



# Species and potential sources of phosphorus in groundwater in and around Mataram City, Lombok Island, Indonesia

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## Abstract

Geochemical evaluation of the species and potential sources of P in groundwater in and around Mataram City, Lombok Island, Indonesia can aid in the initial research on evaluating the fate of P when detailed geological information is unavailable. The results of ion chromatography and inductively coupled plasma-optical emission spectroscopy show that the concentrations of  $\text{PO}_4^{3-}$  and total dissolved P (TDP) in groundwater range from approximately 0.1 to 8.5  $\text{mg l}^{-1}$  and from 0.04 to 2.95  $\text{mg l}^{-1}$ , respectively. Dissolved inorganic P accounted for 86%, on average, of the TDP concentration, and  $\text{PO}_4^{3-}$  represented the predominant P species in this groundwater. The potential sources for most of this dissolved  $\text{PO}_4^{3-}$ , according to indices developed based on the PHREEQC software and groundwater quality data, could be the dissolution of hydroxyapatite and/or vivianite minerals. However, the potential sources of dissolved  $\text{PO}_4^{3-}$  in groundwater with a TDP concentration of  $\geq 1 \text{ mg l}^{-1}$  is likely to be the reduction of Fe(III)–(hydro)oxides, the initial decomposition of organic matter, or the dissolution of carbonate-rich fluorapatite considering the  $\text{Fe}^{2+}$ , dissolved organic carbon,  $\text{Ca}^{2+}$  and  $\text{F}^-$  concentrations measured. In addition, as several groundwater samples had a TDP concentration of  $\leq 1 \text{ mg l}^{-1}$  and comparatively high concentration of  $\text{NO}_3^-$ , other potential sources of dissolved  $\text{PO}_4^{3-}$  in this groundwater could be anthropogenic.

**Keywords** Phosphorus · Groundwater · Indonesia · Geochemical analysis

## 1 Introduction

In recent years, extensive research has been conducted on submarine groundwater discharge in tropical developing regions such as Indonesia because such groundwater discharge can be an important contributor of nutrients to coastal marine ecosystems [1–3]. This is particularly important in Indonesia, which hosts one of the largest coastal ecosystems consisting predominantly of coral reefs [4]. Therefore, it is important to clarify the nutrient cycle of submarine groundwater discharge processes in the area where this occurs and understand the nutrient cycle of groundwater in coastal recharge areas in Indonesia.

The population and the levels of industrial and economic activities including tourism are increasing rapidly in Indonesia, and understanding the impacts these have on the natural environment can lead to increased awareness about groundwater quality. Many studies on groundwater pollution, especially from nitrogen and arsenic, have been conducted in Indonesian coastal cities such as Jakarta, Mataram, and Indramayu [5–12]. However, phosphorus cycling in groundwater ecosystems, which relates to nutrients present in groundwater in such cities, has not been extensively investigated.

Previous detailed research on the phosphorus cycle in groundwater has been conducted mainly on highly

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contaminated septic systems in shallow sand aquifers [13–15]. In the UK, although the phosphorus cycle of groundwater in sandstone, chalk, and limestone aquifers—among others—has been described, phosphorus is still less characterized than nitrogen in groundwater [16]. In the USA, the subsurface transport of orthophosphate in five agricultural watersheds composed of deposits of sand and clayey silt, alluvium, sand and gravel, glacial debris, and quartz sand and gravel has been considered in the studies of stream water eutrophication [17, 18]. In addition, Lewandoski et al. [19] extensively reviewed nutrient transport from groundwater to lake water. Given the adverse impacts of high nutrient concentrations in ecosystems, there is urgent need for detailed research to quantify the different sources of nutrients in groundwater and the likelihood of these being transported, transformed, and stored along flow paths [19]. More recently, there have been an increasing number of studies on the phosphorus cycle as it relates to arsenic contamination in groundwater in South and Southeast Asian floodplains and delta aquifers [20, 21]. However, the complete analysis of the phosphorus cycle in aquifers in volcanic deposits on a volcanic island has yet to be conducted.

Therefore, herein, the area around Mataram City, which is located on the coast of a volcanic island, is used as a study site. The main objectives of this study were to 1) study the species and distribution of phosphorus in the local groundwater and 2) evaluate potential sources of phosphorus and its species using groundwater quality data. Future research will focus on submarine groundwater in this area.

## 2 Study site

The island of Lombok is a part of the Lesser Sunda Islands chain, with the Lombok Strait dividing Bali to the west and Sumbawa to the east. It experiences consistent sunlight for several hours and a warm temperature throughout the year—a minimum of 24 °C and a maximum of 34 °C during hot months and 20 °C–31 °C during cooler months. There is a dry season that runs from April to September and a rainy season that stretches from October to March [22].

One of the most striking features of the Lombok Island region is that most of its cities and densely populated settlements are located in valleys or sedimentary basins or on hills. It has a total area of 4,725 km<sup>2</sup> and is a part of the West Nusa Tenggara Province of Indonesia. The provincial capital and largest city is Mataram, which is located on the western part of the island. The population of Mataram was 441,064 in 2015 [23].

The Lombok Island region experiences a very high level of seismic activity; the last known eruption was in

September 2016 and the most recent earthquake with a magnitude of 6.9 occurred in September 2018. This is due to its position in the Indian Ocean, which places it adjacent to the zone of collision between the Eurasian and Indo-Australian plates [24]. Lombok Island is composed of relatively young Tertiary to Quaternary sediment. The lithology of Lombok Island is dominated by volcanic rocks such as volcanic breccia, various igneous rocks, and sandstone. The eastern part of Lombok Island is formed of breccia, igneous rock, and tuff, among others, from the Tertiary sediment; the western part of the island consists of alluvial or loose rock such as sand, gravel and mud; and the northern part of the island consists of Quaternary volcanic rock [24]. In Antareja, Mataram City, the first layer is composed of smoothly alternating of clay, sand, gravel, coarse grains of pumice, mud, and black sand, with an average thickness of 13 m, extending up to a depth of 28 m from the ground surface. The second layer consists of fine sand and black mud. The third layer is silt and fine sand saturated with water and occurs at an average depth of 39 m from the ground surface. The third layer, which began at a depth of 47 m from the ground surface, is interpreted as the bedrock consisting of sandstone and mudstone [25]. The rock that made up the layers of the bed of the volcanic deposits included clay, gravel, pumice sand, sand, rough pumice granules, silt, and fine black sand [25].

## 3 Hydrochemical sampling and analyses

Groundwater samples were obtained from 19 wells in and around Mataram City and 1 natural spring (Fig. 1). The sampling points were located in an alluvial formation, dating from the Holocene period [26], and consists of pebbles, granule, sand, clay, peat, and fragments of coral (Fig. 2). It is a lowland surrounded by volcanoes (part of the Kalibabak and Pengulung formations). Standing water equivalent to at least one well volume was drawn from the wells before the groundwater samples were collected. The sampling campaign was conducted from September 4–7, 2017, i.e., during the dry season. Field measurements of the pH of the water at its surface were carried out using a pH meter (WM-32EP, DKK-TOA Co.).

Water samples were typically collected over a period of 1–2 h. First, unfiltered splits were taken for the field measurements of pH and the laboratory measurements of alkalinity; samples for the latter were collected in 100 mL polyethylene bottles. Filtered splits (filter: polytetrafluoroethylene; DISMIC-25<sub>HP</sub>; pore size: 0.2 μm) were taken for the laboratory measurements of dissolved organic carbon (DOC) and cation and anion concentrations. Subsamples of the filtered water sample were transferred to 100 mL polyethylene bottles and acidified to pH < 2 using ultrapure

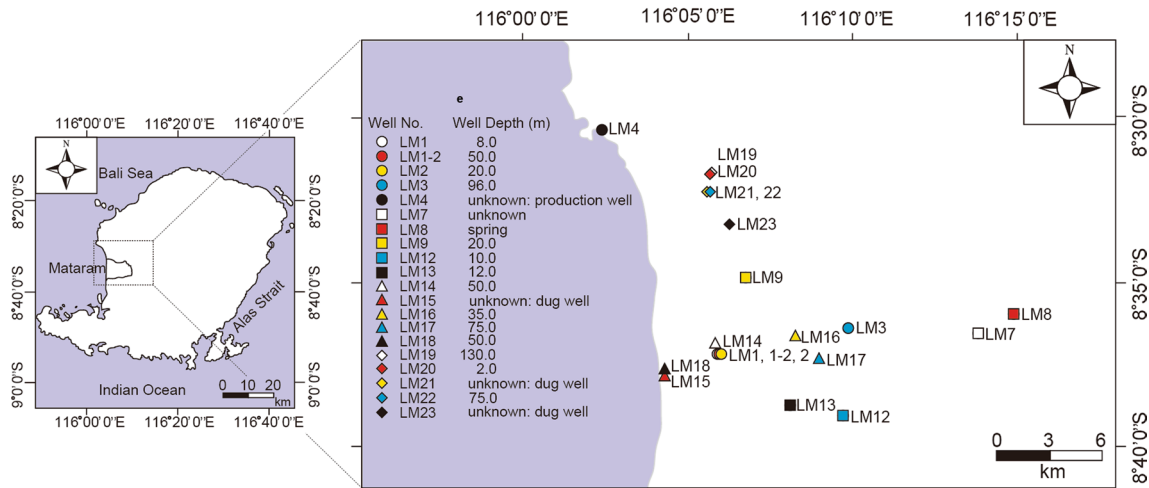


Fig. 1 Study area and sampling locations in and around Mataram

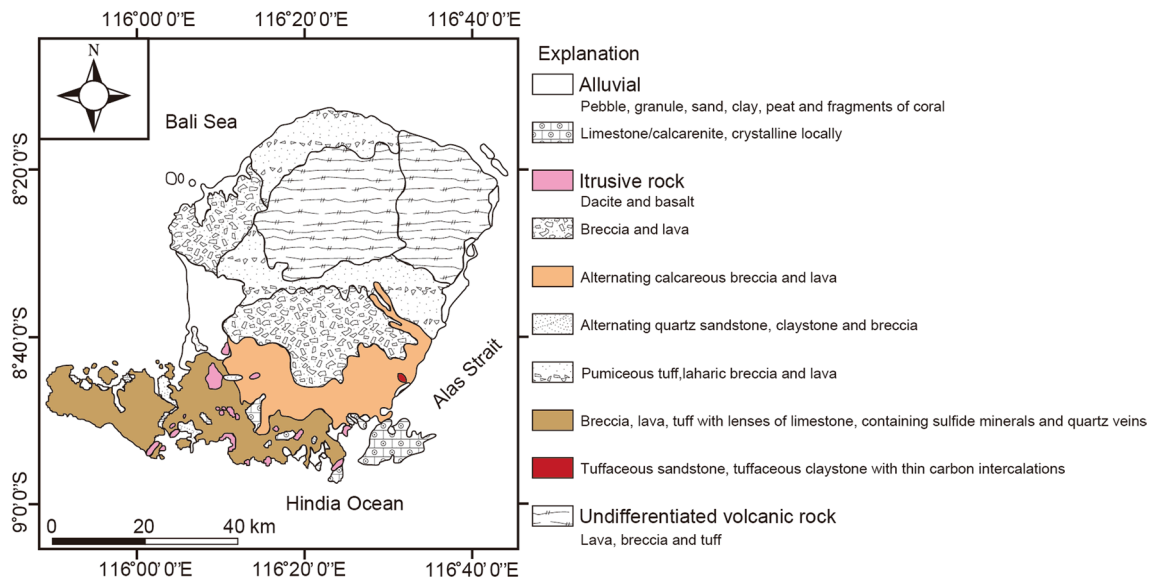


Fig. 2 Geology of Lombok Island (adapted from [26])

nitric acid before the concentrations of Fe, Mn, Sr, Ba, B, Cu, Zn, Si, and P were measured. Unacidified splits needed for cation ( $\text{Na}^+$ ,  $\text{NH}_4^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$ ) and anion ( $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$  and  $\text{SO}_4^{2-}$ ) analyses were kept in 100-mL polyethylene bottles, while those for DOC estimation were kept in 50 mL glass vials.

The elemental analyses were performed at the geothermal engineering laboratory at Hirosaki University, where the concentrations of Fe, Mn, Sr, Ba, B, Cu, Zn, Si, and P were determined using inductively coupled plasma-optical emission spectroscopy (Optima 7000DV, PerkinElmer Co. Ltd.). The concentrations of  $\text{Na}^+$ ,  $\text{NH}_4^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$  were determined via ion chromatography with conductivity detection (ICS-1100, Thermo Fisher Scientific

Inc.). The concentrations of  $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ , and  $\text{SO}_4^{2-}$  were determined via ion chromatography with conductivity detection (ICS-2100, Thermo Fisher Scientific Inc.). The DOC concentration was measured using a total organic carbon analyzer (TOC-V<sub>C<sub>PH</sub></sub>, Shimadzu Co.). Alkalinity measurements were carried out in the field via titration, and the values were expressed in terms of the concentration of  $\text{HCO}_3^-$  (milligrams per liter of water). In terms of the error in the charge balance between the cations and anions, 16 samples were within  $\pm 3\%$ , 2 were within  $+ 4\%$ , and another 2 samples were within  $+ 9\%$ .

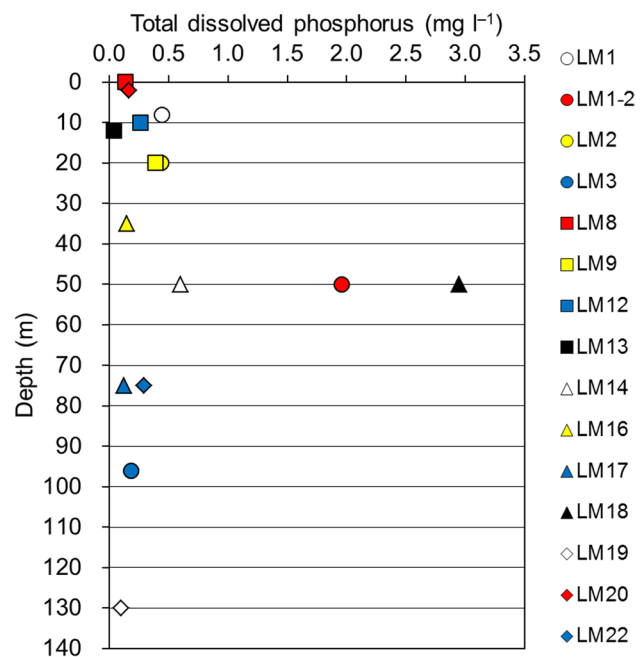
The saturation indices ( $\text{SI} = \log(\text{ion activity product/solubility product})$ ) of the groundwater samples were calculated using the thermodynamic database

(phreeqc.dat) for a mineral phase that might serve as a sink or source for  $\text{PO}_4^{3-}$ , as provided with the aqueous speciation software PHREEQC ver.3 [27]. An annual average air temperature of 27 °C was used as the temperature of analysis because the actual temperature of the groundwater in situ was unknown.

## 4 Results and discussion

### 4.1 Phosphorus species and distribution

The dissolved phosphorus species in 19 samples of groundwater and 1 sample of spring water taken in and around Mataram City were analyzed and the concentrations of total dissolved phosphorus (TDP; or total filterable phosphorus [28]) and  $\text{PO}_4^{3-}$  were determined. The concentrations of TDP and dissolved  $\text{PO}_4\text{-P}$ , as measured using inductively coupled plasma-optical emission spectroscopy and ion chromatography, ranged from 0.04  $\text{mg l}^{-1}$  to 2.95  $\text{mg l}^{-1}$  and from 0.028 to 2.74  $\text{mg l}^{-1}$ , respectively (Table 1). The concentration of dissolved  $\text{PO}_4\text{-P}$  of groundwater from parts of Lombok Island that were outside the study area, measured using standard photochemical methods, ranged from 0.018 to 0.384  $\text{mg l}^{-1}$  (i.e., ranged from 0.58 to 12.4  $\mu\text{mol l}^{-1}$  as  $\text{PO}_4$ ) according to Oehler et al. [3]. The ratio of dissolved  $\text{PO}_4\text{-P}$  that was related to TDP ranged from 67 to 96%; exceptions were values of 14%, 35%, and 172%, respectively, in wells LM9, LM15, and LM4 (Table 1). The reason for the high value from well LM4 is unknown; however, the very low values (14% and 35%) from wells LM9 and LM15 could possibly be due to the fact that two groundwater samples with a high  $\text{Fe}^{2+}$  concentration (1.70 and 2.71  $\text{mg l}^{-1}$ ) were precipitated before the ion chromatography analysis, while  $\text{PO}_4^{3-}$  in the groundwater samples was co-precipitated with Fe(III)–(hydr)oxides [21, 29]. Dissolved inorganic P accounted for 86%, on average, of the TDP concentrations, while  $\text{PO}_4^{3-}$  represented the predominant ion species in this groundwater. The latter result is similar to that obtained in the analyses of groundwater in Asian floodplain and delta aquifers [21]. Figure 3 shows the relationship between TDP concentration and well depth; if the latter was unknown, it is described in the caption of Fig. 3. It was found that the groundwater from wells LM1–2, LM14, and LM18 sampled from wells with a depth of 50 m contained more P compared with samples taken from wells of other depths (Fig. 3). The TDP concentration of these samples was also relatively high, compared to the others.

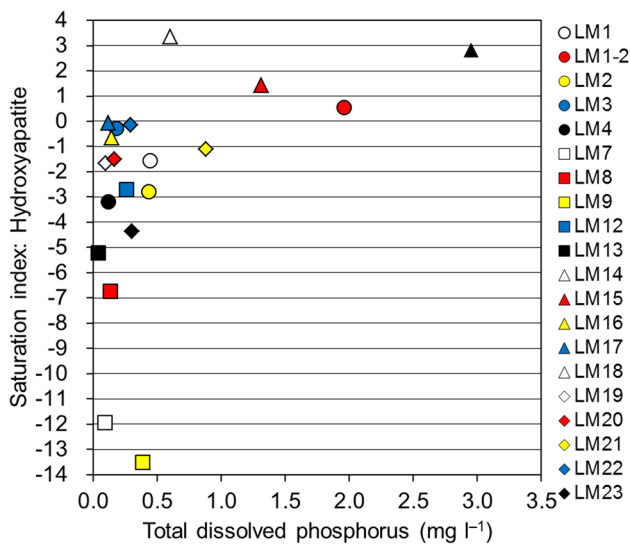


**Fig. 3** Depth distribution of total dissolved phosphorus ( $\text{mg l}^{-1}$ ). The total phosphorus concentrations in the observation wells of unknown depth, LM4, LM7, LM15, LM21, and LM23 were 0.12, 0.10, 1.31, 0.88, and 0.30  $\text{mg l}^{-1}$ , respectively

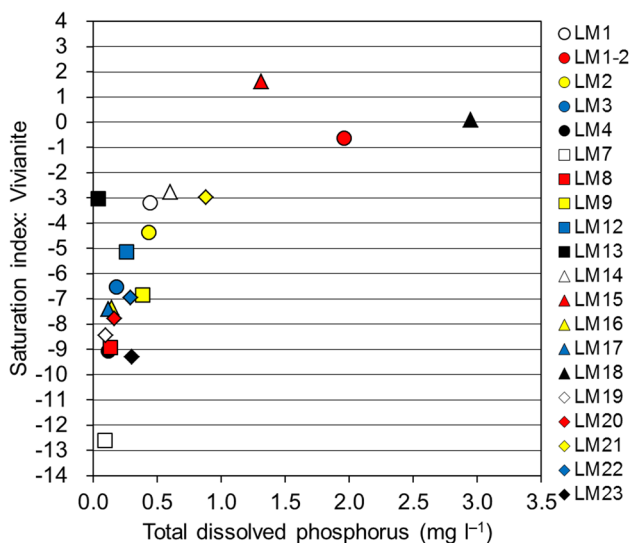
### 4.2 Potential sources of dissolved $\text{PO}_4^{3-}$

One possible source of dissolved  $\text{PO}_4^{3-}$  is the dissolution of minerals (e.g., apatite) that may contain P in some phases [21, 30, 31]. Volcanic rocks and deposits contain P [32, 33], as does lava on Lombok Island; for the latter, the levels of P detected were reported as percentages of  $\text{P}_2\text{O}_5$  ranging from 0.15 to 0.47 [34] and 0.19 to 0.27 [35]. The presence of apatite was also reported [35]. In addition, the microbial degradation of organic carbon (sedimentary and dissolved) and the concomitant reductive dissolution of Fe(III)–(hydro)oxides represent another potential source of P that could have released  $\text{PO}_4^{3-}$  into groundwater [21]. Other potential sources include leachate from arable land and leaking septic tanks or sewer pipes [13–15, 17, 18, 36].

Taking the first potential source into consideration, the contribution of the dissolution of hydroxyapatite and vivianite was evaluated on the basis of the calculated SI (Figs. 4 and 5). Only groundwater sampled from well LM15 appeared to be over-saturated with hydroxyapatite and vivianite. The groundwater sampled from wells LM1–2, LM14, and LM18 were over-saturated with hydroxyapatite only (Fig. 4). In addition, the groundwater sampled from wells LM17 and LM22 was nearly saturated with hydroxyapatite (Fig. 4), while that sampled from well LM18 was nearly saturated with vivianite (Fig. 5). Thus, the dissolved  $\text{PO}_4^{3-}$  in groundwater from

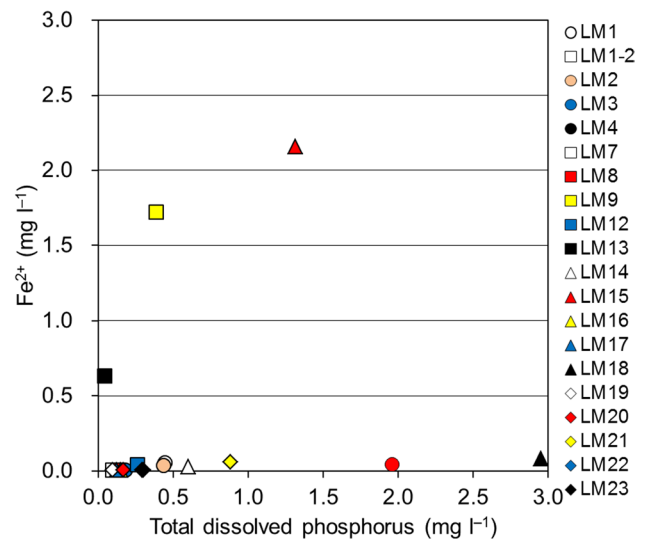


**Fig. 4** Saturation index for a potential phosphate-bearing phase of hydroxyapatite, as calculated by PHREEQC. For the PHREEQC analysis of the groundwater sampled from wells LM9 and LM15, the concentrations of total dissolved phosphorus, instead of  $\text{PO}_4^{3-}$ , were used as the input value for P

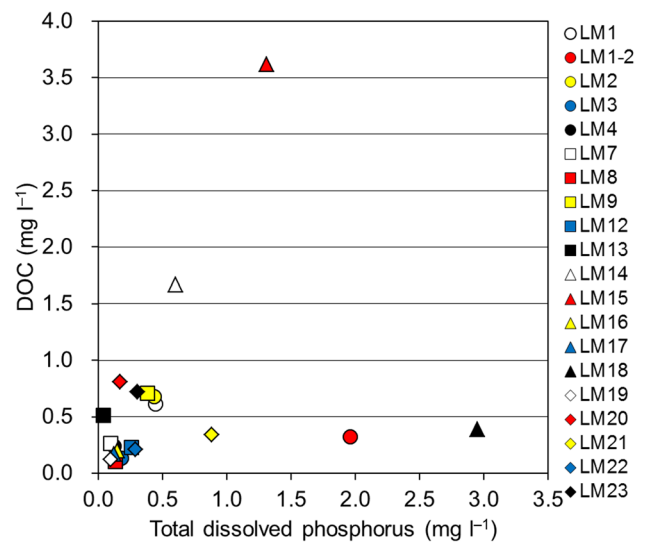


**Fig. 5** Saturation index for a potential phosphate-bearing phase of vivianite, as calculated by PHREEQC. For the PHREEQC analysis of the groundwater sampled from wells LM9 and LM15, the concentrations of total dissolved phosphate, instead of  $\text{PO}_4^{3-}$ , were used as the input value for P. All Fe concentrations measured using inductively coupled plasma-optical emission spectroscopy were input to PHREEQC as  $\text{Fe}^{2+}$ . When the Fe concentration measured using this method was less than the lower limit of quantification, the lower limit of quantification was entered in PHREEQC

all the samples could potentially be sourced through the dissolution of hydroxyapatite and/or vivianite. Notably, the presence of apatite in volcanic lava deposits from



**Fig. 6** Relationship between the concentrations of  $\text{Fe}^{2+}$  and total dissolved phosphorus. When the  $\text{Fe}^{2+}$  concentration was less than the lower limit of quantification, the latter was entered in PHREEQC

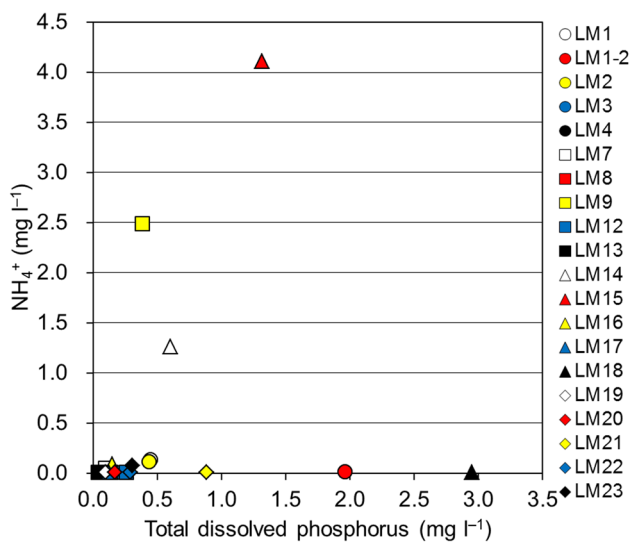


**Fig. 7** Relationship between the concentrations of dissolved organic carbon and total dissolved phosphorus

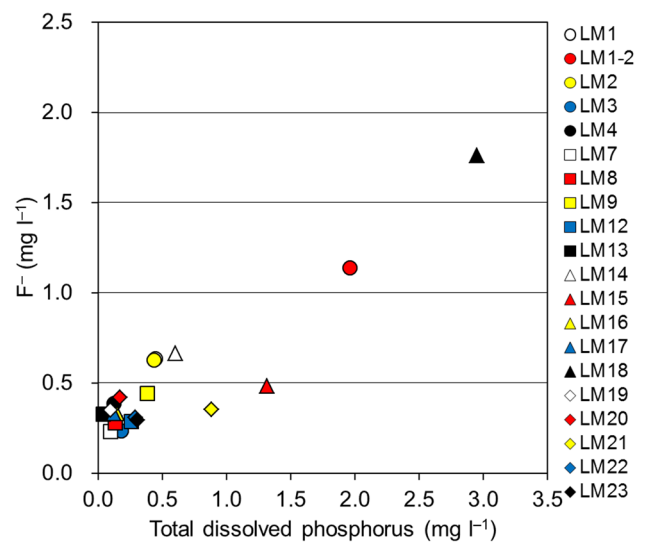
Mount Rinjani has already been reported [35]. However, only well LM15 may have other sources.

The groundwater sampled from well LM15 contained  $1.31 \text{ mg l}^{-1}$  of TDP and high concentrations of  $\text{Fe}^{2+}$ , DOC, and  $\text{NH}_4^+$  (Figs. 6, 7, and 8). Thus, the reduction of Fe(III)–(hydro)oxides or the initial decomposition of organic matter are considered potential key mechanisms underlying the enrichment of  $\text{PO}_4^{3-}$  in groundwater from this well. Furthermore, one characteristic of the groundwater sampled from wells LM1-2 and LM18 is that

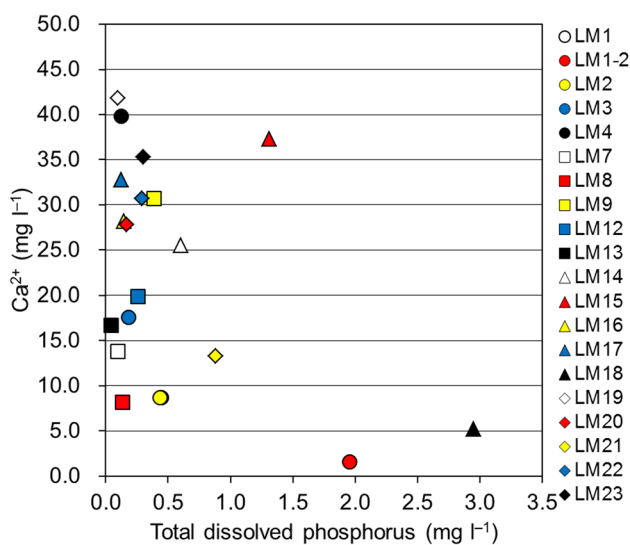




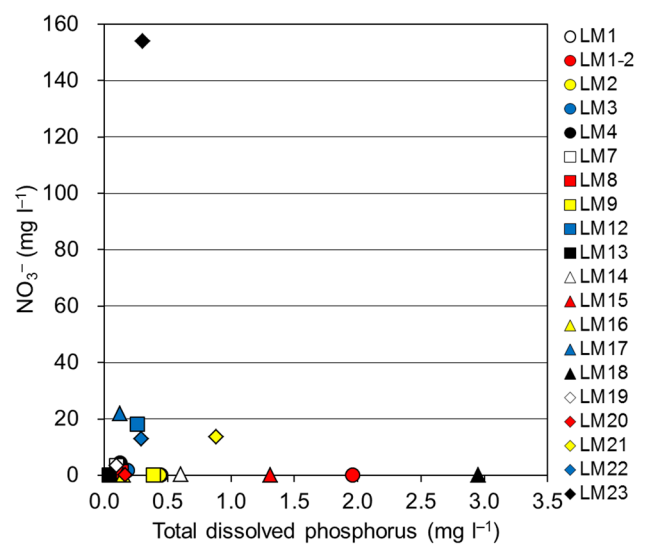
**Fig. 8** Relationship between the concentrations of  $\text{NH}_4^+$  and total dissolved phosphorus. When the  $\text{NH}_4^+$  concentration was less than the lower limit of quantification, the latter was entered in PHREEQC



**Fig. 10** Relationship between the concentrations of  $\text{F}^-$  and total dissolved phosphorus



**Fig. 9** Relationship between the concentrations of  $\text{Ca}^{2+}$  and total dissolved phosphorus



**Fig. 11** Relationship between  $\text{NO}_3^-$  and concentrations of total dissolved phosphorus. When the  $\text{NO}_3^-$  concentration was less than the lower limit of quantification, the latter was entered in PHREEQC

the  $\text{Ca}^{2+}$  concentrations are very low, at 1.57 mg  $\text{l}^{-1}$  and 5.8 mg  $\text{l}^{-1}$ , respectively, while the concentrations of  $\text{F}^-$  are high at 1.14 mg  $\text{l}^{-1}$  and 1.76 mg  $\text{l}^{-1}$ , respectively (Figs. 9 and 10). In addition, the concentrations of DOC,  $\text{Fe}^{2+}$ ,  $\text{NO}_3^-$ , and  $\text{NH}_4^+$  in these samples were low (Figs. 6, 7, 8, and 11). These results indicate that the origin of dissolved  $\text{PO}_4^{3-}$  in these wells is neither the microbial degradation of organic carbon nor the concomitant reductive dissolution of Fe(III)–(hydro)oxides. Furthermore, these results show that there is no anthropogenic influence here as these samples contain no N components. Thus, the dissolved

$\text{PO}_4^{3-}$  in these samples may be considered to have a geological origin—the dissolution of carbonate-rich fluorapatite [31]. The low  $\text{Ca}^{2+}$  concentrations are most likely a result of several mechanisms, including (1) mostly cation exchange reactions and (2) to a lesser degree, the formation of the hydrated di-basic calcium phosphate surface and sorption [31].

Finally, the groundwater sampled from well LM14 had high DOC and  $\text{NH}_4^+$  concentrations (Figs. 7 and 8). The decomposition of organic matter is considered the potential source of dissolved  $\text{PO}_4^{3-}$  in these groundwater

**Table 1** Groundwater quality data

	pH	mg l <sup>-1</sup>											
		DOC	F <sup>-</sup>	Cl <sup>-</sup>	Br <sup>-</sup>	NO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	PO <sub>4</sub> <sup>3-</sup>	HCO <sub>3</sub> <sup>-</sup>	Na <sup>+</sup>	NH <sub>4</sub> <sup>+</sup>	K <sup>+</sup>	Mg <sup>2+</sup>
LM1	7.45	0.61	0.635	6.39	0.032	<0.01	0.854	1.23	220	29.9	0.135	11.3	21.8
LM1-2	8.26	0.32	1.14	5.45	0.016	<0.01	4.89	5.64	259	97.7	0.017	5.98	0.452
LM2	7.20	0.68	0.629	6.36	0.031	0.012	0.822	1.20	221	29.9	0.118	11.5	22.0
LM3	7.62	0.13	0.236	3.13	0.012	1.73	4.45	0.47	144	15.5	<0.01	4.43	11.2
LM4	6.77	0.24	0.388	229	0.771	4.47	39.3	0.64	281	187	<0.01	6.89	21.1
LM7	5.85	0.26	0.231	3.82	0.008	3.37	5.67	0.228	94.6	12.4	0.049	5.37	6.49
LM8	6.70	0.1	0.281	4.72	0.01	1.16	4.56	0.377	65.3	10.3	0.010	3.63	4.70
LM9	5.10	0.71	0.441	16.3	0.03	0.1	8.22	0.16	213	25.9	2.49	12.4	12.6
LM12	7.02	0.23	0.285	10.5	0.018	18.0	10.2	0.609	150	23.8	<0.01	11.4	11.4
LM13	7.12	0.51	0.329	56.9	0.043	<0.01	14.30	0.085	174	64.0	<0.01	12.5	10.4
LM14	7.92	1.67	0.664	14.9	0.043	0.4	2.81	1.76	236	67.7	1.26	12.9	6.46
LM15	7.17	3.62	0.482	40.3	0.103	0.01	0.619	1.42	339	58.5	4.11	26.4	17.9
LM16	7.48	0.20	0.331	8.42	0.064	0.027	8.56	0.317	180	20.2	0.088	4.86	15.1
LM17	7.60	0.17	0.330	17.6	0.039	22.0	13.0	0.35	293	38.0	<0.01	6.49	31.5
LM18	8.18	0.39	1.76	133	0.456	<0.01	24.5	8.4	326	204	<0.01	9.60	2.84
LM19	7.17	0.12	0.348	12.7	0.049	3.51	8.16	0.280	249	28.6	<0.01	2.48	19.4
LM20	7.23	0.81	0.419	12.9	0.031	<0.01	14.3	0.422	234	41.8	<0.01	16.8	9.88
LM21	7.11	0.34	0.353	10.5	0.023	13.5	7.22	2.38	105	21.1	<0.01	18.3	4.93
LM22	7.27	0.21	0.309	14.9	0.042	12.8	9.28	0.816	135	24.6	<0.01	6.33	10.7
LM23	6.50	0.72	0.294	30.0	0.039	154	11.0	0.779	70.6	38.7	0.075	10.4	13.2

	pH	mg l <sup>-1</sup>											
		Ca <sup>2+</sup>	Fe	Mn	Sr	Ba	B	Cu	Zn	Si	TDP**	PO <sub>4</sub> -P*	PO <sub>4</sub> -P TDP <sup>-1</sup>
LM1	7.45	8.69	0.054	0.220	0.097	0.020	0.081	<0.004	0.021	36.9	0.44	0.401	90%
LM1-2	8.26	1.57	0.042	0.006	0.023	0.016	0.101	<0.004	0.051	22.2	1.96	1.839	94%
LM2	7.20	8.71	0.036	0.147	0.098	0.018	0.081	<0.004	0.007	32	0.44	0.391	90%
LM3	7.62	17.6	<0.005	<0.001	0.093	0.004	0.036	<0.004	<0.003	38	0.18	0.153	84%
LM4	6.77	39.8	<0.005	<0.001	0.384	0.002	0.069	<0.004	0.096	42.5	0.12	0.209	172%
LM7	5.85	13.8	<0.005	0.001	0.102	0.004	0.039	0.004	0.016	31.4	0.10	0.074	78%
LM8	6.70	8.16	<0.005	0.001	0.052	0.002	0.097	<0.004	<0.003	27	0.13	0.123	92%
LM9	5.10	30.7	1.7	2.184	0.26	0.032	0.043	<0.004	<0.003	39.5	0.39	0.052	14%
LM12	7.02	19.9	0.040	0.002	0.17	0.013	0.102	<0.004	0.068	33.9	0.26	0.199	76%
LM13	7.12	16.7	0.633	0.107	0.123	0.021	0.103	<0.004	0.036	34	0.04	0.028	67%
LM14	7.92	25.5	0.029	0.049	0.164	0.023	0.137	<0.004	0.127	25.8	0.60	0.574	96%
LM15	7.17	37.3	2.16	1.233	0.365	0.019	0.070	<0.004	0.015	39	1.31	0.463	35%
LM16	7.48	28.2	<0.005	0.002	0.22	0.009	0.037	<0.004	0.012	39.0	0.15	0.103	70%
LM17	7.60	32.8	<0.005	0.001	0.206	0.010	0.068	<0.004	0.031	35.3	0.12	0.114	94%
LM18	8.18	5.18	0.080	0.016	0.067	0.013	0.453	<0.004	0.097	27.3	2.95	2.739	93%
LM19	7.17	41.8	<0.005	0.001	0.29	0.006	0.031	<0.004	0.081	48.3	0.10	0.091	94%
LM20	7.23	27.8	<0.005	0.024	0.289	0.097	0.043	<0.004	0.013	38	0.17	0.138	82%
LM21	7.11	13.3	0.061	0.001	0.139	0.074	0.036	<0.004	0.034	45	0.88	0.776	88%
LM22	7.27	30.7	<0.005	0.003	0.27	0.017	0.033	<0.004	0.011	44.5	0.29	0.266	91%
LM23	6.50	35.3	<0.005	0.043	0.36	0.11	0.040	<0.004	0.023	51.2	0.30	0.254	84%

\*PO<sub>4</sub>-P was calculated from the concentration of PO<sub>4</sub><sup>3-</sup> as analyzed by ion chromatography

\*\*TDP is the concentration of P as analyzed by inductively coupled plasma-optical emission spectroscopy

samples, particularly given that the latter may have a very low concentration of Fe(III)–(hydro)oxides. In addition, because the groundwater sampled from wells LM12, LM17, LM21, LM22, and LM23 have a relatively high concentration of  $\text{NO}_3^-$  (Fig. 11), it is also likely that anthropogenic sources may be considered as having a potential impact on the levels of dissolved  $\text{PO}_4^{3-}$  measured therein.

## 5 Conclusion

The chemical composition of groundwater in and around Mataram City, Lombok Island, Indonesia was investigated to identify the species and potential sources of P in groundwater. The concentration of TDP in the groundwater samples ranged from approximately 0.04 to 2.95  $\text{mg l}^{-1}$ , with  $\text{PO}_4^{3-}$  representing the predominant ion therein. The potential source of dissolved  $\text{PO}_4^{3-}$  in most of the groundwater samples is the dissolution of hydroxyapatite and/or vivianite. However, the potential source of dissolved  $\text{PO}_4^{3-}$  in groundwater with a TDP concentration of  $\geq \text{mg l}^{-1}$  is more likely to be the reduction of Fe(III)–(hydro)oxides, the decomposition of organic matter, or the dissolution of carbonate-rich fluorapatite. The geochemical approach used in this study was effective, even in the absence of detailed geological data, for the evaluation of the potential sources of P in groundwater. The geochemical findings could aid researchers working on coastal marine ecosystems.

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## Compliance with ethical standards

**Conflict of interest** On behalf of all the authors, the corresponding author states that there are no conflicts of interest to declare.

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