

Groundwater–surface water interactions of Ciliwung River streams, segment Bogor–Jakarta, Indonesia

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Abstract Ciliwung River water quality and its vicinity have been continuously degraded with the increasing population. The objective of this research is to understand the association between river and groundwater, and the water quality profile. Field measurements were taken from 65 stations from Bogor to Jakarta. Water level, temperature, pH, and TDS were measured to build the water flow map and hydrochemical profile. Small-scale geoelectrical survey was conducted at five locations to capture the aquifer's geometry. We identified three types of stream relationships between river and groundwater: effluent from Bogor to Katulampa (Segment 1), perched at the University of Indonesia (UI) area (Segment 2), and influent from UI to Muara (Segment 3), with low gradient from <0.1 to 0.3. The temperature profile of river and groundwater shows similar pattern as well as TDS profile. All similarities support close connection of river and groundwater. The increasing TDS towards downstream shows increasing enrichment and contamination. The erratic pattern of pH indicates chemical instability due to high contamination. This study highlights the benefit of understanding the hydrodynamic relationship between river water and

groundwater. Such interaction triggers water quality exchange between both water bodies. Therefore, a similar study should also be done on other riverbanks in Indonesia to protect water quality.

Keywords River–groundwater interaction · Hydrodynamic · Hydrochemistry Ciliwung River

Introduction

The gap between water demand and water supply has been the major issue in developing countries. Such gap has been widened through time with the increase of population and economic activities. An example is obtained from Pandey and Kazama (2011). The author stated that the local water supply company in Kathmandu Valley, Kathmandu Upatya Khanepani Limited (KUKL), had extracted 62.2 % of the total groundwater in the area. As a result, groundwater discharge is more than twice the natural recharge, estimated at 4.61–14.6 MCM/year (Pandey and Kazama 2014). Pandey et al. (2010) argued that the drivers of such massive extraction are population growth, urbanization and increase in tourism. Water accessibility decreases with the increase of population. A high rate of urbanization has also changed water-use pattern and groundwater pollution. Tourism has also developed rapidly leading to an increasing number of hotels in the area with large water demand. Such demand has been supplied by groundwater. To solve the problem, Pandey et al. (2011) has proposed a groundwater sustainability (GS) framework which consists of five components and 16 indicators.

In another case in China, groundwater irrigation has been the main driver of agricultural boom in the period of 1970–1995. The same situation also occurred in Pakistan

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and Bangladesh (Shah et al. 2003). The authors proposed that the major barrier for groundwater management is lack of subsurface information. Das Gupta and Babel (2005) stated that excessive groundwater pumping had increased the rate of land subsidence in the eastern suburb of Bangkok from 2.0–3.0 to 3.0–3.5 cm/year observed in 1989–1990.

As well as the above-mentioned countries, Indonesia as the largest country in Southeast Asia, both in population and in area, is also facing the same problem. Jakarta, the capital of Indonesia, has been experiencing groundwater over-withdrawal. Braadbaart and Braadbaart (1997) mentioned that manufacturers are mainly the cause of the 60 % increasing groundwater withdrawals during 1950–1990. Lubis et al. (2008, 2013) stated that water demand is 450,000,000 m³/year. This number is 50 times more than in 1945. Fifty percent of the demand has been supplied from numerous shallow and deep aquifers, while the safe harvesting threshold from both aquifers is 60,000,000 m³/year. It leads to measured land subsidence rate of 1–10 cm/year from 1997 to 2005. Another half of the demand has been supplied from river water. Ciliwung River is one of the raw water sources for the city. Wilkins (2014) mentioned that Ciliwung River is one of the critical rivers,

based on the river water monitoring data on dissolved oxygen, biological oxygen demand, chemical oxygen demand, faecal coli and total coli form, compared to Groundwater Quality Standards (Ministry of Health Regulation 2001). Fachrul et al. (2007) also mentioned that the water quality index value (WQI) of the river has been decreased by 33 % in a 12-year time span.

This paper mainly discusses water flow and water quality in Ciliwung River. This river is a part of the Ciliwung–Cisadane watershed. It is a 5,293 km² watershed that flows from the volcanic highlands (averagely 1,000 masl) to northern Java lowlands (0–100 masl). The Ciliwung River is 140 km in length and flows through three major cities: Bogor at upstream, Depok at middle stream, and Jakarta at downstream (Fig. 1). In volcanic environment as in the Bogor–Jakarta area, highly undulated terrain and unconfined productive aquifers build local groundwater flow systems (Ministry of Public Works of Indonesia 2007; Indonesian Science Foundation (LIPI) 1988). This system demonstrates a close interaction between groundwater and surface water (river water). A hydrological process associated with the surface water bodies, such as seasonally high fluctuation, is one of the major causes of seasonal dynamic groundwater flow (Winter 1999; Woessner 2000).

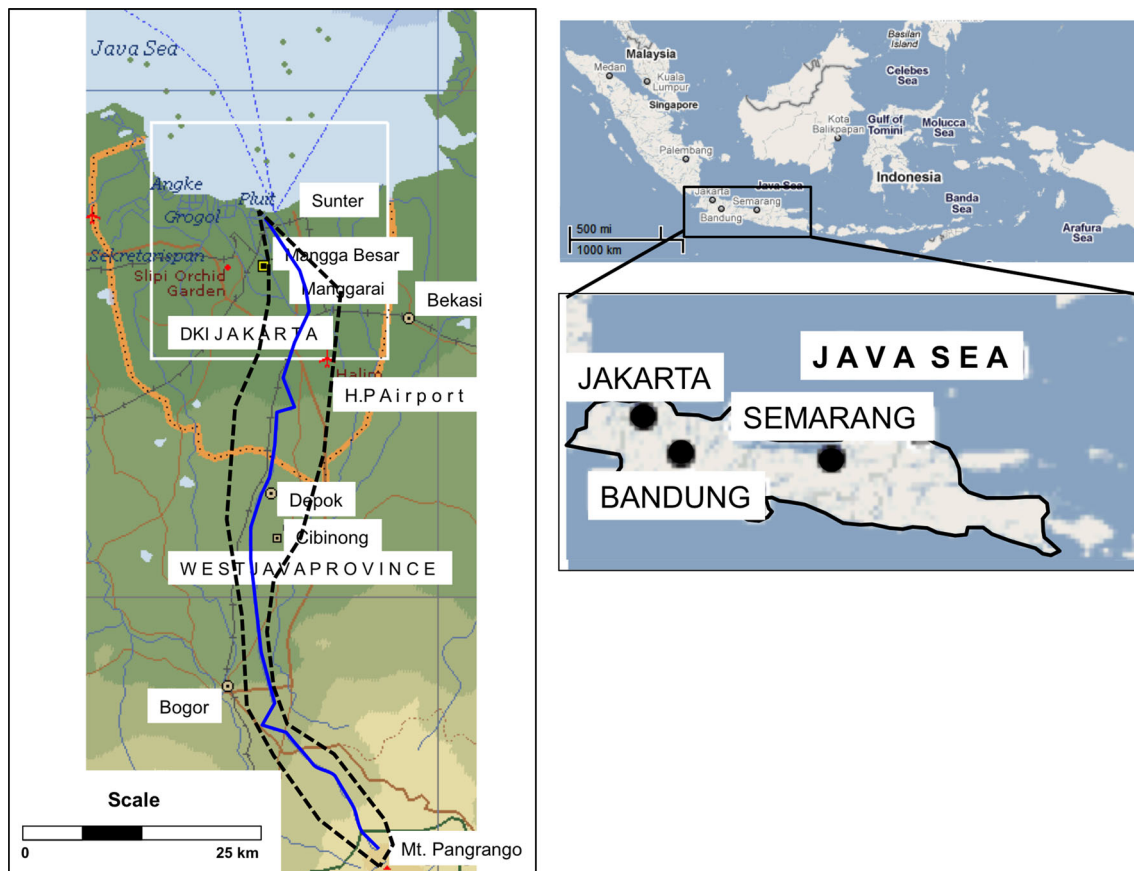


Fig. 1 Location of the study area

Following the above-mentioned problems, the objective of this paper is to come up with the hydrodynamic relationship between river water and groundwater of Ciliwung River bank. Specifically, it focusses on the temporal river water and groundwater level, related to the geological characteristics of river bed and river bank.

General hydrogeological setting

The location of this study is a part of the Ciliwung–Cisadane catchment with an area of 435 km², only 8 % from the total catchment area. It extends from the foot slope of Gunung Pangrango (3,019 masl) to Jakarta Bay. The study area has a high annual rainfall (1,500–3,200 mm/year). Maximum rainfall occurs during the month of November to March, while the minimum is in May to September.

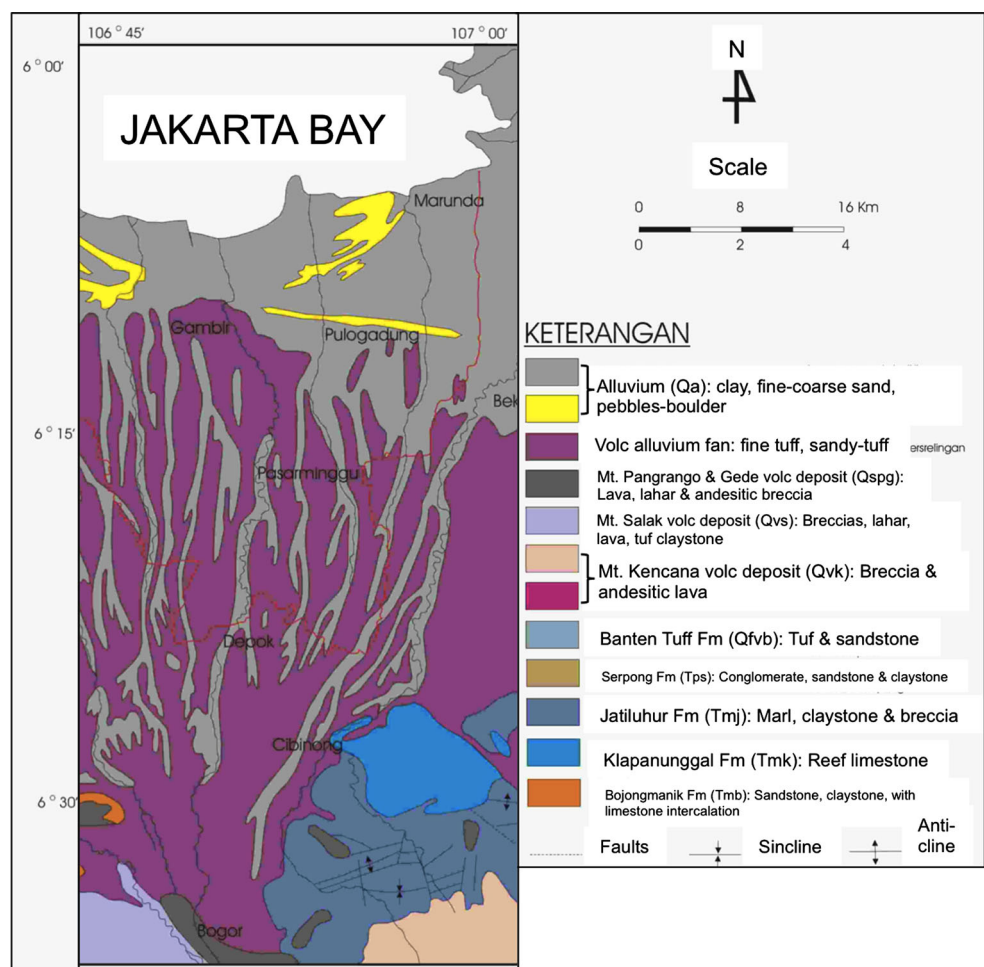
Volcanic deposits mainly build up the morphology in this area. It can be divided into three main hydrogeological units: volcanic core, slope, and volcanic fan (Assegaf and Puradimaja 1998). Another paper divided the area into five geomorphological units (Fig. 1): old volcanic core of

Gegerbentang, volcanic core of Pangrango, volcanic core of Lemo, slope of Pangrango, and Bogor volcanic fan (Indonesian Science Foundation (LIPI) 1988).

Geologically, the study area is dominated by Quaternary volcanic sediments that unconformably deposited on top of impermeable Tertiary sediments as basement. The Tertiary sediments consisted of Bojongmanik Formation, Klapanunggal Formation, Jatiluhur Formation, and Serpong Formation. All of the formations resemble the transition process from marine to terrestrial environment that contain a series of low impermeable sandstone, claystone, and reefal limestone. Then in the early Quaternary Age, volcanic activities started and built up volcanic formations of Mount (Mt.) Kencana, Mt. Salak, Mt. Pangrango, and Mt. Gede. Then, all of the volcanic products were eroded and deposited northward to lowlands in the form of volcanic fan deposit (Effendi 1974; Turkandi 1992), (Fig. 2).

Based on spring and geological observations and also stable isotopes measurements, water recharge comes from elevation higher than 1,000 masl. Then it flows towards lowland and forms groundwater springs in a radial flow pattern (Fig. 3). Groundwater springs are commonly

Fig. 2 Geological map of Ciliwung catchment



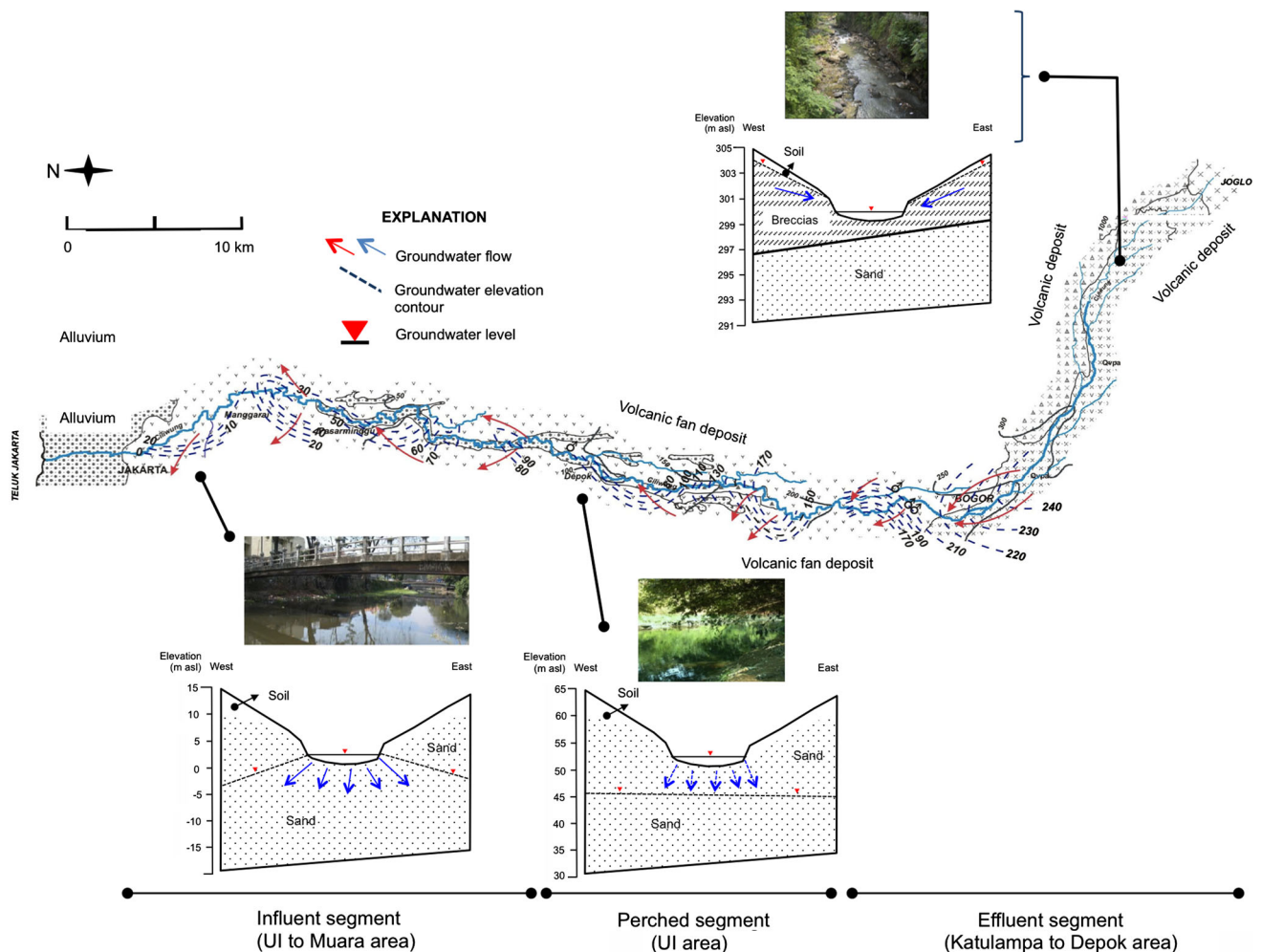


Fig. 3 Conceptual model of groundwater and river water relation

located at 300–750 masl. They are fed by highly productive aquifer of breccias, lahar and fractured lava deposits. These facts lead to the interpretation of the local groundwater flow system (Assegaf and Puradimaja 1998). According to the same research, the discharge area is located in the central and northern part of the Jakarta Groundwater Basin. There are also spots of transition area, located the middle of the basin that act as both local recharge and discharge areas (Lubis et al. 2008).

Materials and methods

Selection of observation points

The methodology applied in this paper was a combination of surface field measurements consisting of geological observations, groundwater flow net analysis, and hydrochemical analysis. Field measurements were taken at 65 stations, consisting of groundwater samples from dug wells

at left and right part of the river bank and river water samples, as summarized (see attached supplementary data sheet). Observations were conducted in May to August 2006 from Bogor to Jakarta, passes Katulampa, Cibubur, Depok, University of Indonesia (UI), Matraman, Mangga Besar, Pasar Minggu, Kemiri, and Muara. All locations were selected based on geology according to the regional geological map and groundwater well availability.

We also conducted shallow and small-scale geoelectrical survey at five locations to capture the aquifer's geometry. At each location we measured four geoelectrical points with 50 m length configuration: two points at west riverbank and two points at the east.

Groundwater flow net analysis

The team used Portable Hanna Water Level Detector to mark water level and standard GPS to locate the coordinate. Using water level measurement data, the team built groundwater flow net map as a graphical representation of

two-dimensional steady-state groundwater flow through aquifers. The proper construction of traditional flow nets is still one of the most powerful analytical tools used by the hydrologist to analyse groundwater flow (Fetter 1988). Winter (1999) and Lubis and Puradimaja (2006) have also used this method to study the concept of interactions between groundwater and surface water in their researches.

Hydrochemical analysis

For this study, we analysed 65 groundwater and river water samples as summarized in Table 1. Stream discharge and water levels at river and dug wells were measured with portable custom-made water level meter (Baxter et al. 2003; Johnson et al. 2005). All water samples were collected by hand and immediately filtered through 0.45 mm membranes. We used 2 L of low-density polyethylene (LDPE) sampling bottles to store all samples. Samples for cation analysis were acidified to pH less than two with nitric acid. Unstable parameters such as pH, temperature, electrical conductivity (EC), and total dissolved solids (TDS) were measured using Hanna Instrument equipment. All instruments were calibrated daily on the field.

Seven major elements concentration were measured in the laboratory by Standard Methods for the Examination of Water and Wastewater (APHA 1992), consisting of: calcium (Ca²⁺), sodium (Na⁺), magnesium (Mg²⁺), potassium (K⁺), chloride (Cl⁻), bicarbonate (HCO₃⁻), sulphate (SO₄²⁻), and fluoride (F⁻) (Table 1). Chemical test results were then validated using general ion balance equation, before further analyses with 20 % of maximum error balance. Samples with error balance higher than 10 % were re-tested, while samples with error lower than 10 % were directly included in interpretation. Major element concentrations were tested to evaluate the similarity between river water and surrounding groundwater. A similar concentration will support general indications of groundwater and river water relation.

Table 1 Laboratory testing standard

No	Major elements	Units	Methods
1	Carbonate	mg/l	SMEWW 2,340-C
2	Calcium	mg/l	SMEWW 3,500-Ca
3	Magnesium	mg/l	SMEWW 3,500-Mg
4	Chloride	mg/l	SMEWW 4,500-Cl
5	Sodium	mg/l	SMEWW 4,500-Na
6	Sulphate	mg/l	SMEWW4,500-SO ₄
7	Potassium	mg/l	SMEWW 3,500-K
8	Bicarbonate	mg/l	SNI 06-2,420
9	Fluoride	mg/l	SMEWW5,210-F

Results and discussion

Groundwater–river water relation

The general interaction between groundwater and river water on a river stream is divided into effluent stream, influent stream, isolated stream, and perched stream, or a combination between the four types, controlled by topography, geological conditions, and aquifer depth (Lubis and Puradimaja 2006). Based on groundwater flow net analysis, we can identify three groundwater and river water relations at Ciliwung River stream, as described in the following subsections (respectively from Bogor to Jakarta). The groundwater and river water level dataset is listed in ESM Table 1.

Type one: effluent stream

Effluent stream was identified from Bogor to Katulampa (Segment 1). At this segment, groundwater moved out to the river. This stream type was also found mostly at the upstream of Ciliwung. The geological condition was composed mainly of volcanic breccias of Pangrango volcanic deposit. Groundwater level contour indicated groundwater discharge from east and west riverbank with 3.5 % of hydraulic gradient (Fig. 3). Moving to downstream, the percentage of volcanic breccias deposit decreased, while volcanic fan and alluvium deposit increased.

Type two: perched stream

Perched stream was recognized at the University of Indonesia (UI) area (Segment 2). Results from geoelectrical survey suggested that aquifer layers were not directly in contact with the river basement. It was located on average 5 m below the riverbed. Moreover, groundwater level was found 6 m from the riverbed (Fig. 3). Therefore, there was presumably a thick hyporheic zone above the groundwater zone.

Type three: influent stream

The observation on this segment (Segment 3) was divided into four subsegments: from UI to Pasar Minggu, Pasar Minggu to Salemba, Salemba to Mangga Besar, and Mangga Besar to Muara. All locations exposed influent stream type. This segment was generally covered by alluvium deposit, which played the role of aquifer. The aquifers were located directly under the river stream. Based on water level measurements, river water level was higher than groundwater (influent stream type). River water infiltrated the underlying aquifers in divergent pattern, with <0.1 % of hydraulic gradient (Fig. 3).

Hydrochemical

The hydrochemical condition of river water and groundwater were presented by temperature, total dissolved solids (TDS), and pH measurements on river water and groundwater (Fig. 4a–d). Generally, we could see a similar fluctuation pattern on all parameters that suggested the similarity of river water and groundwater. River water temperatures were commonly higher than groundwater as they were directly exposed to sunlight. The differences between both waters were in the range 0.1–3.8 °C. As for groundwater, the temperatures were lower than air temperature with differences varying between 2.8 and 6.7 °C. Such large deviation leads to the possibility of deep and shallow groundwater mixing, since there were some deep wells owned by large industries along the Ciliwung stream flow.

TDS values from river water and groundwater showed high similarity of effluent and perched zone, which were located near upstream. The similarity supported the hypothesis of close connection between both water bodies. Local garbage disposal sites, located at the riverbank, caused small TDS spikes at Cibubur and UI area. The values then increased and differentiated towards downstream, in the influent zone, as an indication of higher contamination. TDS of groundwater were lower than river water in this zone as a result of active aquifer filtration as buffer zone (Table 2). This strip of land between river streams and riverbank acts as a filter to reduce soluble nutrients (at certain level). It works with two main mechanisms: vegetation uptakes and denitrification. However, it

takes more water quality parameters to determine how effectively the buffer zone in this area, such as nitrates, lithium, boron, ammonium, and iron. The TDS spikes are also followed by pH fluctuations. Several pH peaks are related to the occurrence of high SO_4 in several points in the downstream segment.

A close connection between river water and groundwater was also indicated by a piper plot diagram (Fig. 5), which showed magnesium-bicarbonate classification for both river water and groundwater. However, there are visible chemical evolutions in the chemical composition: from Mg to Na+K in cation side and from neutral to $\text{HCO}_3 + \text{CO}_3$ on the anion side. Such chemical evolution occurs from upstream (effluent zone) to downstream (influent zone). Several anomalous Cl and SO_4 values were spotted as a result from riverside garbage dumping sites and nearby industries.

Conclusion

Understanding the catchment-scale patterns of groundwater and stream salinity is important in land and water quality management. The result clearly shows that the spatial variability of groundwater chemistry in emergent springs and seeps along the Ciliwung stream is highly variable and complex at localized scales. At smaller scales, flow path depth variations, reaction kinetics, and water residence times probably interact to explain local variability.

We found three water relationships between river and groundwater at Ciliwung River stream, based on water

Fig. 4 **a** Chart of groundwater and river water temperature profile from upstream to downstream (explanation: *green* Segment 1, *red* Segment 2, *black* Segment 3). **b** Chart of groundwater and river water TDS profile from upstream to downstream (explanation: *green* Segment 1, *red* Segment 2, *black* Segment 3). **c** Chart of TDS correlation between groundwater and river water (explanation: *green* Segment 1, *red* Segment 2, *black* Segment 3). **d** Chart of groundwater and river water pH profile from upstream to downstream (explanation: *green* Segment 1, *red* Segment 2, *black* Segment 3)

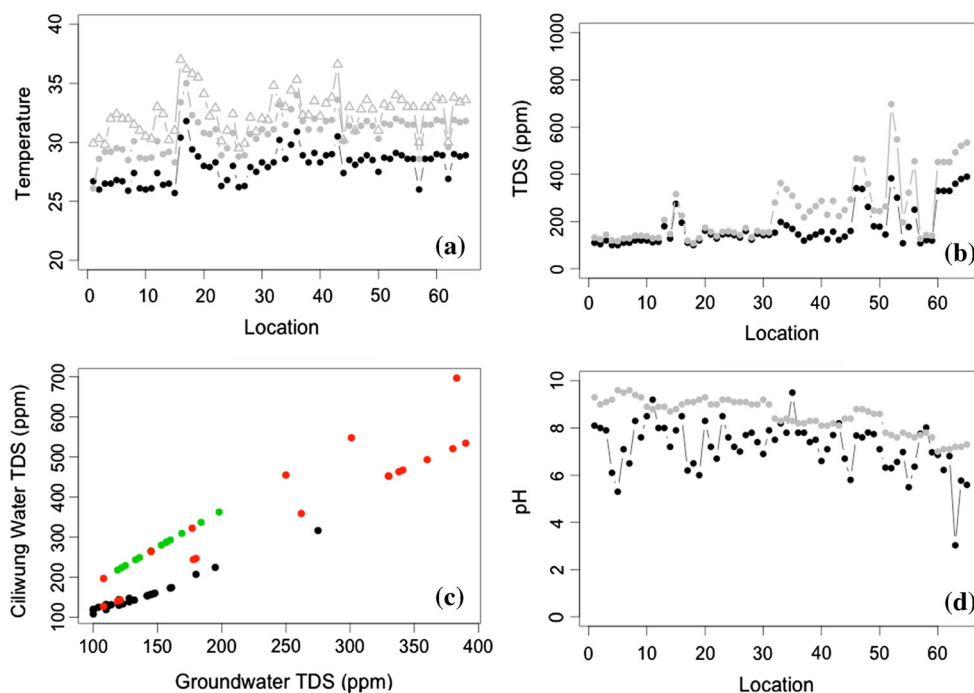


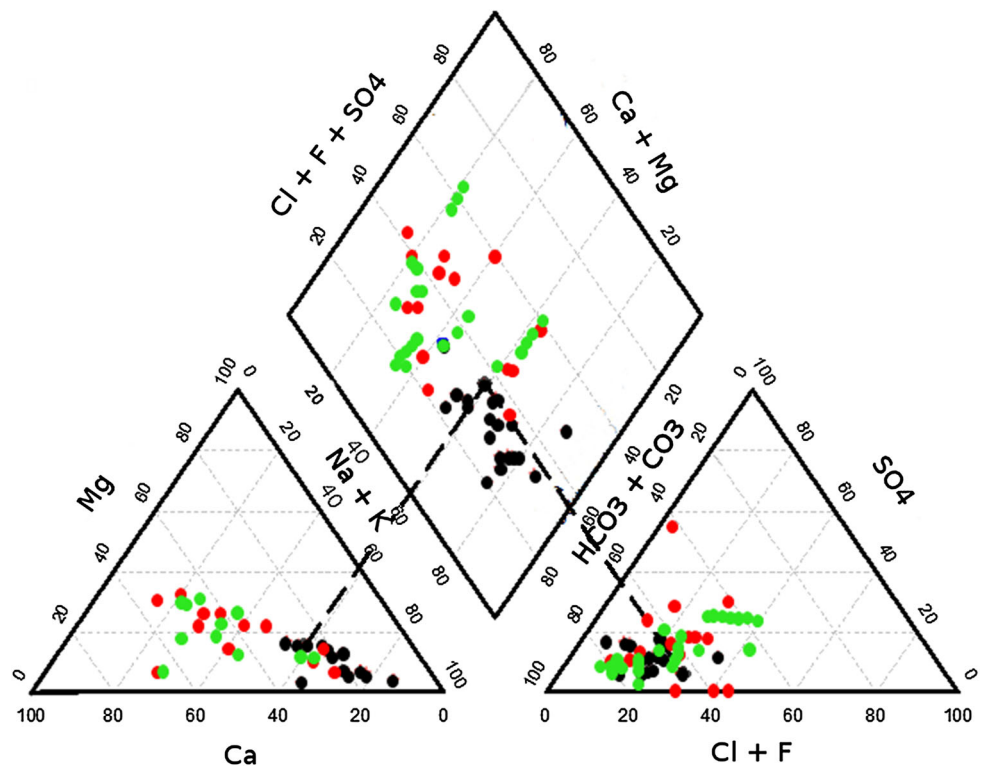
Table 2 TDS profile perpendicular to the river flow direction

Location	Groundwater TDS (ppm) at measured distance from the river to the left bank					River water TDS (ppm)	Groundwater TDS (ppm) at measured distance from the river to the right bank				
	45 m	35	25 m	15 m	5 m		5 m	15 m	25 m	35 m	45 m
Segment 1	80	80	82	82	82	120	81	81	82	82	82
Segment 2	71	71	71	72	72	120	71	72	71	72	70
Segment 3	95	112	117	117	120	144	110	104	80	78	70

Segment	TDS at distance (m) from the river stream to the west riverbank						TDS at river stream
	−45	−35	−25	−15	−5	0	
1	80	80	82	82	82	82	120
2	71	71	71	71	72	72	120
3	95	112	117	117	120	120	144

TDS at distance (m) from the river stream to the east riverbank					
5	15	25	35	45	
81	81	82	82	82	
71	72	71	72	70	
110	104	80	78	70	

Fig. 5 Piper plot of hydrochemical data (explanation: green Segment 1, red Segment 2, black Segment 3)



level maps. Each segment shows local variation of river and groundwater interaction. Groundwater flow net presented in this paper will be the preliminary result to build the groundwater model. Variation of water relations was also reflected in the water quality. The TDS were low at

Segment 1 and 2. Low conductivity indicates low contamination at both segments. Nevertheless, the complete tests of the water samples have to be taken to determine its usability as drinking water. More detailed research on heavy metal concentration, such as Br, in water is needed

to understand the interference of water quality. TDS values increase as the water comes to the downstream segment. Measurements at Segment 3 show TDS fluctuation with high deviation. This condition indicates the higher water pollution of river water and groundwater.

This research illustrates the degradation of river water and groundwater quality in one particular river stream. The degradation is much higher with the growth of settlements and industries along the riverbank. This research also points out that when it comes to water quality, one must not make a distinction between surface water and groundwater, especially unconfined groundwater.

Conceptual model that has been developed is a real example of the interaction between groundwater and river water. The interaction is potential to trigger quality exchange between both water bodies. Hence, we have more scientific basis of integrated water management. A similar study should also be done with many rivers, which flow through big cities in Indonesia, such as Surabaya, Medan, Makassar, etc. Sufficient knowledge on this matter will contribute to the selection of appropriate conservation measures. Adequate datalogger monitoring on water level and water quality may trigger more analysis to explain water behaviour.

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