bu regionda allogen çay hövzələrində nisbətən zəif sukeçirən vulkanik süxurların və kəskin yamacların üstünlük təşkil etməsi qəfil sel hadisələrinin baş vermə ehtimalını artırır. Bu işin məqsədi allogen qidalanma şəraitində fəaliyyət göstərən yeraltı karst kanalları sisteminin hidrogeoloji xüsusiyyətlərini və axın dinamikasını öyrənməkdir. Bunun üçün flüoresan indikatorlardan istifadə edilərək süni trasser təcrübəsi aparılmış, əldə edilən nəticələr flüorimetr vasitəsilə qeydə alınmışdır. Kalimati udulan axarı, Gremenq bulağına nisbətən əhəmiyyətli dərəcədə fərqli hipsometrik səviyyədə yerləşir ki, bu da yeraltı çay sistemində yüksək hidrogeoloji qradiyent və sürətli axın rejiminin formalaşmasına səbəb olur. Aparılmış məlumat təhlili göstərmişdir ki, tədqiqat sahəsindəki karst boşluqları və mağara şəbəkələri əsasən iri ölçülü, tək axınlı kanallardan ibarətdir. Yeraltı çay sistemində böyük su sərfi və kəskin meyillik nəticəsində labirintvari mağara sistemi formalaşmır, əksinə, nisbətən stabil hidrodinamik rejimə malik tək (monokanal) tipli karst kanalı inkişaf edir. Allogen çaylarla Gremenq bulağı arasında əlaqənin müəyyənləşdirilməsi göstərir ki, Gremenq bulağının karst mənşəli su toplanma hövzəsi, əvvəlki tədqiqatçılar tərəfindən irəli sürüldüyü kimi, Beton karst hövzəsinin bir hissəsi deyil. Bu nəticə, süni indikator sınaqları istisna olmaqla, müxtəlif tədqiqat üsullarından istifadə etmiş əvvəlki tədqiqatların fərqli nəticələrini təkzib edir və bulağın müstəqil hidrogeoloji sistemə mənsub olduğunu vurğulayır.

Açar sözlər: *allogen çay, süni trasser sınağı, mağara keçidinin yuyulması, flüoresan indikatorlar*