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Research Article

Assessment of groundwater leakage source using hydrochemical data and isotopes in the Pandanduri dam tunnel, Lombok Island, Indonesia

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Abstract

Leakage or seepage in reservoirs and dams has the potential for structural instabilities persuaded by water leakage pathways and linked to economic consequences. An environmental isotopic and hydrochemical research was conducted to determine the source and origin of seepages on the tunnel of Pandanduri dam, Lombok Island, Indonesia. This study aimed to examine the source of the tunnel leak on the dam site and the origin or source of water at the point of leakage based on water chemistry data and stable isotopes. To identify the source of the leakage water in the tunnel dam, 33 samples of the leakage water, groundwater, reservoir water, river water, and rainfall water were taken for chemical and isotopic composition analysis. The field measured the reservoir level, spring discharges, and physicochemical parameters (EC, pH, TDS, TSS). The physicochemical parameters show that the leakages water is similar to reservoir water. The types of leakage water in the tunnel belong to alkaline water, predominantly sulfate-chloride. This type of water is deep groundwater with a higher sulfate and chloride concentration than surface water or shallow groundwater. Hydrochemical and isotope analysis showed that water origin at leakage points is dominated by groundwater.

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Introduction

Seepage/leakage is a concentrated water loss originating from structural or construction deficiencies. It includes the contact between the dam body and rock, lack of alluvial lining materials, structural geology (fault and joint), and karstification process. The dam's seepage or leakage causes water loss and potential structural instability triggered by the water leak pathways. Seepage or leakage can occur in the foundation or wall of the dam or the rock around the dam site. In contrast, the groundwater flows through concentrated pathways and creates springs downstream (Bedmar and Araguas, 2002). Corrective action is usually costly and, in most cases, carried out without enough knowledge of the nature of the problem. Therefore, multi-disciplinary techniques are generally required to analyze seepage-related issues properly. The most common techniques used in the research of seepage or leakage in reservoirs and dams include numerical modelling (Gurocak and Alemdag, 2011), geophysical methods (Cho and Yeom, 2007; Sjödahl et al., 2008), hydrometric measurements (Unal et al., 2007), use of artificial tracers (Lee et al., 2007) and environmental isotope measurements (Saravana et al., 2008; Fan et al., 2014; Kharisma et al., 2015).

Although some hydrogeological studies have been stated in previous works to know seepage/leakage problems associated with reservoirs and dams, few studies have applied environmental isotope techniques. Stable isotope and hydrogeochemical analyses have been applied to determine water from different sources (Ma et al., 2007). Natural tracers of water, such as temperature, electrical conductivity, chemical constituents, and stable water isotopes (^{2}H and ^{18}O), prove valuable tracers for identifying the origin of the water. Such is the case with water that appears at discharge points downstream of rivers - dams and infiltration point locations in reservoirs and lakes (Bedmar and Araguas, 2002).

The stable isotopes of ^{2}H and ^{18}O can be applied as ideal tracers to identify the mixing and movement of water from diverse sources (Clark and Fritz, 1997). In addition, environmental tritium, which was formed in the upper atmosphere and the thermonuclear test dropped in the atmosphere from 1950 to 1963, can be used effectively to identify estimated residence time. Many studies have been applied using isotopes, such as assessing the contribution of pond water to groundwater and identification of precipitation to groundwater by means of hydrogen, oxygen, and tritium isotopes (Peng et al., 2012). Then determination of the recharge source based on the ^{18}O isotope and water chemistry data at drainage points in the pit (Liu et al., 2007), estimation of the hydraulic relationship between surface water and groundwater based on hydrochemical and isotopic signatures (Li et al., 2016), identification of river water sources by isotope ratios (Fan et al., 2016), and identification of water source of leakage in the mine tunnel (Guo et al., 2015). Conservative isotopes are more reliable and can avoid mistakes using non-conservative isotopes (Gu et al., 2018). Therefore, the present study implemented the hydrochemical and isotope to identify the water leakage source in the tunnel of Pandanduri dam, Lombok Island, Indonesia. Identifying the source of water leakages will help to determine an appropriate method to solve the problems. Dam leakage reduces the water volume in the reservoir. It will cause an impact on the decreasing irrigation water, especially in the dry season. Therefore, the land and agricultural productivity will decrease.

Methods

The research location is in Pandanduri dam, Lombok Island, Indonesia, as shown in Figure 1. Measurement and sampling were carried out at 31 observation points, including three rainwater samples, consisting of water samples from dug wells (SG-1-SG2), drilled well (SB-1SB2), springs (MA1-MA2), monitoring wells (OW1 - OW8), reservoir water (B1-B5), water seepage/ leakage in the tunnels (1-8), river water (S1-S3) and rainfall water (AH1-AH3). The implementation of hydrochemical studies is carried out by measuring the physicochemical properties of water, such as pH, temperature, total dissolved solids (TDS), and electrical conductivity (EC), to determine the origin of the water.

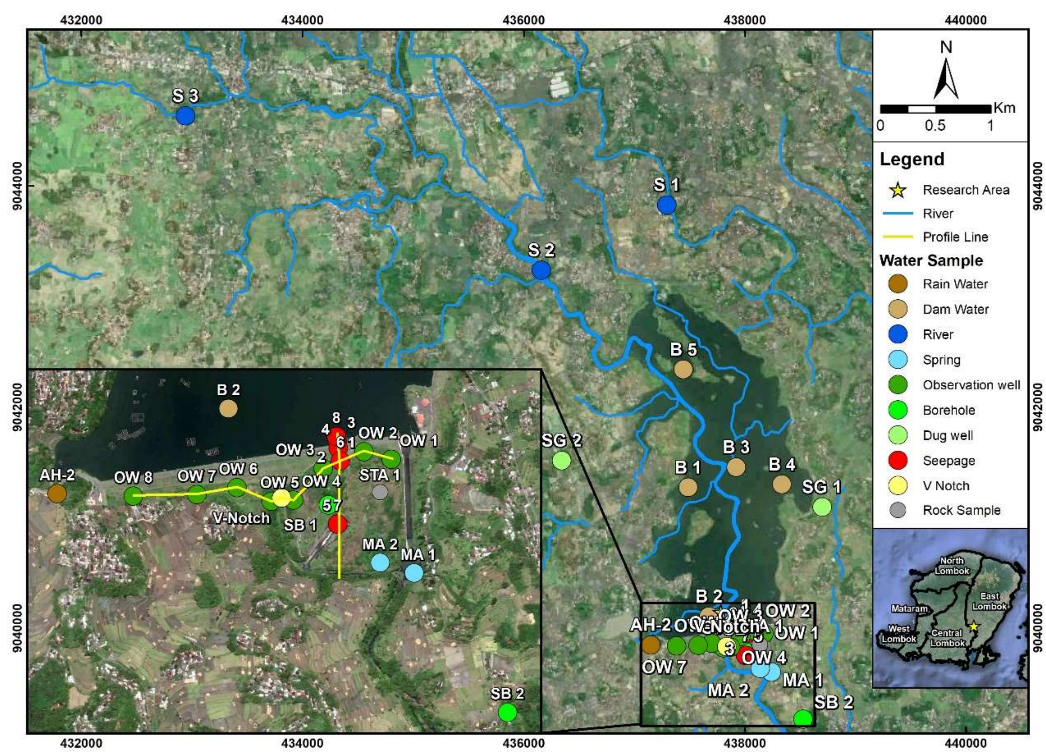

Figure 1. The field observation and water sampling location are plotted in the google images (Google Earth, 2022).

The instrument used to measure the physicochemical properties of water in the field was the Hanna Instruments HI9812-5 water test kit and calibrated according to the equipment manual before it was used. A water sampling for the major ion content test was taken at the sampling location for 31 samples. The water was put into the 100 mL sample bottle, filtered through a 0.45 mm filter, and then stored in a cool box before being sent to the laboratory.

The water samples were analyzed to identify the content of the major ions, including sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^+), chloride (Cl^-), nitrate (NO_3), sulfate (SO_4^{2-}), and bicarbonate (HCO_3^-). The analytical analysis accuracy was determined by calculating the ionic balance error, generally within ±5%. The analysis was carried out by ion chromatography (IC) at the GetIn-CICERO Laboratory, Department of Geological Engineering, Gadjah Mada University, Indonesia. Meanwhile, 33 water samples were taken for Isotope Oxygen-18 (^{18}O) and Deuterium (^2H) analysis. The sample water was collected at 100 mL without being filtered and put into the High-Density Polyethylene (HDPE) bottle. Air bubbles should be avoided in the bottle and then closed tightly. The water samples were transported in a cool box to avoid evaporation because both isotopes are very sensitive to evaporation. The isotope test was carried out using a mass spectrometer method at the Isotope and Radiation Technology Application Center Testing Laboratory (PAIR) BATAN, Jakarta, Indonesia. The contribution of groundwater to water samples affected by reservoir water was calculated based on the value of $\delta^{18}O$ using the following formula (Clark and Fritz, 1997):

$$f_{gw} = \frac{\delta gw - \delta}{\delta a - \delta w} \quad (1)$$

where,

f_{gw} = groundwater percentage

δgw = the value of $\delta^{18}O$ groundwater in the sample

δa = the value of $\delta^{18}O$ groundwater according to the closest Local Meteoric Water Line (LMWL) to the sample

δw = the value $\delta^{18}O$ average reservoir water from the total reservoir water sample taken

Results

The hydro-stratigraphic system in the Pandanduri dam area is shown in Figure 2. The figure shows that the research area has three hydro-stratigraphic units distinguished from lithology. Colluvial deposits act as aquifers, volcanic breccias (andesite breccias) act as aquitard-aquifer, and volcanic sandstone acts as an aquifer. Aquifers are rock formations that can store and drain groundwater in abundance. Aquitard is a rock formation that can hold and drain a limited amount of groundwater (Fetter, 2000). It is estimated that water flow from the reservoir supplies groundwater through the colluvial sediment layer, which acts as an aquifer and affects groundwater in the dam's monitoring wells, as shown in Figure 2. Groundwater in the study area has an elevation of around 248 masl (meter above sea level) to 265 masl. In the north-south cross-section, groundwater flows towards regions with lower topography relative to the south.

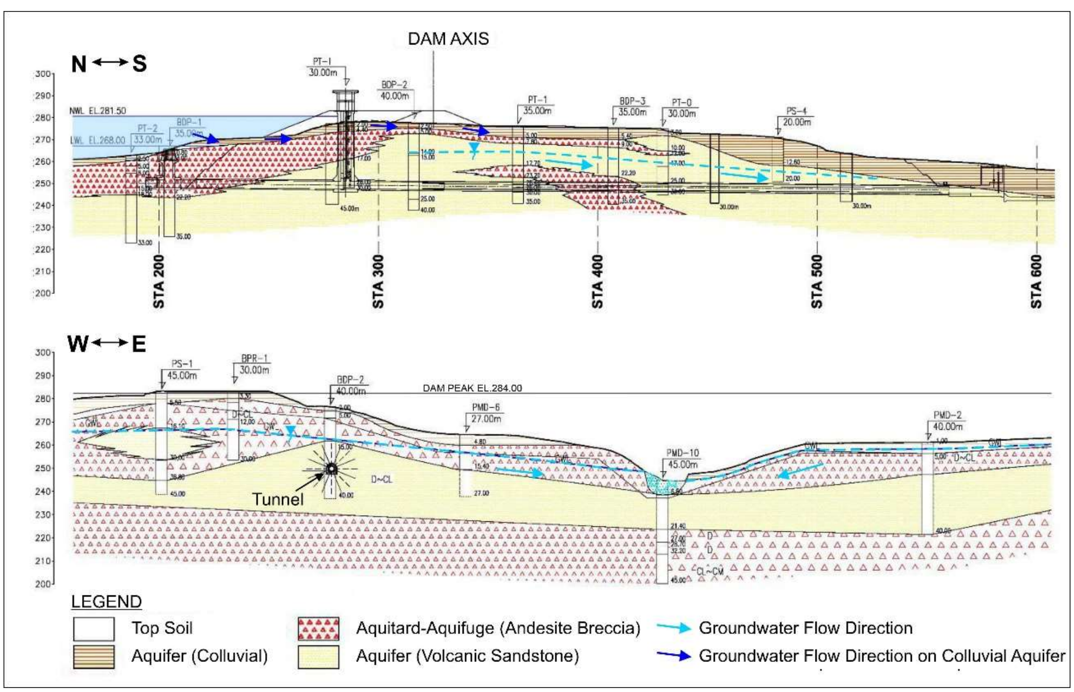

Figure 2. Hydro-stratigraphic system in Pandanduri dam (LKFT UGM, 2021).

Groundwater flow in the west tends to the east towards the river, and the groundwater in the east leads to the west towards the river. The river body is currently becoming a spillway. The existence of these construction has changed the morphology of the surrounding area and impacts changes in groundwater flow patterns in the Pandanduri Dam area.

Relationship between reservoir water elevation and groundwater level

The relationship between reservoir water elevation and groundwater is seen by comparing the reservoir water elevation data with the groundwater level at the monitoring wells. The relationship between reservoir water elevation and the groundwater level from January 2018 to January 2021 is shown in Figure 3. Groundwater elevation at monitoring wells OW-1, OW-2, OW-3, OW-4, and OW-9 shows water level fluctuations similar to reservoir water elevation fluctuations. It indicates that groundwater in the area around the location of the four monitoring wells (main dam area east to west of the spillway) has a strong influence from reservoir water. Meanwhile, the groundwater level elevation at the monitoring wells OW-5, OW-6, OW-7, and OW-8 showed a relatively stable pattern. It means reservoir water does not affect groundwater around the monitoring wells OW-5, OW-6, OW-7, and OW-8. Groundwater level fluctuations in the area at the four monitoring wells are not significant. Changes only range from 1-2 m when the reservoir water drastically rises or falls. Figure 4 shows a graph that compares the reservoir's water level with the groundwater level in the monitoring well OW-1 and OW-8. It shows that the groundwater level of OW-1 changes along with changes in reservoir water elevation, with an R^2 value of 0.5, as presented in Figure 4(a). Meanwhile, the groundwater level of OW-8 tends to be stable at an elevation of 271-273 masl when the reservoir water elevation increases or decreases with the R^2 of 6E-05, as shown in Figure 4(b). Based on the data, it can be concluded that there is groundwater in the monitoring wells directly affected and not affected by reservoir water in the area around the main dam and spillway.

Hydrochemistry of reservoir water, groundwater, and leakage point water

The results of field measurements, chemical analysis, and water isotope tests are shown in Table 1. The condition for the maximum ion balance value is |10%|. The ion balance value from the laboratory analysis is considered very good if it is less than |4.99%|, so it is suitable for water facies analysis. Chemical comparisons between reservoir water samples (B), monitoring well water (OW), dug well water (SB), drilled well water (SB), and tunnel leak point water were carried out using the Schoeller diagram. Schoeller diagrams show similarities and differences in the ratio of significant ion values/concentrations in water samples depicted in a line pattern. The same line pattern indicates the same origin/source. The Schoeller diagram helps to identify the origin of the water source at the point where the tunnel leaks. The chemical comparisons with the Schoeller diagram are presented in Figures 5 and 6.

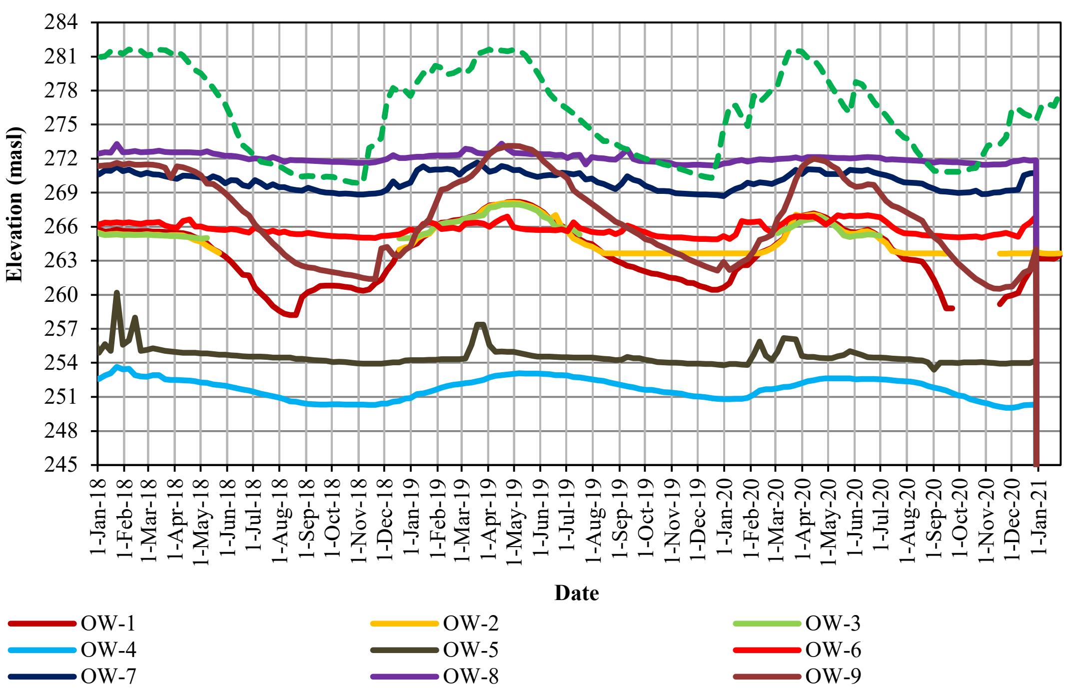

Figure 3. Patterns of fluctuations in reservoir water level and groundwater level.

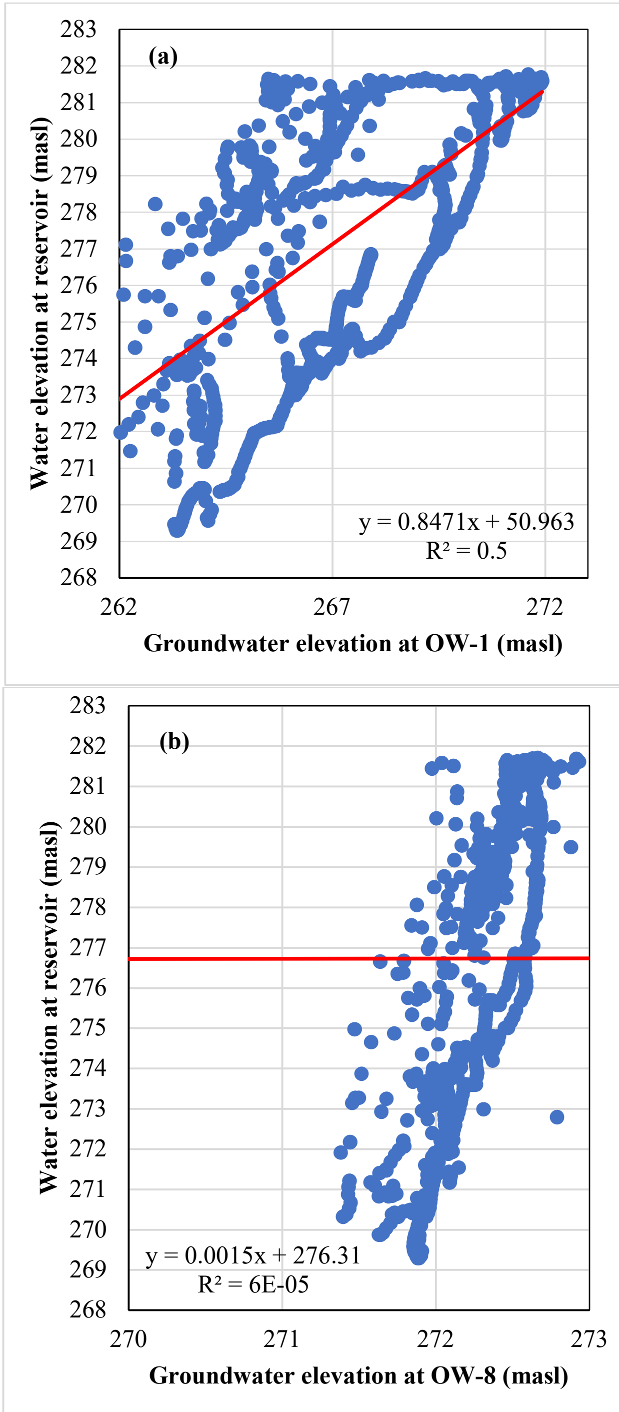

Figure 4. Comparison graph of reservoir water elevation with groundwater level OW-1 (a) and OW-8 (b).

Based on Figure 5, the line pattern on the water samples of tunnel leak points 1 (Sta 285), 2 (Sta 285), 5 (Sta 330), and 8 (Valve) form a similar pattern to the reservoir water samples B1-B5. It is estimated that the water at tunnel leakage points 1, 2, 5, and 8 comes from reservoir water. Based on Figure 6, the line pattern on the tunnel leak point water samples 3 (Sta 300), 4 (Sta 320), 6 (Sta 360), and 7 (Sta 480) forms a pattern similar to the groundwater sample of SG-1 dug well and drilled well SB-1. It is estimated that the water at tunnel leak points 3, 4, 6, and 7 comes from shallow groundwater that is not affected by reservoir water.

The type of water was determined using a Piper diagram to identify the dominant ion in each water sample (Wilopo and Putra, 2020). Major ion data from 31 water samples that have been tested are presented in Table 1.

Table 1. Chemical and isotope data of water samples.

No.	Sample Code	Coordinate		Water Source	pH	EC (µs/cm)	TDS (mg/L)	Major Ion (mg/L)								Ion Balance (%)	$\delta^{18}O$	$\delta^{2}H$
		X	Y					Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}	Cl^{-}	NO_3^{-}	SO_4^{2-}	HCO_3^{-}			
1	S 1	437295	9043830	River	7.2	320	150	27.41	10.68	24.16	10.12	7.04	n.d	6.47	183	2.47	-5,047	-32,288
2	S 2	436160	9043239	River	7.4	280	130	22.06	9.75	21.74	8.41	6.76	n.d	7.43	170.8	-2.61	-4,070	-26,993
3	S 3	432944	9044638	River	7.1	340	160	29.98	14.07	25.48	8.72	11.65	n.d	11.66	183	1.11	-4,477	-28,002
4	B 1	437488	9041276	Reservoir	7.9	230	110	21.07	10.09	18.44	6.75	7.21	n.d	7.64	146.4	-2.09	-4,027	-27,503
5	B 2	437675	9040109	Reservoir	8.5	240	110	21.09	10.08	18.47	6.74	7.25	n.d	7.64	134.2	1.69	-4,121	-26,976
6	B 3	437924	9041459	Reservoir	8.2	230	110	20.18	9.61	16.68	6.36	6.91	n.d	7.62	140.3	-3.42	-4,120	-27,041
7	B 4	438335	9041303	Reservoir	8.3	230	110	20.55	9.84	18.30	6.71	6.01	n.d	6.74	134.2	1.95	-4,134	-26,894
8	B 5	437445	9042343	Reservoir	7.8	230	110	20.96	9.93	18.99	6.97	6.94	n.d	7.42	134.2	2.59	-4,209	-27,350
9	SB 1	437981	9039814	Drilled well	6.7	550	260	77.29	5.18	34.10	17.97	16.35	0.09	21.17	317.2	4.46	-3,866	-22,825
10	SB 2	438529	9039178	Drilled well	7.3	1480	730	217.83	32.42	76.94	27.62	95.36	n.d	459.80	219.6	1.69	-4,545	-24,876
11	MA 1	438243	9039605	Spring	6.7	750	370	51.40	3.91	54.54	27.29	73.86	0.07	35.40	317.2	-4.69	-4,670	-27,717
12	MA 2	438139	9039637	Spring	7.1	600	290	58.68	3.76	42.15	23.85	30.76	n.d	88.00	219.6	3.17	-3,956	-23,649
13	SG 1	438702	9041099	Dug well	6.9	860	420	109.09	10.69	51.30	24.06	28.60	12.61	59.82	414.8	2.69	-	-
14	SG 2	436345	9041519	Dug well	8.1	1100	540	79.17	106.05	76.58	20.68	78.09	62.49	42.80	439.2	1.64	-5,487	-35,174
15	1	438005	9040023	Seepage	7.1	190	90	16.51	8.84	15.99	5.63	5.51	n.d	5.79	109.8	3.01	-5,502	-36,160
16	2	438005	9040023	Seepage	7.5	190	90	16.32	9.09	16.25	5.57	5.38	n.d	5.52	109.8	3.38	-5,711	-37,053
17	3	438008	9040008	Seepage	7.1	420	200	52.03	5.53	24.73	12.68	10.26	0.44	16.53	244	0.43	-3,687	-22,198
18	4	438011	9039988	Seepage	7.0	470	220	59.60	4.28	27.72	13.84	12.12	0.89	31.83	213.5	7.22	-3,316	-19,881
19	5	438009	9039755	Seepage	7.2	210	90	16.60	8.90	16.37	5.87	5.34	1.03	5.56	134.2	-4.96	-5,540	-35,913
20	6	438017	9039949	Seepage	6.8	270	130	27.95	7.77	19.50	7.99	7.46	n.d	13.64	146.4	2.53	-5,047	-32,288
21	7	438009	9039755	Seepage	7.1	270	130	27.80	7.70	19.24	7.93	7.40	n.d	13.79	158.6	-1.28	-5,540	-35,913
22	8	438005	9040023	Seepage	7.1	230	110	16.45	8.82	16.20	5.75	4.05	1.32	4.06	109.8	4.79	-5,667	-36,885
23	OW- 1	438173	9039954	Monitoring well	6.7	440	210	46.06	5.60	32.75	13.00	22.86	12.43	45.53	195.2	-1.46	-4,221	-25,549
24	OW- 2	438090	9039977	Monitoring well	6.7	570	270	67.42	8.00	49.14	9.36	23.88	n.d	62.84	268.4	-0.20	-4,768	-30,077
25	OW- 3	437965	9039926	Monitoring well	6.7	490	230	34.81	12.72	38.83	8.20	8.65	8.16	61.97	158.6	2.13	-4,317	-25,312
26	OW- 4	437874	9039829	Monitoring well	6.9	280	130	28.17	10.01	21.15	6.78	6.00	1.35	4.39	176.9	-1.42	-4,977	-32,854
27	OW- 5	437806	9039825	Monitoring well	6.3	200	90	14.36	6.33	16.54	3.88	4.42	0.44	4.54	109.8	-2.42	-5,956	-40,760
28	OW- 6	437701	9039867	Monitoring well	7.3	1040	500	121.89	29.44	71.48	21.20	12.49	0.09	20.91	603.9	3.06	-4,484	-29,796
29	OW- 7	437578	9039846	Monitoring well	7.0	1600	790	194.69	31.05	95.58	33.81	9.18	0.48	65.48	927.2	-0.06	-3,807	-23,603
30	OW- 8	437383	9039841	Monitoring well	7.4	1150	560	219.85	21.77	48.28	20.62	3.30	0.80	37.32	750.3	3.78	-4,924	-31,731
31	V-Notch	437837	9039835	V Notch	6.6	1150	560	143.42	10.58	73.03	40.83	47.45	n.d	78.38	622.2	1.27	-3,866	-3,866
32	AH-1	435893	9055408	Rainfall	-	-	-	-	-	-	-	-	-	-	-	-	-10,221	-68,635
33	AH-2	437151	9039848	Rainfall	-	-	-	-	-	-	-	-	-	-	-	-	-6,354	-43,027
34	AH-3	445941	9030041	Rainfall	-	-	-	-	-	-	-	-	-	-	-	-	-6,554	-44,314

Note: n.d. = not detected; "-" = no data.

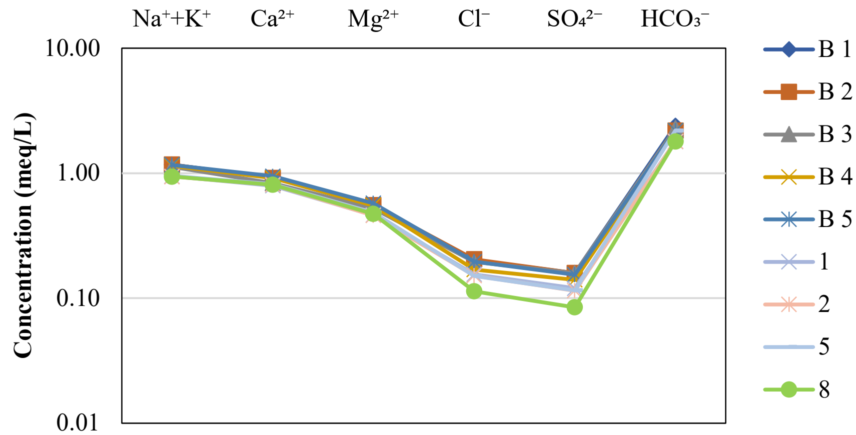

Figure 5. Schoeller diagram of reservoir water samples with water at leakage points 1, 2, 5, and 8.

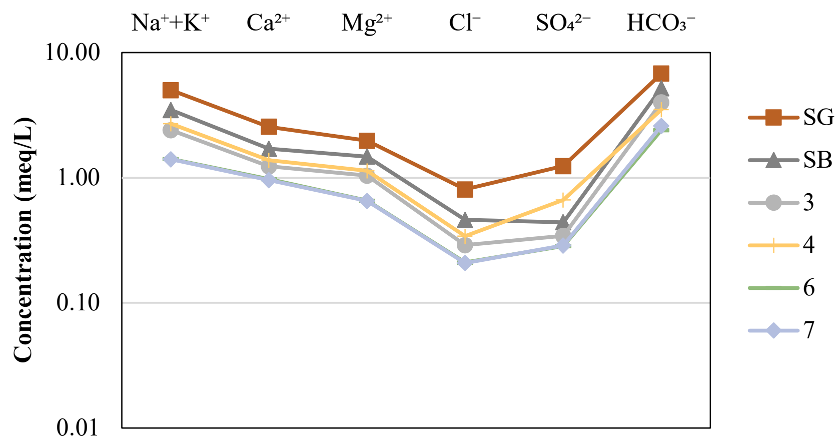

Figure 6. Schoeller diagram of water samples SG1 and SB1 with water at leakage points 3, 4, 6 and 7.

The results of the water type analysis using the Piper diagram are shown in Figure 7. The Piper diagram can classify water based on the concentration of major ions. The type of water in the study area comprises three types of water, namely 1) Alkaline earth water with higher alkaline content, predominantly hydrogen carbonate, 2) Alkaline water, predominantly hydrogen carbonate, and 3) Alkaline water, predominantly sulfate-chloride. Alkaline earth water with higher alkaline content, predominantly hydrogen carbonate, is dominated by surface water, and alkaline water predominantly hydrogen carbonate from shallow water. Alkaline water, predominantly sulfate-chloride, is dominated by the deepwater sample. A higher concentration of sulphate chloride indicates it compared to surface and deep water. Leakage water from the tunnel mainly belongs to alkaline water, predominantly sulphate chloride.

Estimating water leakage in the Pandanduri Dam tunnel was carried out using the oxygen-18 (^{18}O) and deuterium (^{2}H) isotope approaches. Isotopes ^{18}O and ^{2}H were used to identify the mixing pattern and the contribution of each type of water to the discharge water at the tunnel leak point. Also, the water in the monitoring well according to the hydrograph separation. The results of the relative abundances of oxygen-18 ($\delta^{18}O$) and deuterium (δD) are shown in Table 1. The diagram of $\delta^{18}O$ versus δD was drawn up to compare the relative abundances of the isotopes oxygen-18 ($\delta^{18}O$) and deuterium (δD) in each sample of water, as shown in Figure 8. The Local Meteoric Water Line (LMWL) was created based on data on the relative abundance of the isotopes ^{18}O and D in rainwater and groundwater samples from dug wells and boreholes. The ratio of D and ^{18}O isotopes in each water sample relative to LMWL was analyzed to obtain an overview of the genesis of each water sample. Figure 8 shows the results of a plot of the relative abundance ratio of the isotopes ^{18}O and D scattered around the LMWL. This figure indicates that the genesis of most of the water samples in the Pandanduri Dam area has a relationship with the surrounding groundwater. Some water samples also still have a relationship with reservoir water.

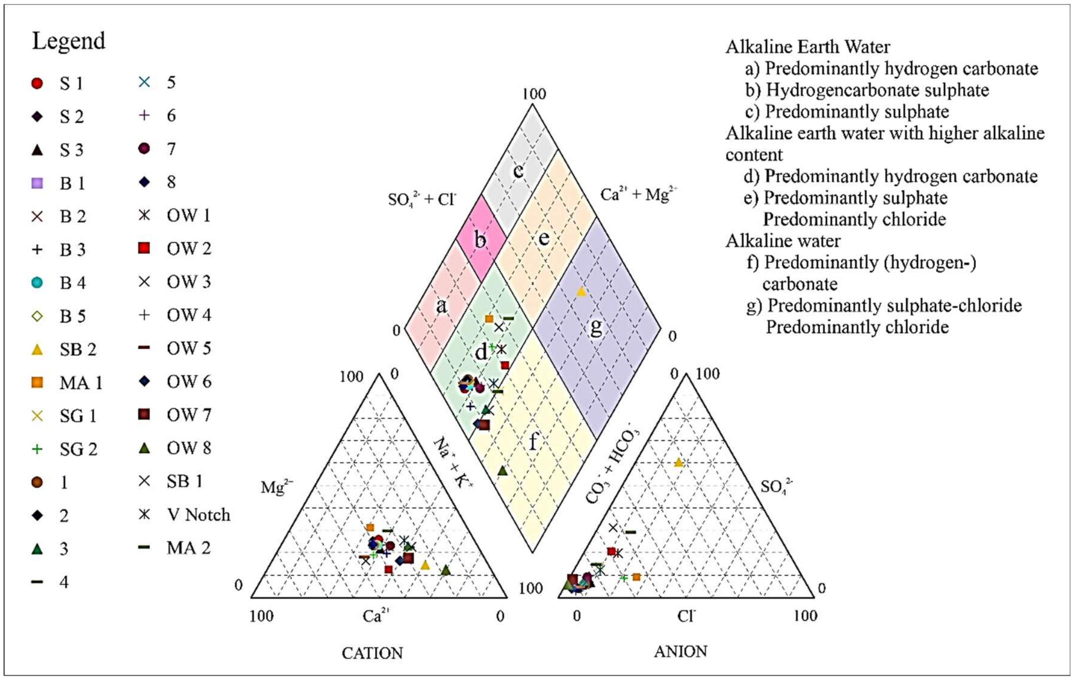

Figure 7. Type of water based on the Piper diagram (Piper, 1994).

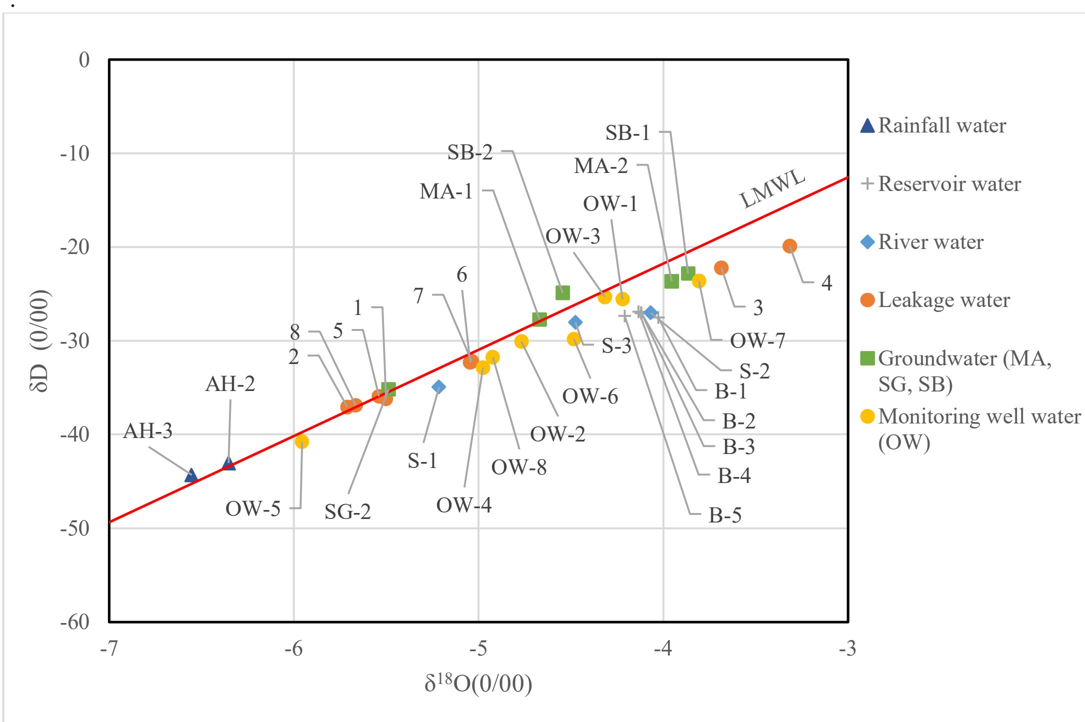

Figure 8. Diagram of the ratio of $\delta^{18}O$ and δD Pandanduri dam water samples.

Water Source in leakage points in the tunnel

Identification of water sources in water samples from the leak point was identified by comparing the relative abundances of $\delta^{18}O$ and δD isotopes of leak water, groundwater, and reservoir water samples. Figure 8 shows the plots of the ratios of $\delta^{18}O$ and δD of leak water samples spread out and adjacent to the points of groundwater samples and LMWL. Water samples at leak points 1 (Sta 285), 2 (Sta 285), 5 (Sta 330), and 8 (Valve) were adjacent to the groundwater sample SG-2. It indicates that the water comes from groundwater around the tunnel at the leakage point. Water samples at leak points 3 (Sta 300) and 4 (Sta 320) are adjacent to groundwater samples SB-1 and MA-2. It shows that the water comes from groundwater around the tunnel at the leakage point. Water samples at leak points 6 (Sta 360) and 7 (Sta 480) are adjacent to the LMWL. The water at the leak point is dominantly derived from groundwater around the tunnel. Thus, all the water that comes out at the leak point of the Pandanduri Dam tunnel comes from groundwater around the tunnel area.

Water source in monitoring wells

Identification of water sources in water samples from monitoring wells was identified by comparing the relative abundances of the isotopes $\delta^{18}O$ and δD in monitoring well water, groundwater, and reservoir water samples. Figure 8 shows the ratio of $\delta^{18}O$ and δD of water samples in monitoring wells spread out and adjacent to the results of plots of groundwater samples from reservoirs and LMWL. The water samples in the monitoring wells OW-1 and OW-3 are close to the reservoir water samples. It shows that the water in the monitoring well comes from reservoir water. Water samples in the monitoring well OW-2, OW-4, OW-5, OW-6, and OW-8 adjacent to the LMWL. It indicates that the water in the monitoring well comes from groundwater around the tunnel. The water sample in the monitoring well OW-7 is close to the groundwater sample SB-1. The water in the monitoring well is dominantly derived from groundwater around the tunnel. Thus, it can be concluded that the water source in the monitoring wells OW-2, OW-4, OW-5, OW-6, OW-7, and OW-8 in the main dam area comes from groundwater around the tunnel area. Only groundwater in OW-1 and OW-3 was significantly affected by reservoir water.

The contribution of groundwater in OW-1 and OW-3 affected by reservoir water can be calculated based on the value of $\delta^{18}O$ using equation 1. The percentage contribution of groundwater to water in the monitoring well OW-1 is 43.9%. Therefore, reservoir water's percentage contribution is around 56.1%. Meanwhile, the percentage of groundwater contribution to water in the OW-3 monitoring well is 85.6%, and the portion of reservoir water contribution is only 14.4%. Thus, the contribution of reservoir water to water in OW-1 and OW-3 is more significant than groundwater compared to other monitoring wells.

Discussions

Hydrochemical and isotope analyses were used to identify the source of water leakages in the tunnel of Pandanduri dam. The hydrochemical analysis results show the source of water leakages in the tunnel from the reservoir and groundwater. The water leakages in the tunnel at points 1, 2, 5, and 8 have a similar pattern to the reservoir water. However, the water leakages at points 3,4,6,7 have similar to groundwater. This condition is also in line with the result of groundwater level in the monitoring wells, where some were related to the fluctuation of reservoir water, such as OW-1, OW-2, OW-3, OW-4, and OW-9, and the rest was not related. The chemical composition of groundwater will possibly change during the flow and evolution processes due to natural and anthropogenic activities (Zhang et al., 2020). Natural processes are dominated mainly by water-rock interaction and recharge conditions in the flow area. In addition, anthropogenic activities mainly refer to human activities such as wastewater discharge, agricultural activities, and groundwater exploitation. The isotopes analysis result indicated that all water leakages in the tunnel dam mostly came from groundwater similar to rainwater. The isotopes of surface water are more enriched than groundwater. Therefore, the tunnel seepage is not related to the reservoir's water but mainly to the groundwater.

Conclusion

Hydrochemical and isotopic studies have been carried out to determine the source of seepage water at the tunnel of Pandanduri Dam, Lombok Island, Indonesia. The combination of hydrochemical and isotope methods shows more accurate results than using only one of the existing methods. Both methods indicate that groundwater is the dominant source of seepage water in the tunnel dam. Therefore, this water seepage does not significantly affect the volume of water in the reservoir, but it will be dangerous for the stability of the existing tunnel building. Appropriate action can be taken to mitigate the leakage problems in the tunnel by knowing that the dominant seepage source comes from groundwater.

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