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THE EFFECT OF ENVIRONMENTAL CHARACTERISTICS ON THE QUALITY OF WATER IN THE BASIN CAPLINA - TACNA (PERU)

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ABSTRACT

In this paper an attempt is made to explain the water quality in the Caplina Basin, considering the main components of geology, environmental setting, hydrology and geomorphology. By geomorphological and geological analysis of the Caplina Basin three geomorphological units were identified, such as the western Cordillera, Puna and Dissected Flank. A few of very inclined slopes in the western mountain range that belong to the Barroso Group that are composed of andesitic and traquiandesitic lavas with intercalations, plus availability of pyroclastic dacites with some zones of alteration also affect the water quality. According to the water monitoring results by the Autoridad Nacional del Agua (ANA), the water has acidic pH value and the presence of iron and aluminium are above the Estándares de Calidad Ambiental (ECA) for category 3. In the geomorphological Puna Unit geological formations constituted by andesitic breccias, tobas daciticas, and andesitic lavas that are altered are indentified. The geothermal spring in the Aruma and Paralocos valley also has elements identified such as arsenic, iron, boron, sodium, aluminium, lead and other elements that are above the NEQ for category 3 predominate. In the geomorphological Dissected Flank Unit, geological formations are composed of andesites and other volcanic rocks and the intrusive Challaviento Unit formed by granodiorites and monzodioriticas, where the water pH is 3.71 (acidic), and predominant arsenic, iron and manganese are located. For this, maps such as geomorphological, geological, slopes, location of water quality monitoring points and maps of areas with the greatest influence on water quality are elaborated

Keywords: Environmental characterization; geology; water quality.

1 INTRODUCTION

A recurring case is to conduct studies on river basin for the purpose of utilizing water resources for different uses. In Tacna there is a water shortage and the demand for its use is wide, which is why it is necessary to carry out different types of studies. Water quality is very important since this parameter restricts its use and it is related to the geological influence that houses it. The interaction of the water cycle where ocean water evaporates and these clouds are carried by the winds to the Cordillera, condensed and later precipitated by the difference of atmospheric pressure and temperature changes. Returning to the issue of water quality resulting in the outflow of a basin where it depends on the geology, geomorphology and the variation of the climate in that basin (Chapman and Kimstach, 1996).

The hydrothermal vents produced by tectonic activity also make a notable influence on the contribution of contaminants such as arsenic, iron, boron, aluminum, etc. to the course of the Caplina River. Precipitating rain on different lithofacies, give rise to water with erosive attack power that acts on the rocks and sediments which produces erosion and this erosion are transported along the riverbed. In this course, the phenomenon of dissolution occurs (Meybeck et al., 1996). That is, the elements that make up the sediments are combined with water and a new product emerges resulting in a certain quality of water. Therefore, to study this type of phenomenon a triple analysis is done, in which the main components such as precipitation, geology and process response are considered (Appelo and Postma, 1993). The study area is located in southern Peru, in the districts of Pachia and Palca of Tacna region (Figure 1).

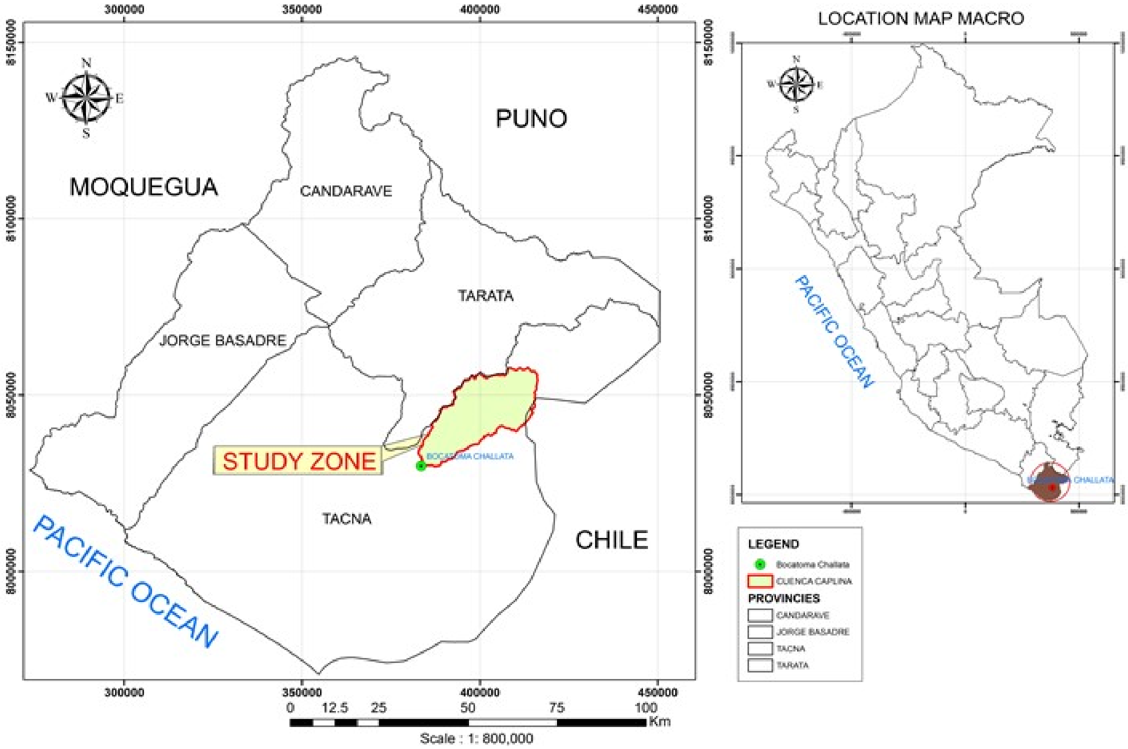

Figure 1. Location map of the study area.

2 METHODOLOGY

In the first place, the historical reference of work done in the study area was reviewed, as well as the revision of geological, hydrological, satellite images, topographic surveys and water quality data and etc. It also includes research activities carried out in the workplace, other research centers and specialized libraries. Subsequently the field work was carried out, where the evaluation of geomorphology, structural geology, geology and hydrology was carried out, followed by the processing of the information collected or raised in the field to develop the models and the correlations of the case. For their respective interpretation, verification of inventories of water sources and measurement of parameters in situ were done with regard to water quality.

3 RESULT EVALUATIONS

In the present study, the area is distributed in the following geomorphological units: Western Cordillera 14%, Puna 25% and Andean Dissection Flank 61% (Figure 2). These geomorphological units have been generated by subduction processes of the Nazca Plate with the Proterozoic basement of the Arequipa Massive (Ramos, 2008; Cobbing and Pitcher, 1972) and covering formations, like the Yura and Toquepala Groups (Sempere et al., 2004). The relief here is that the area is considered as one of the most relevant components to the weathering of rocks besides of the semi-desert climate. The precipitations that occur in the upper part of the basin run through the following creeks: Pisculllane, Aruma, Ancoma, Toquela, Caplina Alta and the main head of the Caplina River and other creeks that contribute to the main river.

The geomorphological Cordillera Unit present slopes that exceed 25° so that the rainwater occurring in summer times circulate in higher percentage by surface runoff eroding the andesitic rocks of the Barroso group through the Piscullane creek. The water transports the hydrothermal alterated andesitic sediments. The andesitic rocks in this geomorphological unit constitute 60% of the area and the rest is formed by trachyte of the volcanic domes. The pH of the water is 4.2 (acidic) and its calcium, iron and manganese concentrations are 241.3, 12.1, 1.18 mg/l, respectively.

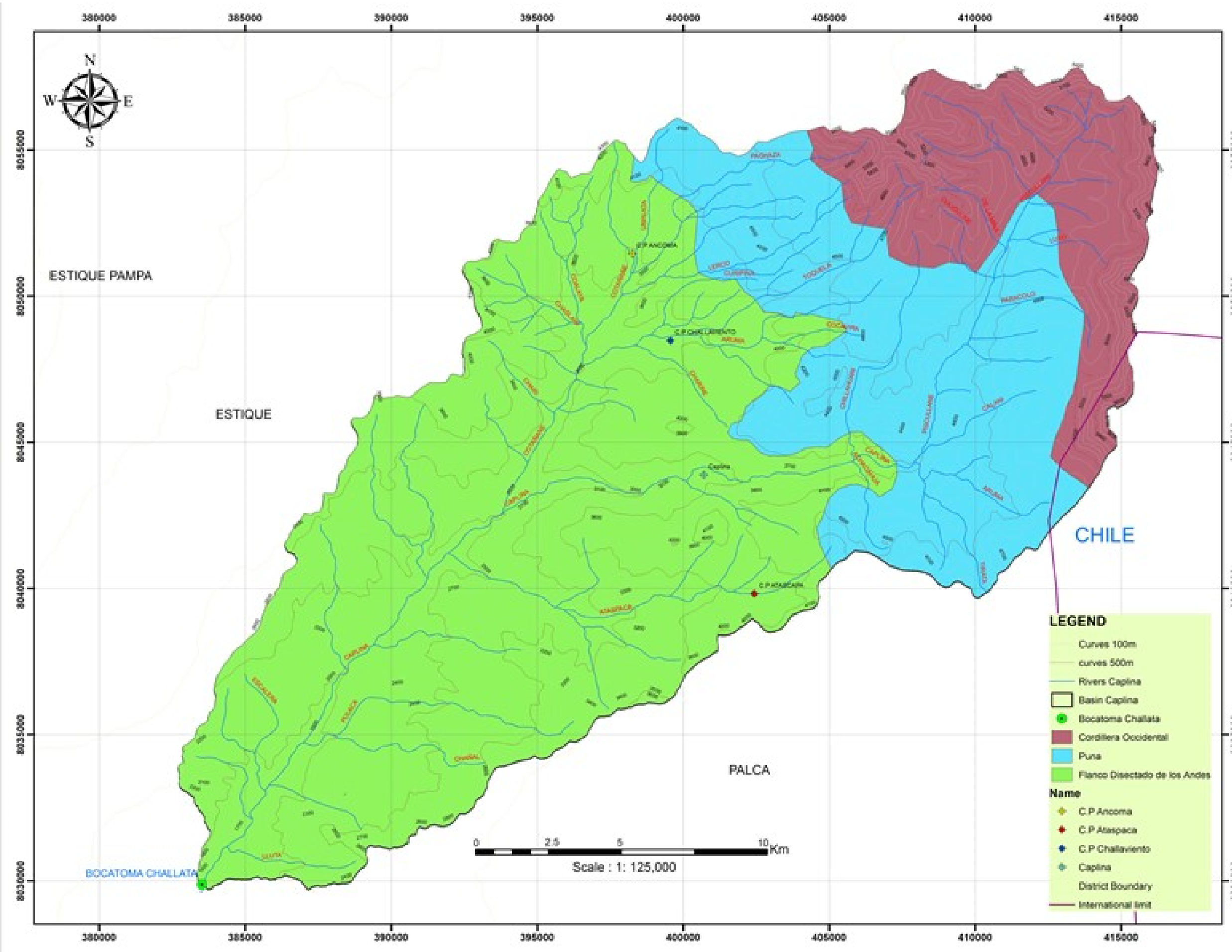

Figure 2. Map of geomorphological units of the Caplina basin.

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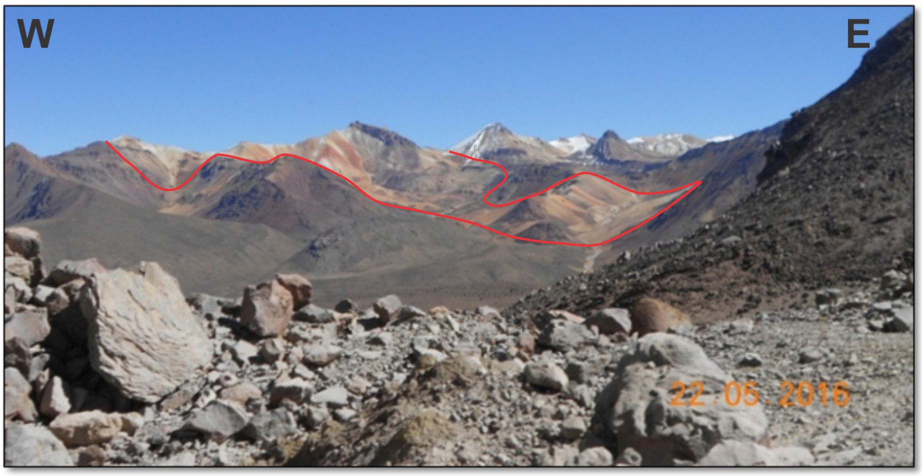

Figure 3. Reddish orange alteration zone in the Barroso group emerging in the area of Piscullane Valley.

After the runoff by the geomorphological Cordillera Unit, they enter the geomorphological Puna Unit, where the flow decreases its velocity and presents a flat and undulating morphology with shallow valleys eroded by the Pachaza, Toquela, Chillihuani and Piscullane rivers. Geologically, the rocks were mainly from the Barroso group and the volcanic Huilacollo constitute it. Lithological of the Barroso group, composed by andesitic rocks, intruded by subvolcanic rocks of porphyritic andesites that form domes that are directly related to the geothermal activity, which is located in the sectors of Paralocos and Aruma (Figure 4). Those thermal springs emanate water at high temperatures with the presence of contaminating chemical elements such as sulphur, arsenic 1.43 mg / l, iron 64.8 mg / l and acidic pH (1.84). There was also a channel for the transfer of water from the Sama basin to the Caplina basin, where the transferred water also comes from areas with geothermal activity where the predominant element is iron 324.4 mg / l.

Figure 4. Aruma geothermal spring.

In the geomorphological unit of the Dissected Flank of the Andes, due to intense tectonic activity, the waters run through beds that have high slopes. In this geomorphological unit, the precipitations was up to 3500 meters above sea level, reaching values between 70 and 150 mm/year, which can produce surface runoff and debris flows, due to the slope inclination and the availability of altered material. In very humid years, precipitation reaches up to 300mm/year. In the intake of Challata, the concentration of arsenic was 0.31 mg/l in dry season and 0.054 mg/l in wet seasons, the iron concentration during dry season is 124.7 mg/l and 9.54 mg/l in rain fall seasons.

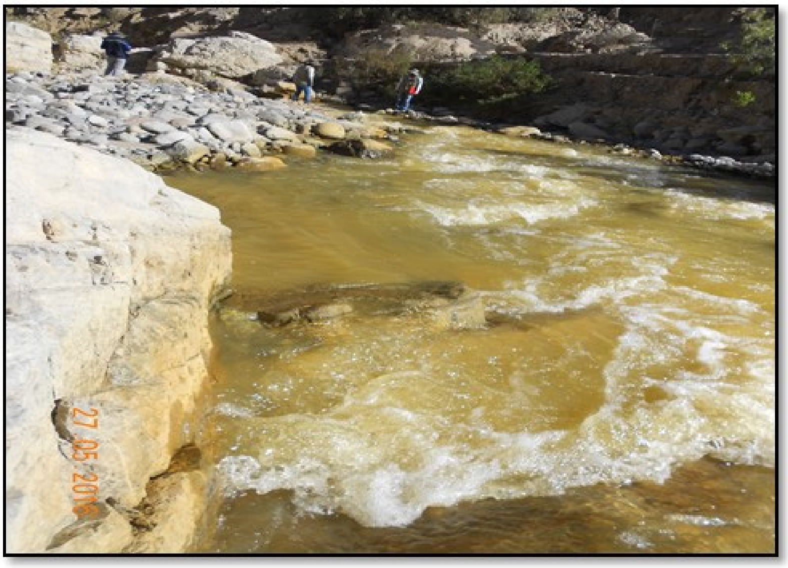

Figure 5. Water coloration due to the presence of iron and sulphur. (Upstream of the intake Challata) in the main course of the Caplina River.

4 TABLES AND GRAPHIC REPRESENTATIONS

According to the results of water quality monitoring; the concentrations of the elements varies in different seasons, as it was shown in the results of monitoring conducted in the year 2011(October), 2012 (December), due to the rainy seasons (Summer) and in April of 2014. The concentrations of arsenic, aluminium, iron and other elements decreases due to dilution and in dry seasons (winter) the concentrations of the same elements increases. This indicates that when the flow increases the concentration of the same elements decrease.

The tributary with the highest concentration of arsenic is the Aruma geothermal spring (Figure 6). Likewise, the source with the highest concentration of iron and aluminium is the Ancoma creek. The high iron content was probably due to the transferred water from the Sama basin to the Caplina basin (Figure 7 and 8).

As can be seen in Figures 8, 9 and 10, the concentrations of arsenic, iron and aluminium shows a decrease their concentration. This is because that the water quality sampling was carried out in different months of the year. Note that sampling in 2011 was on 31 October, in the dry season, which indicates that increasing concentrations of these elements occurred since the beginning of the dry season values. These values are reflected in the reports of water quality monitoring carried out by the Autoridad Nacional del Agua.

Table 1. Concentration of elements in the water during the dry season.

	ECA (Cat. 3)	Tributaries of the Caplina Basin Piscullane creek	Aruma creek	Ancoma creek	Toquela creek	Creek of Caplina 1	Creek of Caplina 3
pH	6.5 – 8.4	4.2	1.84	2.7	-	3.11	3.51
Arsenic (mg/l)	0.05	-	1.434	0.224	0.064	0.181	0.31
Iron (mg/l)	1.0	12.1	64.8	324,37	-	5.25	124.7
Aluminum (mg/l)	5.0	47.19	148.7	157.25	-	14.49	60.8

Source: Autoridad Nacional del Agua (ANA, 2012; 2014; 2016)

Table 2. Concentration of elements in the water during the rainy season.

	ECA (Cat. 3)	Tributaries of the Caplina Basin Piscullane creek	Aruma creek	Ancoma creek	Toquela creek	Creek of Caplina 1	Creek of Caplina 3
pH	6.5 – 8.4	3.71	-	2.94	8.22	3.13	3.84
Ce (µs/cm)	2 000			2 670	796.6	1 258	2 670
Arsenic (mg/l)	0.05	-	1.434	0.0102	0.027	0.122	0.0549
Iron (mg/l)	1	-	64.77	84.73	0.24	4.953	9.55
Aluminum (mg/l)	5	-	148.70	79.38	0.088	12.039	14.41

Source: Autoridad Nacional del Agua (ANA, 2012; 2014; 2016)

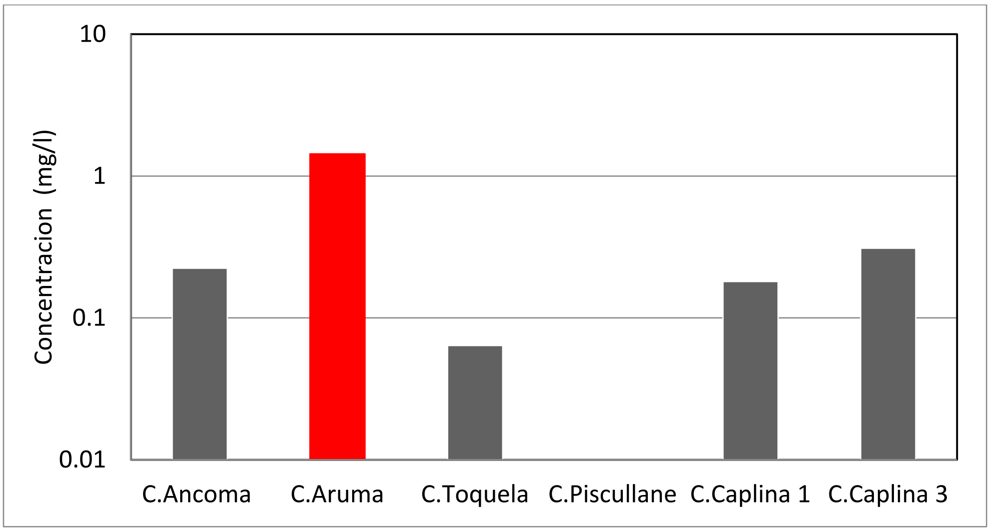

Figure 6. Arsenic concentration at Aruma geothermal spring (mg/l).

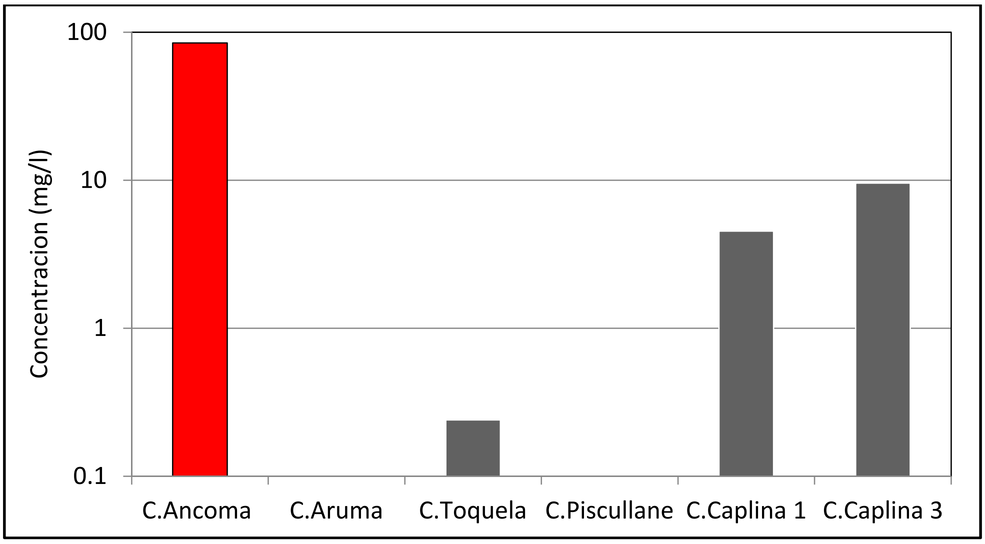

Figure 7. Iron concentration in the Ancoma Creek (mg/l).

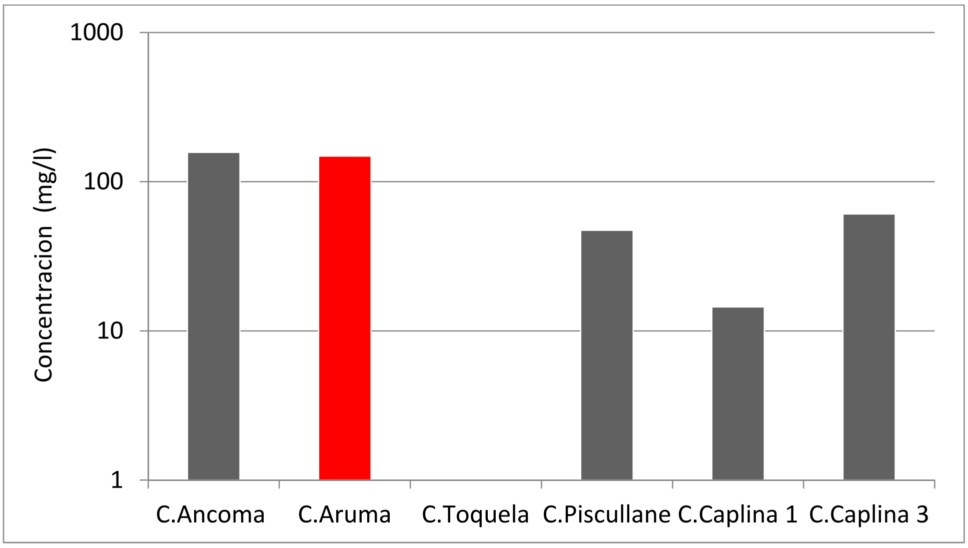

Figure 8. Concentration of aluminium at Aruma geothermal spring (mg/l).

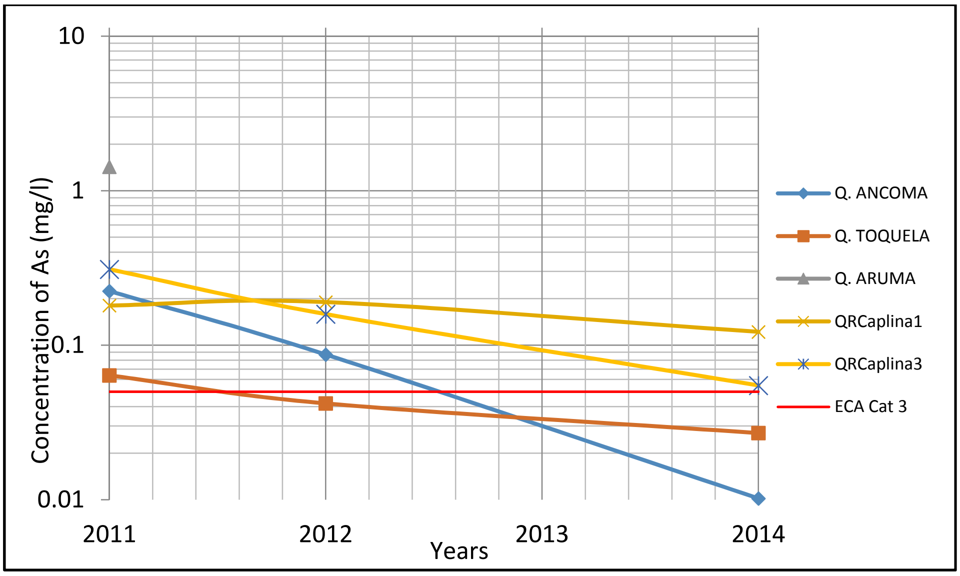

Figure 9. Arsenic concentration in different seasons of the year in tributaries of Caplina River.

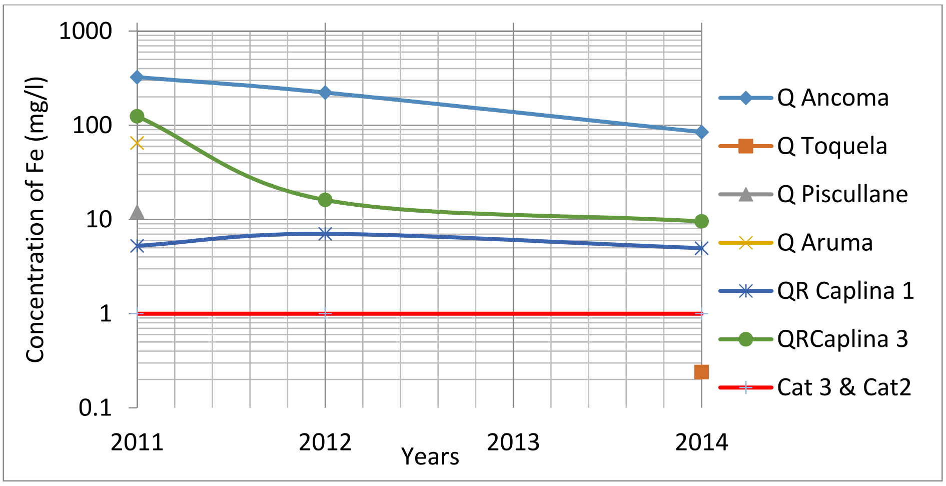

Figure 10. Iron concentration in different seasons of the year in tributaries of Caplina River.

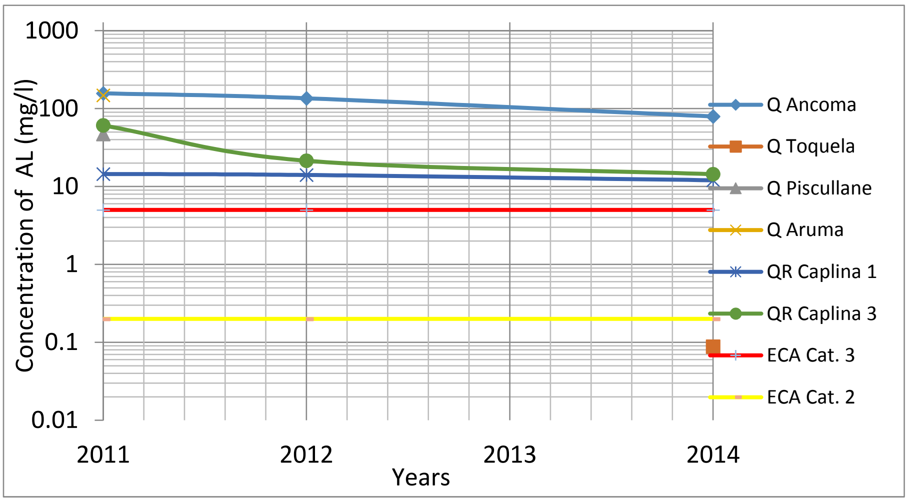

Figure 11. Aluminium concentration in different seasons of the year in tributaries of Caplina River.

Elaborating the geological map and slope map of the Caplina basin after doing the field evaluation.

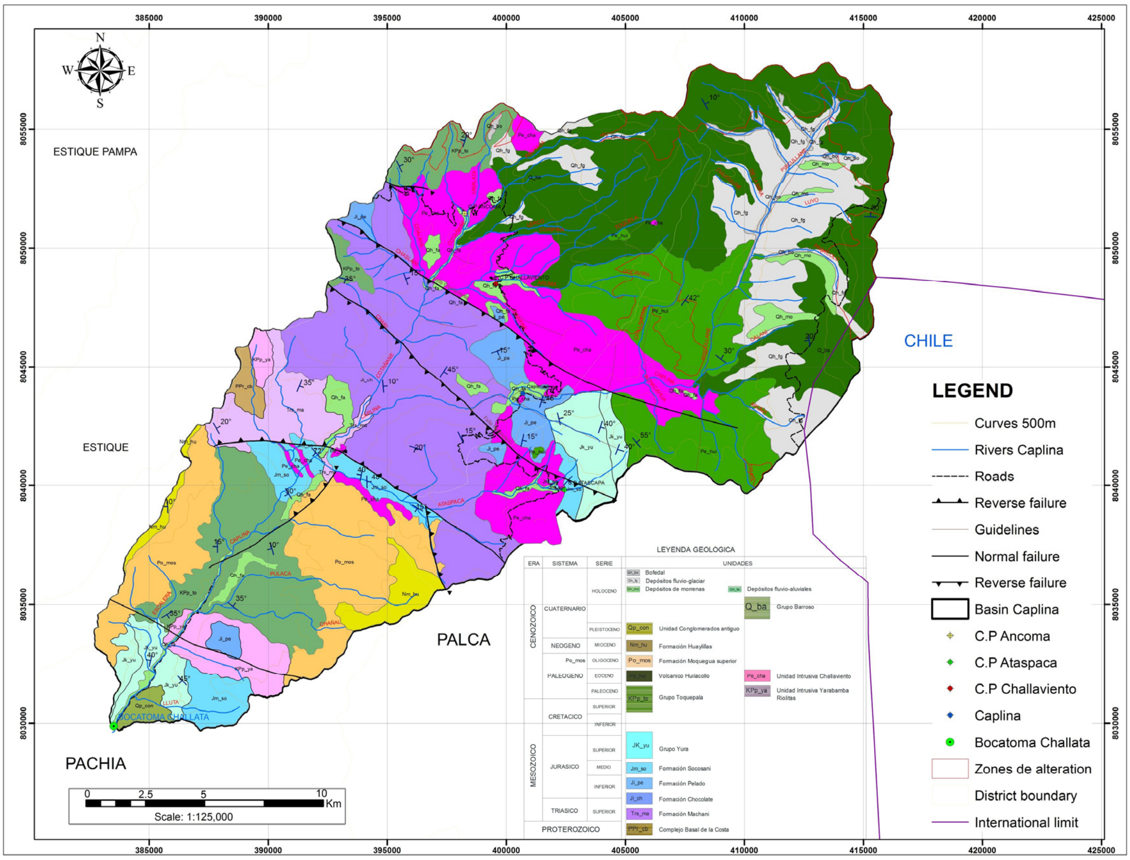

Figure 12. Geological map of the Caplina basin.

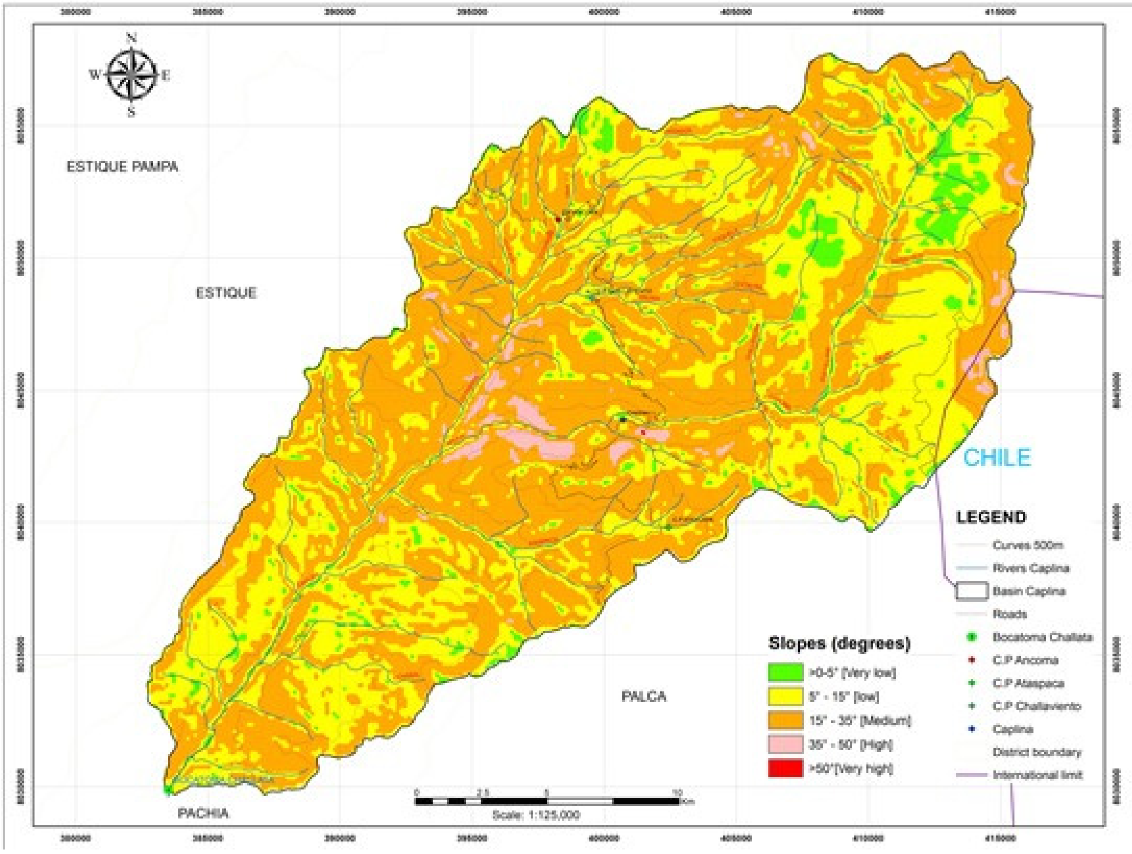

Figure 13. Map of slopes of the Caplina basin.

5 CONCLUSIONS

After respective analysis, it was possible to carry out the environmental and geological characterization, identifying three geomorphological units on which the water generated by the precipitations in the head of the Caplina basin.

Identified during the geomorphological cartography are the units of the Cordillera Occidental, Puna and the Dissected Flank of the Andes. The analysis allowed an explanation on the precipitations that occur in the summer circulate in greater percentage by surface runoff and with greater velocities in the geomorphological Cordillera Unit. The sediments produced by weathering and erosion are transported and deposited in the geomorphological Puna Unit since the present morphology plain had the flow rate decreasing and this loses transport capacity. This is where the water has more contact with the lithofacies of geological formations that are housed in this unit.

It was possible to identify the sources that have the greatest influence on water quality, which were the Aruma and Paralocos geothermal spring emanating water with high arsenic content of 1.43 mg/l. Another main source is the transfer of water from the Barroso Chico sources to the Ancoma creek, a tributary of the Caplina River. This creek has a geothermal activity where the predominant elements are iron 324.36 mg/l in dry season and 84.73 mg/l in wet seasons, arsenic 0.22 mg/l in dry season and 0.010 mg/l in wet seasons.

The interrelationships between geology, climate and hydrology were analysed reflecting the variation of the concentration of the elements in the water during dry and wet seasons.

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INVESTIGATION OF DESIGN FLOW IN SEPARATE SEWER SYSTEMS OF KUANTAN, PAHANG

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ABSTRACT

Flow design parameters such as per capita flow and design criterion are significant in the design of sewerage systems. Malaysian sewerage systems are designed according to the Malaysian Sewerage Industry Guidelines (MSIG). Wrong consideration of flow design parameters brings negative effects in terms of construction cost, human health and environmental issues. The purpose of this research is to analyze and compare the per capita flow as well as design criterion in the sewerage systems of Kuantan, Pahang to their counterpart in the MSIG. Flowrate data was collected from two residential areas, Taman Pandan Damai and Bandar Putra with duration of 49 days. Population equivalent (PE) survey was done at the selected site locations. The resultant PE is 2244 and 1694, respectively. ISCO 4250 Area Velocity Flowmeter was used to collect real time flowrate data with intervals of five minutes. Flowrate data is analyzed separately for weekday and weekend. The average per capita flow result obtained from the sites is 0.277m^3/day/person which is 23% higher than the 0.225m^3/day/person stated in MSIG. Meanwhile, the results of average design criterion was 3.02, 36% lower than the 4.7 mentioned in MSIG. This indicated that the design of the sewerage systems in Taman Pandan Damai and Bandar Putra were effective and is more than enough to cater to the PE surveyed. More data, especially from long-term period collection, is desirable to determine whether revision of the flow design parameters in MSIG is needed.

Keywords: Peak flow factor; design criterion; separate sewer system.

1 INTRODUCTION

Sewerage system is a system composed of several sewer lines (Yap et al., 2016). Its function is to transport sanitary water from residential, industrial and commercial areas to sewerage treatment plants (Rahman et al., 2007). In Malaysia, the separate sewerage system is commonly applied. Guideline for the design of sewerage systems used in Malaysia is contained in the Malaysian Sewerage Industry Guidelines (MSIG) which incorporates the Malaysian Standard Code of Practice for Design and Installation of Sewerage Systems. A sewerage system should be designed for optimum flow (Swamee, 2001). The highest peak flow and large per capita flows need to be considered (Ridenour and Lacy, 1932). Flow design also depends on the wastewater flow contributed by the population equivalent (PE) (MSIG, 2009). The MSIG incorporates the sewer design from MS 1228:1991. However, MS 1228:1991 itself is based on British Standard BS 8005:1987 (Ngien and Ng, 2013; MS 1228:1991). BS 8005:1987 has been revised twice since it was first published, with the latest version in the form of BS EN 752:2008. The design parameters such as design criterion, peak flow factor and per capita flow should be based on the condition of climate, topography, and geography of the country (Ngien and Yap, 2017). Based on this scenario, the current sewerage system design parameters should be verified and checked for suitability in Malaysia. The objective of this research is to analyze and compare the per capita flow as well as design criterion in the sewerage systems of Kuantan, Pahang to their counterpart in the MSIG.

Literatures of similar studies that have been conducted in Malaysia are quite limited. One study that was performed at Skudai, Johor Bahru discovered that the parameters per capita flow and design criterion were 57% and 40% lower than the values stated in MS 1228:1991, respectively (Ansari et al., 2013). Another study done by Rahman et al. (2003) also points toward lower parameter values than recommended in the standard. This group of researchers (Rahman et al., 2003) also extended their study to include water inflow and infiltration parameters in the sewer pipeline. In Kuantan, a research has been conducted in the area of Gambang for five months. The results showed that the parameters investigated were also lower than those in the MS 1228:1991, which led the authors to suggest that more construction cost can be saved by adopting new design parameters (Yap and Ngien, 2015). Internationally, a study was conducted to investigate a small sewerage catchment in Cairo, Egypt where the peak flow factors were estimated and compared using three different methods. The authors mentioned that different plant components should be designed according to their critical peak condition (Iman and Elnakar, 2013).

1.1 Principle of design flow

Flow design parameters such as per capita flow and design criterion are significant in the design of sewerage systems (Zhang et al., 2005). Wrong consideration of flow design parameters may bring negative effects in terms of construction cost, human health and environmental issues (Ngien and Yap, 2017). The value of per capita flow and design criterion are determined through the following equations that are provided in the MSIG. Per capita flow, Q_{pcf} can be calculated by using Eq. [1],

$$Q_{pcf} = \frac{Q_{ave}}{PE} \quad [1]$$

Where Q_{pcf} has a unit of m^3/day/person. Q_{ave} means average daily flow in the sewer line with unit of m^3/day, and PE is population equivalent and has no unit. Eq. [2]. shows the calculation of peak flow in sewer pipelines (Yap and Ngien, 2015),

$$Q_{peak} = PFF \; x \; Q_{ave} \quad [2]$$

Where Q_{peak} stands for daily peak flow with a unit of m^3/day, while PFF refers to the peak flow factor that is unitless. Based on MSIG, the PFF can be calculated using Eq. [3],

$$PFF = k \left(\frac{PE}{1000}\right)^{-0.11} \quad [3]$$

Where k is known as the design criterion with a value of 4.7. It can be calculated by using Eq. [4], which is a combination of Eq. [2] and Eq. [3].

$$k = \frac{Q_{peak}}{(Q_{ave})\left(\frac{PE}{1000}\right)^{-0.11}} \quad [4]$$

As mentioned in MSIG, the design criterion$k$, is prescribed with the value 4.7 in Clause 21.1.14.II. Meanwhile, per capita flow Q_{pcf} is stated as 0.225 m^3/day/person in Clause 2.1.14.I. To accomplish the research objective, these parameters were studied at the study locations.

2 METHODOLOGY

2.1 Site review

This study requires fieldwork at residential areas in Kuantan, Pahang. Collaboration was set up with Indah Water Konsortium Sdn. Bhd. (IWK). IWK is the sole national sewerage company in Malaysia. There are few site locations that had been monitored in this research, but two residential areas were discussed in this paper, Taman Pandan Damai and Bandar Putra. The criterion for the selection of sewer line to be studied was that the manhole has to be the last manhole before the sewerage treatment plant in order to capture the sewage flow from the whole residential area. Thus, critical flow can be determined. Moreover, the condition of manhole must be clean enough, thus the reading would not be affected by obstacles. The manholes were selected at Taman Pandan Damai and Bandar Putra was MHk and MH92b, respectively. Population equivalent survey was done in those areas. The result of the surveys showed that Taman Pandan Damai, and Bandar Putra have PE of 2244, and 1694, respectively.

2.2 Equipment and material used

Ultrasonic technology that adopts the Doppler Effect was used in this research. ISCO 4250 Area Velocity Flowmeter attached to a Low Profile Sensor was installed in the selected manhole at site locations. Before the installation, flowmeter calibration was done at the Hydraulic and Hydrology Laboratory at University Malaysia Pahang (UMP). The results of the flowmeter calibration were incorporated into the analysis section. The flowmeter functioned to collect data in terms of flowrate, velocity as well as water depth of the sewage water in the sewer pipeline at intervals of five minutes. Five minutes of interval data collection is more precise compared to more than 30 minutes (Yap et al., 2016). The condition of sewer flow in sewer pipeline and weather are unexpected. The interval of time being smaller is more valuable to this study. Flowlink software version 5.1 was adopted to retrieve and analyze data from the flowmeter.

3 RESULTS AND DISCUSSIONS

This research was conducted for 49 days and the data was separated into weekdays, weekends and both for the analysis. Table 1 presents the details of the monitored site locations. Data collected at Taman Pandan Damai was divided into three sets from 25 November 2015 to 11 December 2015. The data collected at Bandar Putra was divided into five sets with the period investigated from 11 March 2016 to 8 April 2016.

Table 1. Information summary of the site locations.

Site Location	Data Set	Monitoring Period	Weekday/Weekend
Taman Pandan Damai (PE: 2244)	MHk-01	26 Nov 2015 - 3 Dec 2015	Both
	MHk-02	5 Dec 2015 - 6 Dec 2015	Weekend
	MHk-03	7 Dec 2015 - 11 Dec 2015	Weekday
Bandar Putra (PE: 1694)	MH92b-01	11 Mar 2016 - 13 Mar 2016	Both
	MH92b-02	14 Mar 2016 - 20 Mar 2016	Both
	MH92b-03	21 Mar 2016 - 23 Mar 2016	Both
	MH92b-04	31 Mar 2016 - 3 Apr 2016	Both
	MH92b-05	4 Apr 2016 - 8 Apr 2016	Weekday

3.1 Per capita flow, Q_{pcf}

In this study, Q_{pcf} was calculated by using the average daily flow obtained from the sites divided by the PE surveyed in the area, as displayed in Eq. [1] previously. Table 2 shows the calculated results of Q_{pcf} for each data set and each site.

Table 2. Tabulated data of Q_{pcf}.

Site Locations	Data Set	Average daily flow, Q_{ave} (m^3/d)	Per capita flow, Q_{pcf} ($m^3/d/person$)
Taman Pandan Damai (PE: 2244)	MHk-01	405.75	0.181
	MHk-02	749.00	0.334
	MHk-03	603.97	0.269
Bandar Putra (PE: 1694)	MH92b-01	547.99	0.323
	MH92b-02	487.96	0.288
	MH92b-03	501.11	0.296
	MH92b-04	501.10	0.296
	MH92b-05	439.84	0.260

From Table 2, it can be seen clearly that the result of Q_{pcf} during weekend at Taman Pandan Damai was the highest with the amount of 0.334 m3/day/person compared to the data sets of MHk-01 and MHk-03. In overall, the Q_{pcf} data was measured from Taman Pandan Damai was 0.261 m3/day/person which was 16% and this was slightly higher than 0.225 m3/day/person mentioned in MSIG. Meanwhile, there was only one set of Q_{pcf} data that was lower than the value stated in MSIG and it came from data set MHk-01. By comparing weekday to weekend, the Q_{ave} was relatively higher during weekends than weekdays.

Moreover, the result of Q_{pcf} at Bandar Putra was tested and the same result as Taman Pandan Damai with higher value than value mentioned in MSIG obtained. The range of per capita flow results from the location was 0.260 m3/day/person to 0.323 m3/day/person. The overall result of Q_{pcf} was calculated at Bandar Putra with amount of 0.293 m3/day/person. This may have been due to high wastewater flow through the monitored sewer pipeline from the residents of Bandar Putra. The resultant per capita flow from both locations was calculated as 0.277 m3/day/person which is still 23% lower than 0.225 m3/day/person in the MSIG.

3.2 Design criterion, k

Peak flow and average daily flow were obtained from sites and input into Eq. [4] to get the result of k, which is the main parameter in designing a sewer line. Table 3 shows the calculation of design criterion from the monitored sites. Based on the result shown, the k obtained from field data was lower than 4.7 stated in the MSIG in all the data sets. The highest k value was found in Taman Pandan Damai at MHk-01. This could have happened due to Q_{ave} being indirectly proportional to$k$. When Q_{ave} increase, k will relatively decrease. Design criterion from data set MHk-01 was the highest among all the sets of data from both locations. The average k at Taman Pandan Damai was calculated to be 3.38. Meanwhile, the amount of average k at Bandar Putra was only 2.65 which is lower compared to Taman Pandan Damai. The resultant k calculated from all data sets from the sites was 3.02 which is 36% lower than 4.7. The sewer lines investigated in Taman Pandan Damai and Bandar Putra were effective and enough to cater to the amount of PE there.

Table 3. Design criterion calculation.

Site Locations	Data Set	Peak flow, Q_{peak} (m^3/d)	Average daily flow, Q_{ave} (m^3/d)	Design Criterion, k
Taman Pandan	MHk-01	1571.10	405.75	4.23
Damai	MHk-02	1315.96	749.00	1.92
(PE: 2244)	MHk-03	2203.29	603.97	3.99
Bandar Putra	MH92b-01	1242.09	547.99	2.40
(PE: 1694)	MH92b-02	1142.29	487.96	2.48
	MH92b-03	1036.20	501.11	2.19
	MH92b-04	1410.74	501.10	2.98
	MH92b-05	1333.50	439.84	3.21

3.3 Flow pattern

Flow pattern of the three different site locations were investigated. Figure 1 shows the average flow, maximum flow and minimum flow analyzed in a day at Taman Pandan Damai. Based on Figure 1, it can be seen clearly the amount of daily flowrate at early of the day from period of 4am to 9am morning is higher compared to the end of the day from period of 9am to 12am midnight at Taman Panda Damai. However, there is another peak flow that occurred at 11.50am. This may happen and it does not rule out the high amount of rainfall that occurred and inflow to sewer pipeline at the time during the investigated period.

Figure 2 shows the daily flow pattern in Bandar Putra from 11 March 2016 to 8 April 2016. It can be seen clearly the peak flow happened at 5.20am morning. The peak flow in between the period from 5am to 9am was high compared to over the entire period. The high volume of sewage flow was detected in monitored manhole. This may happened due to residents preparing to go to work or school at the period, thus higher amount of wastewater was detected. It does not rule out the high amount of rainfall involved, because the peak flow was too high over the period. Another peak occurred during the period from 6pm to 8pm evening. This may happened due to residents coming back from work or school where sanitary activities were done.

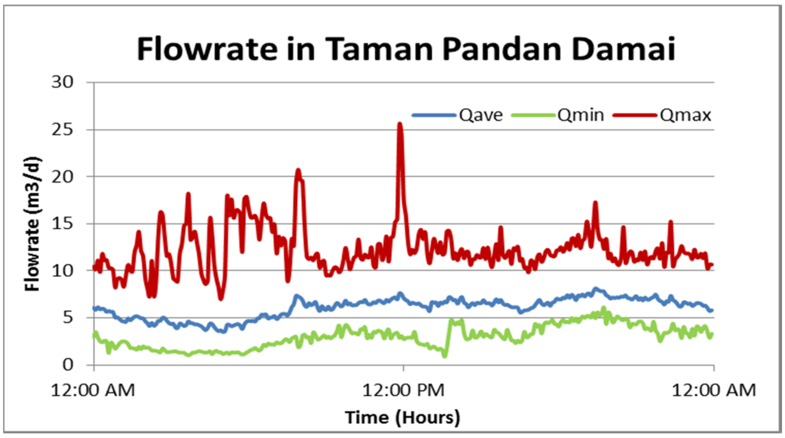

Figure 1. Daily flowrate in Taman Pandan Damai.

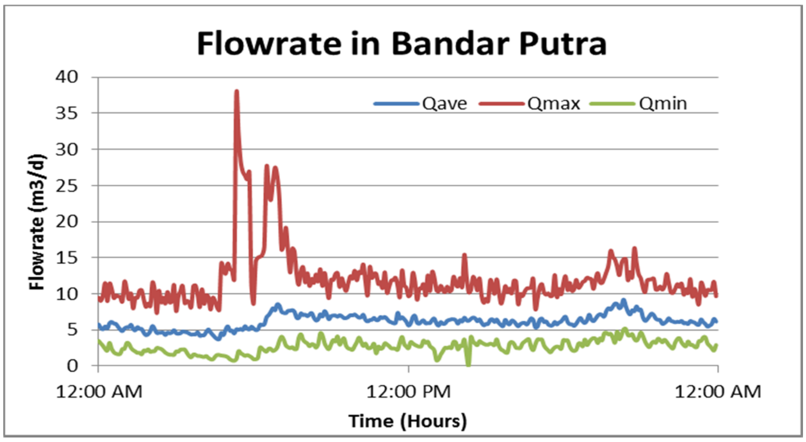

Figure 2. Daily flowrate in Bandar Putra.

4 CONCLUSIONS

The present study was designed to determine and compare the per capita flow as well as design criterion in the sewerage systems of Kuantan, Pahang to their counterpart in the MSIG. The objective was achieved. The overall average per capital flow, Q_{pcf} in this study is measured at 0.277 m^3/day/person, which is 23% higher than the 0.225 m^3/d/person stated in MSIG. Meanwhile, the resultant design criterion, k obtained from this study was 3.02, 36% lower than 4.7. This study has found that generally the sewer lines in the areas studied are sufficient to cater to the PE of those sites. Sanitary flow in sewer line is unpredictable, hence long term period investigations are necessary, with added input such as real time rainfall intensity data.

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HYDROLOGIC PERFORMANCE OF A BIORETENTION BASIN AFFECTED BY GROUNDWATER INTRUSION

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ABSTRACT

Bioretention basins, at-source control structural elements for stormflow control and water quality improvement, have become common Best Management Practices in Water Sensitive Urban Design for stormwater management. New urbanization in Perth, Western Australia (WA) occurs in areas prone to perched groundwater capable of intersecting bioretention systems during the rainy season and its impact on the hydrologic performance and nutrient removal capacity of structural elements is unknown. This work presents results of an intensive monitoring program aimed to assess the hydrologic performances of a 0.35 m depth - 370 m^3 capacity bioretention basin affected by high groundwater. Continuous records of hydrometric and passive tracer (electrical conductivity) data at inflow, surface water storage, and outflow stations were collected for a year in 2015 to quantify the water balance and to identify the timing of the groundwater intrusion and its effect on the hydrologic performance of the bioretention basin. Results from hydrometric and the passive tracer data indicated that groundwater interactions impacted the performance for a period of 50 days from mid-August to late-September affecting volume control and to a less extend peak flow reduction. The bioretention basin achieved outflow/inflow volumetric ratio (%) of 17% and 44% for small and minor rain events in absence of groundwater interactions but increased to 73% (27% reduction) when groundwater intercepted the underdrain outflow pipes. Hydrologic performance for peak flow reduction was achieved at 98% for small events and 74% and 79% for minor events with and without groundwater interactions, respectively. A transition stage in the bioretention basin functioning was identified from the interplay of inflow peaks, groundwater dynamics and water losses (exfiltration). The study showed and concluded on the need to properly identify groundwater interactions and their implications on nutrient loading and removal assessment that are often neglected.

Keywords: Stormwater treatment; bioretention basin; hydrologic performance; groundwater interactions; water quality.

1 INTRODUCTION

Bioretention systems, at-source control structural elements for stormflow control and water quality improvement have become common Best Management Practices in Water Sensitive Urban Design (WSUD) and Low Impact Development (LID) practices for stormwater management. Initially designed to promote natural hydrology via reduction of peak flow and runoff volume control, their usage was expanded to tackle pollutant removal through adsorption, filtration, sedimentation and biological decomposition and pant uptake processes.

Extensive research conducted since the 1990s has led to design improvement (Davis et al., 2009; Roy-Poirier et al., 2010) and guidelines to assist practitioners on their applications and adoption (Payne et al., 2015). High hydrologic performance, based on the reduction from inflow to outflow, has been reported in the literature varying from 40% to 97% upon rainfall characteristics and physical aspects of the design (Davis et al., 2009; Roy-Poirier et al., 2010). Peak flow reduction and significant increases in the time to peak for outflows have also been reported, mimicking pre-development hydrology characteristics (Hunt et al., 2006; Davis et al., 2009). Some research questions remain outstanding on how hydrologic performance of bioretention systems is impacted by some aspects of the physical design, seasonality in hydrological inputs and the specific metric for assessment (Ahiablame et al., 2012). Although fill media depth (Brown and Hunt, 2011) and media underdrain outflow (Davis et al., 2012) have been identified as important factors in adding complexity in hydraulic functioning of the bioretention system outflows, the seasonality in climatic forcing (i.e. rainfall and evaporation) has been shown to impact hydrological performance, as exfiltration to surrounding soils was decreased by higher water tables and increased outflows (Hunt et al., 2006).

New metrics to quantify hydrological performance of bioretention systems, that account for internal processes and thresholds, are needed to assess long term performance and allow site intercomparisons (Agiablame et al., 2012). For example, traditional volume reduction metrics such as ratio of outflow to inflow

(Davis et al., 2009) or its variation such the 24-hr outflow to inflow ratio (Davis, 2008; Olszewski and Davis, 2013) would be misleading if an additional source of water (i.e. groundwater) contributed to the outflow during a rainfall event (e.g. via sub-soil drains into the bioretention basin). This is also true for pollutant removal as the perched groundwater will have a different chemical composition to the inflow runoff. Field scale experiments specifically tailored to provide data for the above questions are rarely reported.

New urbanization in the Perth Coastal Plain in Western Australia is occurring in areas where high groundwater (< 4 m depth) results from a combination of seasonal rainfall inputs and sandy-duplex soils (sand over a clay layer). New housing developments comply with regulations for stormflow control and water quality targets by means of at-source control structural elements. Retention basins initially used for stormflow control in the 1990s gave way to re-engineered bioretention basins following principles of WSUD design (DoW, 2004). New bioretention basins in areas with high groundwater are characterized by shallow depth and large surface area storage basins (30 cm depth, 300-1500 m^2 plan area) and shallow fill depth (~0.5 m) with sub-surface drains acting as the main outflow mechanism. The potential for interaction with high groundwater has been reported at both event and seasonal time scales (Appleyard, 1993) and would have implication for hydrologic and pollutant removal efficiency. This work presents results from a field scale investigation aimed at documenting the timing of groundwater interference and its impact on the hydrologic performance of a bioretention basin in Perth, Western Australia. The work address the following questions: Does the hydrologic performance of the bioretention basin change at seasonal scales? How does groundwater interaction influence the bioretention outflow? What are the implications for pollutant load and removal efficiency metrics?

2 STUDY SITE

The study site was within The Glades development, a residential area in Byford approximately 35 km south-east of Perth, Western Australia (Figure 1a). Located at the foothills of the Darling Scarp, the topography of the area presents gentle to very-gentle slopes (4 to 1.5 %) towards the west following the drainage network of tributaries and streams of the Peel-Harvey Estuary. The natural soil consists of sands overlying clay and hardpan layers (duplex soils) ranging in depth from 0.6 to 1.8 m. The area experiences a Mediterranean climate characterised by dry hot summers and wet winter seasons with average annual rainfall of 859 mm and pan evaporation of 1800 mm (period 1970-2012, Bureau of Meteorology (BOM), Cardup station 009137). Approximately 90% of the annual rainfall falls between May and October when evaporation is at the lowest. A seasonally perched water table (at depth of < 3m) develops as a result of the soil setting and rainfall characteristics (low intensity-highly seasonal), with the regional (deeper) water table typically rising over winter but remaining below the perched water table in below-average rainfall years (JDA, 2009).

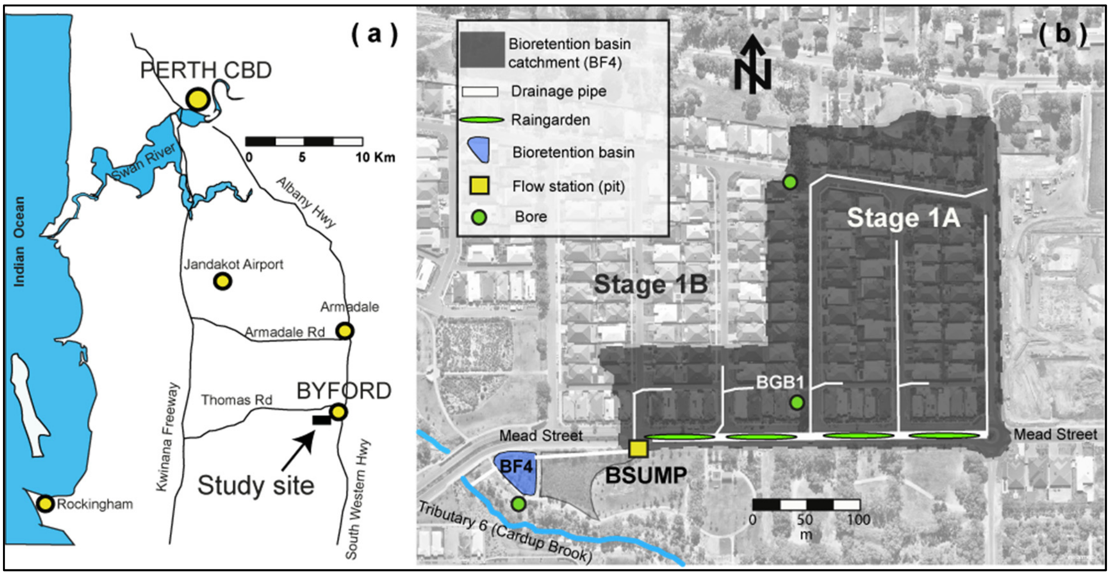

Figure 1. Study site area and bioretention basin location: a) Location of Byford area and b) The Glades Stage 1 (A and B) and bioretention basin (BF4) location on the treatment train.

To meet development requirements at the site, approximately 0.8 m of fine-sand fill was applied and a subsoil drainage system installed (at a depth of 1.2 m below ground level) to protect infrastructure from the high groundwater. Building construction began in 2009, with Stage 1A (Figure 1b) and surrounding green space areas comprising 8.7 hectares (4.9 ha building lots, 2.4 ha roads and 1.4 ha of public open spaces). The directly connected impervious area (roads, driveways and paths) has an average slope of 0.035 m/m and stormflow is collected by a piped network (Ø 0.225 m) and discharged into a 0.9 m diameter piped main drain at Mead Street (Figure 1b). A series of median strip raingardens along Mead Street also collects surface runoff from adjacent roads and discharged treated runoff into the main drain. All runoff from Stage 1A is directed into the bioretention basin (see BF4 in Figure 1b) at the end of the catchment before discharging into a surface water tributary.

The bioretention basin meets the most relevant local design guidelines at the time of construction (DoW, 2004) and it was sized to treat a 1 year-1-hour Average Recurrence Interval (ARI) event (16.9 mm hr^{-1}). The basin's physical dimensions are 0.3 m depth, maximum surface area of 1200 m^2 and with a 370 m^3 volume capacity for the 1-yr ARI event (Figure 2a). A homogenous layer of amended soil (locally known as red Gingin loam) was used as fill media. The media depth is 0.5 m with a saturated hydraulic conductivity (Ks) of 6 m/day. The bioretention basin was five years old during monitoring and had well-established, mature vegetation. Native plants (*Melaluca lateritia, Juncus pallidus, Ficinia nodosa, Eucalyptus rudis)* were used in the basin to promote nutrient uptake and improve amenity.

Stormwater inflow to the bioretention basin is via two pipes (Ø 300 mm, 40 m long) connecting the main pit of the catchment outlet (BF4IN-BSUMP) to the BF4 basin (Figure 2a). For rainfall events in excess of the design capacity, stormwater is directed (via an overflow structure) into the adjacent public open space that serves as a high flow detention basin (up to 100-year ARI event). Outflow from the bioretention basin occurs via a series of subsurface slotted pipes (underdrain at the bottom of the fill media) that collects treated stormwater (as it infiltrates through the fill media) and groundwater (as it reaches the underdrain) and convey them to a manhole, prior to final discharge into Tributary 6 via a concrete pipe (Ø 300 mm). Any overflow from the basin is directed to Tributary 6 via a small spillway (using 1 m of the footpath). The basin is not sealed, but lined with the local clay from the natural landscape. Figure 2b shows the basin with standing water after a small rainfall event.

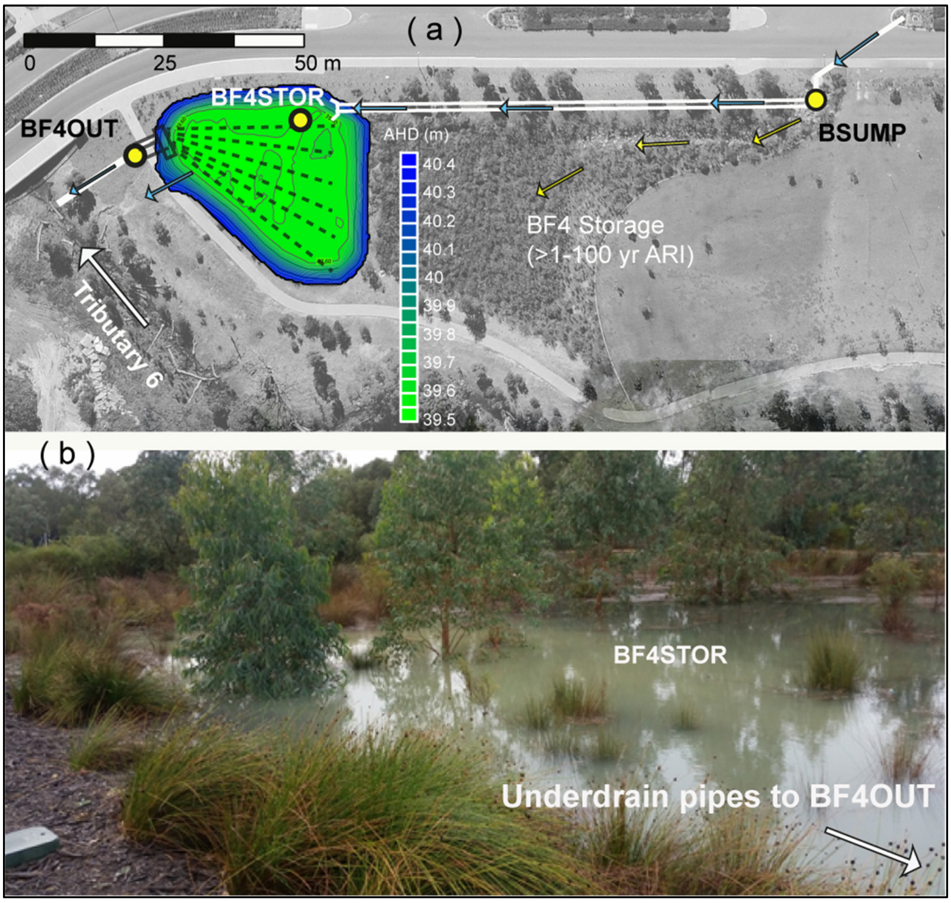

Figure 2. Bioretention basin drainage components and view: a) Bioretention basin (BF4) for the 1-yr ARI event, and b) view of the storage area (BF4STOR) after small rainfall event. Dashed lines in (a) represent underdrain slotted pipes. Elevation in contour map corresponds to Australian Height Datum (A.H.D).

3 METHODS

The bioretention basin was monitored from October 2014 to December 2015 to assess its hydrologic performance across rainfall events of different magnitude and the impact of the high perched groundwater on its functioning. A total of 37 rainfall events were selected for the water balance analysis and hydrologic performance assessment. The broader monitoring program included physicochemical data and water sampling for nutrients (nitrogen and phosphorus) analysis.

3.1 Hydrological and passive tracer data collection

Continuous hydrological monitoring stations were installed at three surface water sites at the bioretention basin: inflow (BSUMP station), surface water storage (BF4STOR) and outflow (BF4OUT) as shown in Figure 2a. Data collection and recording was initially set at 5-minute intervals and then changed to 2-minute intervals to capture the rapid response of the urban catchment to high-intensity rainfall events (time of concentration ~ 10 minutes).

The inflow station with a 3G telemetry (Neon-Unidata) provided water level (Unidata pressure transducer) and rainfall data (rain gauge RIMCO) and informed field visits for in-situ physicochemical measurements and water sample collection. Atmospheric pressure was also recorded using a Barologger (Solinst) to allow correction of the pressure transducer sensors that monitored water levels. A conductivity-temperature-depth or CTD probe (YSI 600 LS) was also deployed to record specific conductance (the electrical conductivity of the water at 25^{o}C) which was used as passive tracer to track groundwater intrusion into the bioretention basin outflow pipes. The surface water storage station (BF4STOR) comprised of a staff gauge and a CTD probe (Solinst LTC). Water level readings from the staff gauge were taken during field visits to check automatic recording data from the CTD.

The outflow station (BF4OUT) was located inside a manhole (1.2 m diameter) and treated stormwater from the fill media and intercepted groundwater water were conveyed by the underdrain. Another CTD probe (YSI 600 LS) recorded water levels and specific conductance data. Water exited the manhole via a 0.3 m diameter concrete pipe to Tributary 6 as shallow depth flow (up to 0.12 m) under free surface hydraulic conditions.

The shallow water table was monitored at four locations using 3 shallow bores (up to 3 m depth) as well as levels inside the pits during intra event periods as they reflected water table dynamics (unsealed pits). A combination of capacitance probe (ODYSSEY) and pressure transducers were used and manual readings (with a tape measure) were taken during field visits.

3.2 Data processing, water balance and hydrologic performance

Water level values at all stations were corrected by atmospheric pressure variations, related to a local height datum system and checked against manual water level readings for quality control and assurance. Theoretical rating equations were developed for each station (Department of Water WA- Hydrosmart) based on hydraulic conditions and the geometry of pits and pipes. Eight events at the inflow station required partial adjustment of water levels (over 15 minutes) due to backwater effects from the surface storage area and then used to compute inflow discharge by means of the station’s rating curve. Opportunistic volumetric discharge measurements (using a stopwatch and flexible buckets) along the pipe network for the inflow station and underdrain pipes at BF4 outflow station, were used to verify and adjust the theoretical ratings.

Inflow and outflow volumes were computed (at 2-minute intervals) for individual events by integrating the discharge hydrograph over the stormflow duration. The outflow volume reduction to the inflow was used initially to assess hydrologic performance (Davis et al., 2009) as follows:

$$fv(\%) = \left(\frac{Outflow\ volume}{Inflow\ volume} \right) \times 100 \qquad [1]$$

A similar metric was used to compute hydrologic efficiency for peak flow reduction by replacing inflow and outflow volumes quantities by peak flow discharge values.

To investigate how inflow volume, water losses (exfiltration) and fill storage volumes impacted on hydrologic performance, the portion of inflow volume required to trigger outflow (Sr_out) from the underdrain pipes was computed from observed inflow and outflow hydrographs. This threshold volume value associated with water losses to the groundwater (exfiltration from fill media) and a fill storage moisture content value (estimated to be ~ 25 m^3), provided valuable information to interpret hydrologic performance of the bioretention basin and the underlying hydrological condition of the area (i.e. groundwater interactions). Evapotranspiration and evaporation losses were neglected over the time scale of the events as they occurred mainly in late evening and early morning.

3.3 Groundwater intrusion to bioretention basin

Timing of groundwater intrusion was identified using water table records, changes in specific conductance (SC) for the outflow location and volume thresholds required to trigger outflow discharge. Characteristic SC values for the high groundwater and fill media were also used.

4 RESULTS AND DISCUSSIONS

4.1 Rainfall, water table and bioretention basin outflow dynamics

A total rainfall of 611.8 mm was recorded in 2015 at the site, which was 247 mm below the long-term average for the area (Figure 3a). The observations from the rain gauge were of similar magnitude and monthly distribution to that of the nearby BOM station (634.9 mm).

The high groundwater at BGB1, located 35 m upstream of the drainage pipe at Mead Street, developed in early July (Figure 3c) despite minor and major rainfall events in mid-May (33.4 mm) and mid-June (61.2 mm). The first noticeable increase in water table was observed on July 9 after two minor rainfall events (totaling 28.8 mm), followed by 71.8 mm of rainfall for the second half of July. The water table continued to rise during August and reached a maximum level of 2.01 m on September 13 (Figure 3c). Finally, the water table began to recede as the air temperature increased and evaporative demands appeared to outweigh rainfall inputs by small events. The bore dried out by the end of November 2015.

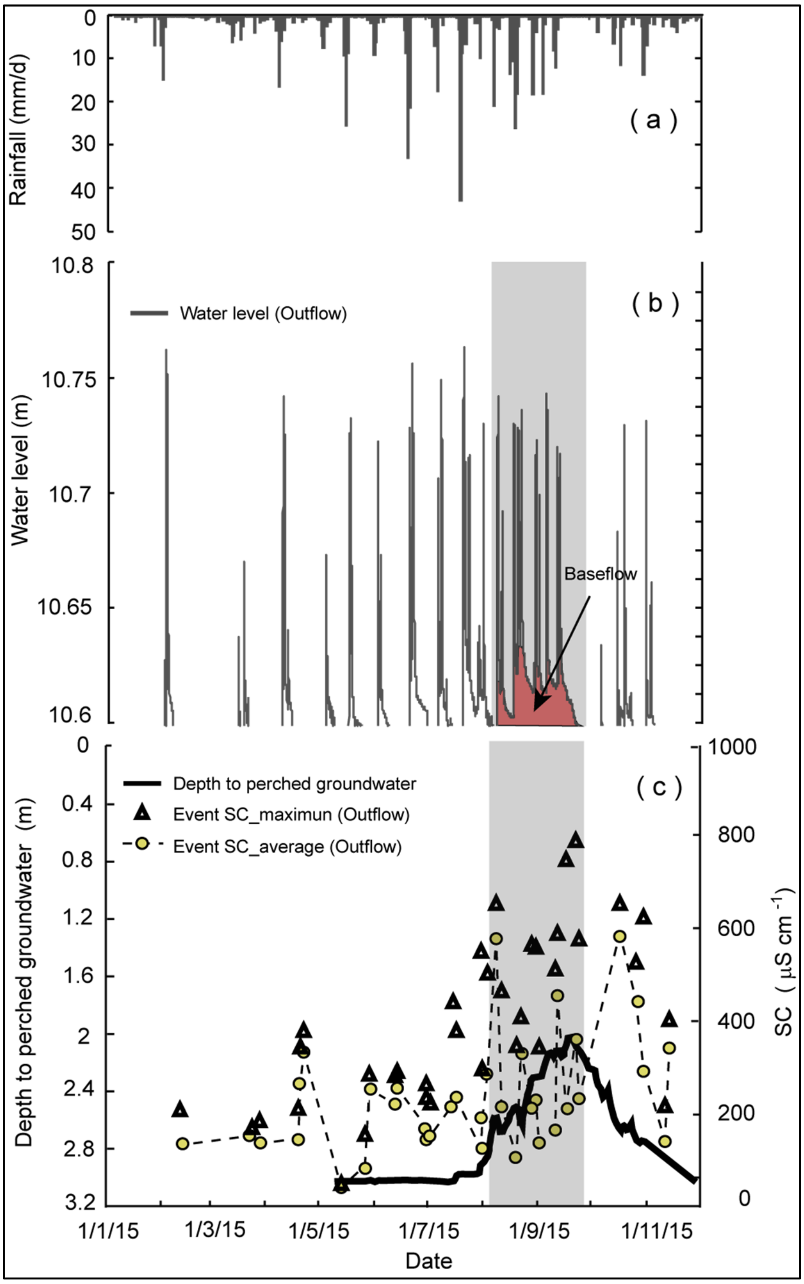

Figure 3. Hydrological and tracer data for selected events in 2015: a) rainfall total (mm/day), b) bioretention basin outflow hydrographs (BF4OUT), c) depth to perched groundwater and specific conductance (SC) corresponding to bioretention basin outflow. Depth to perched groundwater (m) from ground level. Shaded areas indicate time of groundwater interactions with the bioretention basin.

Hydrometric data at the bioretention basin outflow (Figure 3b) showed two different patterns across the year. The first pattern corresponded to the outflow discharge ceasing, shortly after the occurrence of a rainfall event from May to July and then towards the end in the spring season (from October to November). The second pattern was observed from mid-August to late-September and displayed hydrographs comprising continuous baseflow discharge and runoff event responses, and it coincided with an increasing water table (shaded area in Figure 3b). The hydrometric data showed that groundwater interacted with the bioretention outflow and further analysis was warranted.

Based on the topographic elevation of different elements of the drainage network at Mead Street (main stormwater drainage pipe and pits), it was possible to confirm interactions between the high groundwater and the stormwater system. The water table was well above (by 0.5 m) the invert of the stormwater pits at Mead Street and was effectively contributing to the flow of the main drainage network and groundwater was intercepting the bioretention basin underdrain pipes at the outflow (BF4OUT).

Groundwater contribution to the BF4 outflow was further confirmed by a sharp increase in SC (electrical conductivity at 25^{o}C) at the BF4 outflow, measured at times of high groundwater. Figure 3c shows event average and maximum SC recorded across 2015. Specific conductance of the high groundwater showed small variability across the season with a mean value of 1556 μS cm $^{-1}$ (± 32 μS cm^{-1}) and the highest value coinciding with the time of the water table peak around mid-September. This value largely exceeded those corresponding to subsoil media of the raingardens containing the same fill material used in the bioretention basin (SC range 180 - 360 μS cm $^{-1}$) and direct runoff from impervious areas (SC range from 45 - 90 μS cm $^{-1}$). The event SC maximum value occurred prior to or at the early stages of the event outflow hydrograph and it represented the contribution of groundwater to the outflow.

4.2 Hydrologic performance of the bioretention basin

The 37 events (including 9 events recorded from late-October to late-November 2014, not shown) ranged in magnitude from 0.8 mm to 40.8 mm and most of these fell within the most frequent events for water quality treatment purposes (6-month - ARI). One event on 4 September 2015 had similar characteristics of the 1year-ARI event (intensity of 42 mm hr^{-1} over 10 minutes, total rainfall 17.8 mm) and its occurrence coincided with high groundwater. For the purpose of this study and based on the above results, events were grouped by total rainfall amount into small < 10mm, minor (up to 25 mm) and major to reflect differences in inflow volume for hydrologic performance assessment and with and without interference of groundwater.

Results for volume control using Eq. [1] showed that an average *fv* value of 17% (SD ± 12%) was obtained for small events occurring at times when there were no groundwater interactions and corresponded to the periods October 2014-June 2015 and October-November 2015. In other words, 83% of the inflow volume was successfully managed (approximately one third retained by fill water storage and the remained lost) by the bioretention basin. Minor events over the same periods showed an important increase in average *fv* value to 44% (SD ± 17%) and slightly higher than aimed 33% recommended by guidelines. This increase resulted from the inclusion of two events on 31 July and 22 October 2015 presenting *fv* values of 72% and 63% reflecting the water table development and recession for the former and latter events respectively. Finally, two major events over the same periods resulted in an average *fv* value of 56% and reflected performance during overloaded flow conditions.

The volumetric control by the bioretention basin was compromised by interactions with groundwater from mid-August to late-September and resulted in an average *fv* value of 73% (SD ± 13%). High *fv* values were found irrespective of the rainfall amount. The 1 year-ARI event (4 September 2015) occurred close to the time of water table peak, and resulted in an *fv* value of 83% (only 17% of the inflow volume was managed). Although major events were no part of the current analysis, there were no significant reductions of the outflow volume as *fv* values were between 92 % and 95 % with the exception of one event under dry antecedent condition, which showed *fv* of 80%.

Figure 4 presents inflow and outflow volumes for the 37 events computed from the observed hydrographs. It can be seen that small events (inflow volume < 75 m^3) were successfully managed with an average volume reduction of 83%. Data for inflow volumes in the range 100 - 400 m^3 displayed a large degree of scatter and reflected the influence of groundwater. A regression line fitted to the 37 events showed a R^2 of 0.91. However, R^2 were improved to 0.969 and 0.988 when datasets without and with groundwater interactions were separated (see regression lines in Figure 4). The above results showed the impact of the underlying hydrology of the area on the hydrologic performance of the bioretention basin for volume control.

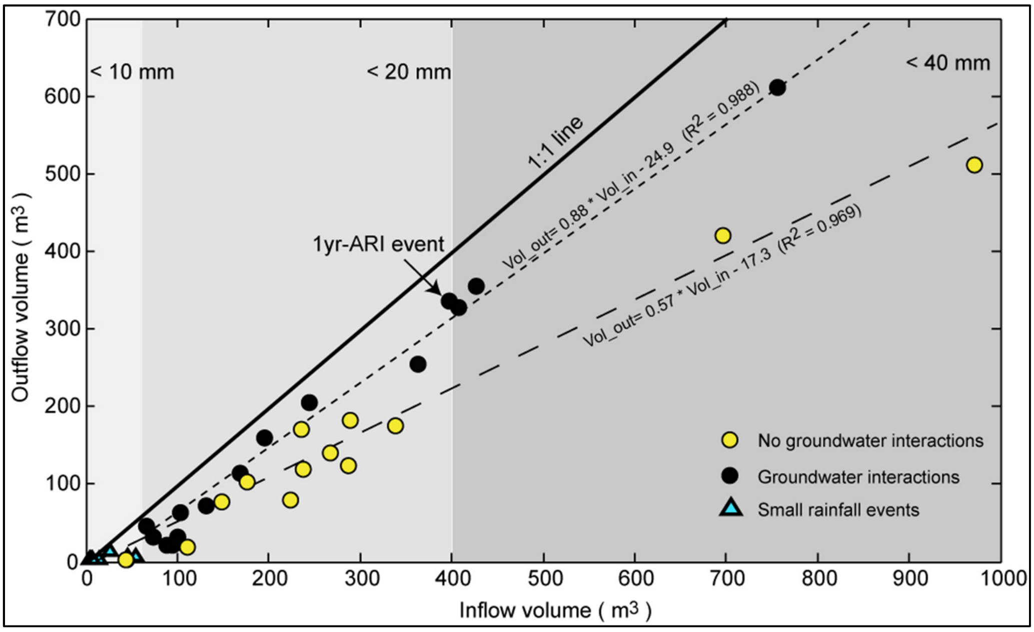

Figure 4. Volumetric performance of the bioretention basin for the 37 events. Shaded area indicates rainfall event magnitude. Regression lines and equations for both data sets are included.

The bioretention basin achieved its intended hydrologic performance in relation to peak flow control with a peak flow reduction of 98% (SD ± 3.1%) for small events and 74%(SD ± 10%) and 79% (SD ± 10%) for events with and without groundwater interactions respectively. The small difference in performance for events with and without groundwater interactions suggested a possible control by rainfall characteristics and inflow magnitude in relation to the size of the surface water storage, water storage condition of the fill and exfiltration losses. Figure 5 presents instantaneous peak flows for the events at the inflow and outflow and associated peak flow reduction values (in brackets as %). The data grouped relatively well for inflow peak values < 12 L/s (events experiencing up 98% reduction) and peak values > 35 L/sec representing reductions between 70 and 84 %, with the latter corresponding to inflow that occupied more than 75% of the capacity of the basin surface water storage. However, two sets of data for peak flow values in the range 12-35 L/s grouped apart suggests that some transitional stage in bioretention functioning occurred that was related to internal water storage (fill media) and exfiltration losses.

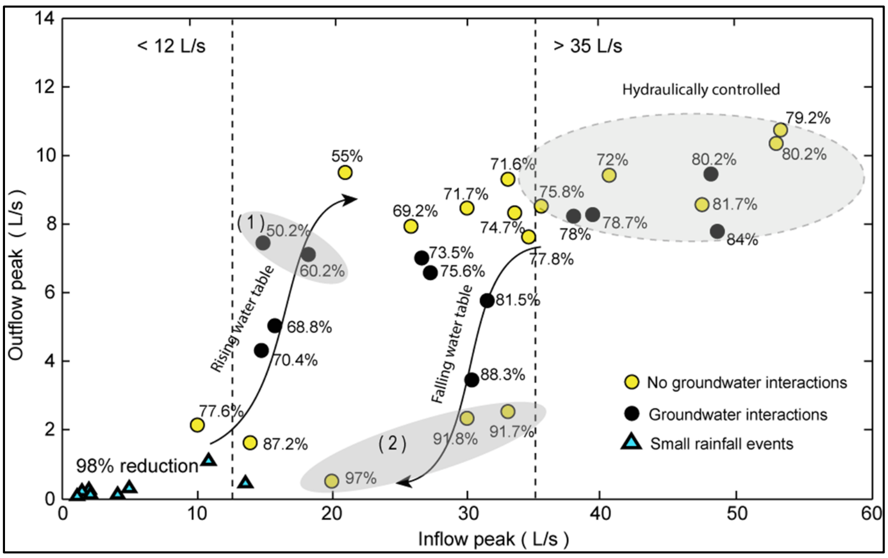

Figure 5. Peak flow reduction performance for all events. Light-grey shaded area indicates inflow peaks > 35 L/s and events with outflow controlled by surface water storage discharge from the basin. Dark-grey shaded area and numbers in brackets highlight events of similar characteristics showing performance differences in relation to groundwater dynamics (S-shaped lines).

The comparison of volume threshold values required to trigger outflows (Sr_out) for events of similar characteristics during the suggested transitional stage, provided insight on the role of the groundwater interactions on peak flow reductions. Two events in September (shaded area (1) in Figure 5) reduced peak flow on average by 55% during rising water table and were lower than the 94% reduction achieved for the period March - May (shaded area (2) in Figure 5). The difference was mainly attributed to magnitude of Sr_out values presented by the September events at 25 m^3 (closer to the estimated field capacity of the fill) and 41m^3 and 62 m^3 for the March and May events, respectively (larger volume losses via exfiltration). These results agreed with expected reduction of exfiltration losses as the water table gets closer to the underdrain pipes (Hunt et al., 2006). It is also important to consider that the geometry and size of the basin and the underdrain pipes setting could contribute to the transition stage (control on water losses and water storage) and to the good performance for high inflow peaks (Figure 5, hydraulically controlled) as presented in Davis et al. (2012).

The peak outflow during the transitional stage could have important practical implications in monitoring nutrients (phosphorus and nitrogen) for performance assessment as high nutrient masses (resulting in unusual concentrations) could result from effective mobilization by high flow rates. Knowledge about the internal functioning of the bioretention would assist in the interpretation of pollutant removal assessment.

4.3 Implication of the findings for hydrologic performance and pollutant removal metrics

A better understanding of the internal processes of bioretention systems is needed to improve metric for assessment of the hydrologic performance that accounts for physical aspects of the design, thresholds, seasonality in hydrological inputs and the groundwater interactions.

A key outcome of this work was to timely capture and document the temporal dynamics of the perched groundwater and its distinctive SC signal confirming groundwater contribution to the outflow. This was possible due to continuous monitoring of the inexpensive passive tracer (SC) and a large difference in SC of the different water sources (i.e. inflow runoff, water through fill media and high groundwater). The hydrometric and SC data indicated that groundwater interacted with the underdrain pipes for a period of 50 days in a year with below average annual rainfall. Data for year 2016 (unpublished) indicated higher groundwater levels and longer interaction (~ 150 days) in response to a rainfall amount equal to the long-term average annual. Monitoring activities gathering data for pollutant removal assessment need to consider this issue in systems interacting with high groundwater.

The separation of data set to account for groundwater interactions facilitated the analysis and interpretation of the results for hydrologic performance, particularly in terms of volume control. The data demonstrated that the performance was affected by groundwater interactions. Using the regression equation for events without groundwater interactions (Figure 4) and the observed performance for the 1 yr-1hr ARI event under high groundwater conditions, it was possible to estimate that groundwater interaction affected negatively its performance by 30%. This effect is not commonly included in engineering practices for the design of bioretention basins in areas with high groundwater and has implications for pollutant loading to receiving waterways.

Changes in volumetric performance for the bioretention basin will affect outflow volumes and pollutant loading and consequently its real treatment capacity and removal mechanisms. In this study case, the groundwater intrusion impacted on outflow volume and concentration of some elements, in particular for nitrate (i.e. mobile inorganic form of nitrogen). The comparison of two similar events (~13 mm) on 31 July and 11 September 2015 showed a large increase of nitrate loading (380%) for the latter that could not be explained by the increase of outflow volume alone (groundwater interactions) but required an increase in concentration from a nitrate-rich water source (Ocampo et al., 2016). Hydrograph separation technique analysis using SC were conducted for the events and indicated that the groundwater contributed 24% of the outflow volumes and presented high nitrate concentration.

Most of the frequent events for water quality treatment in the study case coincided with periods of high groundwater and inflow peaks within the suggested transition stage in bioretention functioning (Figure 5). Application of standard metrics for pollutant removal performance (i.e. inflow to outflow ratio of event mean concentration values) should account for groundwater contribution by means of a correction factor which incorporates the additional water and pollutant masses. This task will require tailored field experiments similar to this study to corroborate the findings.

5 CONCLUSIONS

This study demonstrated that groundwater interactions with structural elements for stormflow control and water quality improvement occur and have an impact on the hydrologic performance of such elements when they are built in areas with high groundwater. Seasonality in rainfall inputs combined with shallow sandy soils resulted in a perched groundwater that interacted with the underdrain pipes of a bioretention basin affecting its intended functioning and performance. The duration of the interaction depended on the total annual rainfall amount but not its occurrence, which was documented in a year with 28% less than the average annual rainfall.

The groundwater interactions with the bioretention underdrain pipes were successfully tracked by continuous monitoring of the outflows SC and it was fundamental for the separation of events into two groups with and without groundwater interactions. This step facilitated the interpretation of the results for hydrologic performance.

The results demonstrated that the hydrologic performance of the bioretention basin for volume control was compromised by interactions with groundwater from mid-August to late-September, achieving 27% volume removal and resulting in 30% reduction in performance for the 1 yr-1hr ARI event used for the design and stormwater treatment purpose. The bioretention basin achieved its intended hydrologic performance in relation to peak flow control at 79% even with groundwater interactions. A transition stage in the bioretention functioning was identified from the data that reflected the interplay among inflow peaks, bioretention basin storages (i.e. surface and fill), groundwater dynamics and exfiltration losses.

Findings from the study also highlighted the need to improve metrics for hydrologic performance to account for groundwater intrusion due to its contribution to water and pollutant masses. This study provided guidance for similar experiments to be conducted elsewhere and to allow intercomparison of sites for hydrologic and pollutant removal performance.

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QUALITY AND FIRST FLUSH ASSESSMENT OF URBAN HIGHWAY STORMWATER RUNOFF IN MALAYSIA

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ABSTRACT

Highway stormwater runoff has been identified as the main contributor that deteriorates the receiving water quality. Many studies have been conducted throughout different countries to determine the relationship between highway runoff and its effects to the water bodies. This issue is important to Malaysia due to the rapid development of highways and increasing traffic volumes in recent years. Thus, the objectives of this study are to (i) determine the highway stormwater runoff quality; and to (ii) investigate the transport mechanisms of highway pollutants under different storm sizes. A total of three storm events have been monitored at the Kajang Silk Highway and 19 stormwater samples with 500 ml volume each were collected using manual grab technique. The stormwater flow rates were measured and water samples were collected during the rising and falling limbs of storm runoff. The stormwater samples were analyzed for COD, DO, pH, TSS and turbidity. The event mean concentration (EMC) and first flush effect were determined for each pollutant in every storm event. The results showed that the EMCs for COD, DO, pH, TSS and turbidity were 38.5 mg/L, 9.48 mg/L, 7.9, 86.4 mg/L and 33.8 NTU, respectively. The highway runoff quality in this study was categorized as class III based on Department of Environment Malaysia's water quality index classification, which required extensive treatment for water supply. TSS and COD both showed strong first flush effects in this study. The results suggested that initial treatment is required to reduce the pollutant loadings in highway stormwater runoff.

Keywords: Event mean concentration; first flush; highway stormwater runoff; non-point source pollution; urban catchment

1 INTRODUCTION

Highway developments associated with urbanization process have grown tremendously in Malaysia in recent years. Currently, there are more than 30 expressways that connects cities and states in Malaysia as well as locations in neighbouring countries. High daily traffic volumes in these urban highways have resulted in the build-up of various pollutant loadings on the road surface that are ready to be flushed into the receiving water bodies during storm events. These highway pollutants include particle, heavy metal, nutrients, oil and grease, bacteria and toxic substance that normally comes from vehicles and road materials. Heavy metals such as arsenic, copper, cadmium, nickel, lead and zinc normally tend to affiliate with sediment and are carried away from road surface. High intense and short duration storms in Malaysia will transport the highway pollutants instantly into drainage system. In Malaysia, most of the highway runoffs are discharged directly into the natural streams without any treatment. These highway runoffs have contributed to the contamination of natural aquatic environments and subsequently affect the water resources in the catchment area.

Pollutant normally shows higher concentration at the initial part of runoff volume which the phenomenon is known as first flush effect. First flush phenomenon is normally related to the pollutant types, catchment size, contributing impervious area and rainfall characteristics (Li et al., 2006). Different pollutants show different first flush effect and magnitudes under various storm sizes. The first flush effect is usually being defined based on the normalized cumulative pollutant mass against normalized cumulative runoff volume curve. First flush will occur if the normalized cumulative curve is greater than the 1:1 uniform curve. Often, particle and sediment will exhibit stronger first flush effect than other dissolved pollutants. In fact, these particles with different size distributions have different transport mechanisms and different pollutants attached to them. Variation in particles size distribution has resulted in higher uncertainty to the removal performance of highway stormwater runoff treatment system.

Understanding the highway runoff quality and transport mechanism is crucial for the selection of best management practices (BMP) (Li et al., 2005). Engineers required adequate data and information for designing the best treatment solutions such as sedimentation tank, swales, detention pond or dry basins (Chartes et al., 2015, Selbig et al., 2013). The operation and maintenance of the treatment systems are highly depended on the stormwater quality and pollutant removal process (Bughrara, 2008). This issue is important to Malaysia due to the rapid development of highways and increasing traffic volumes in recent years. Thus,

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the objectives of this study are to (i) determine the stormwater runoff quality from a highway site; and to (ii) investigate the transport mechanisms of highway pollutants under different storm sizes.

2 METHODOLOGY

2.1 Study area

The study site is located at Kajang SILK Highway which is near to the environmental laboratory of Universiti Tenaga Nasional (UNITEN). Nearer site was chosen in order to reduce the transport time for water samples analysis. The Kajang SILK Highway experiences heavy traffic daily with the average daily traffic volume of more than 140,000 vehicles per day. The highway structures are similar at both lanes which are made up of normal asphalt pavement with concrete shoulders and storm drains. The slope of monitored highway site is approximately 2%. Figure 1 shows the sampling point for highway stormwater runoff samples in this study.

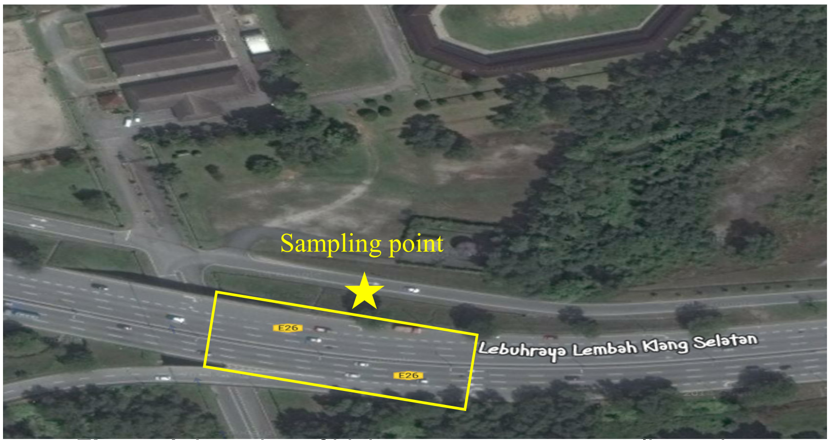

Figure 1. Location of highway stormwater sampling point.

2.2 Stormwater samples collection and analysis

A total of three storm events were monitored at the studied site. Rainfall data were collected using 0.2-mm tipping bucket rain gauge that was installed within the campus of Universiti Tenaga Nasional (UNITEN). The flow level was measured using stage gauge while flow velocities for different depths were measured using current meter during the storm events. The hydrograph was plotted for each storm event and total runoff volume was determined as the product of flow rate and runoff duration. Stormwater samples were manually grabbed by using 1 liter HDPE bottle during the rising and falling limb of the hydrograph. Depending on the storm size, the number of samples per storm event varies from 4 to 10. All stormwater samples were immediately brought to the environmental laboratory in UNITEN and analyzed for total suspended solids (TSS), chemical oxygen demand (COD), dissolved oxygen (DO), pH and turbidity. All water quality analyses were performed based upon the Standard Method for Water and Wastewater (APHA, 2005).

2.3 Data analysis

2.3.1 Event mean concentration (EMC)

Pollutant loadings were estimated using EMC which is defined as the total constituent mass, M discharged during an event divided by the total runoff volume, V during the event (Huber, 1993), expressed as:

$$\mathrm{EMC} = \overline{C} = \frac{M}{V} = \frac{\int_0^t Q(t)C(t)\mathrm{d}t}{\int_0^t Q(t)\mathrm{d}t} \quad [1]$$

where M is total mass of pollutant during the entire runoff (kilograms), V is total volume of runoff (cubic meters), C(t) is time varying pollutant concentration (milligrams per liter); Q(t) is time variable flow (liter per second); and t is total duration of runoff (seconds).

2.3.2 First flush effect

First flush phenomenon represents the disproportionately high delivery of either concentration or mass of a constituent during the initial portions of a rainfall-runoff event (Sansalone and Cristina, 2004). The first flush effect is determined by using Equations (2a) and (2b):

$$L = \frac{m(t)}{M} = \frac{\int_0^t C(t)Q(t)dt}{\int_0^n C(t)Q(t)dt} \quad [2a]$$

$$F = \frac{v(t)}{V} = \frac{\int_0^t Q(t)dt}{\int_0^n Q(t)dt} \quad [2b]$$

where, L is ratio of the instantaneous mass (m(t)) over the sum of the total of the mass of the pollutant (M) at the end of the event and F is the ratio of the instantaneous volume (v(t)) over the cumulative runoff volume (V). t is the time between the initiation of runoff (t0) and the cessation of runoff (n). Q(t) is a function denoting the measured runoff and C(t) is a function denoting the measured constituent concentration as a function of time. A first flush exists at time t if the dimensionless cumulative pollutant mass L exceeds the dimensionless cumulative runoff volume F at all instances during the storm events. A 1:1 line, on a plot of L vs. F, indicates that pollutants are uniformly distributed throughout the storm events. If the data for a particular storm falls above the 1:1 line, a first flush is suggested (Bertrand-Krajewski et al., 1998; Deletic, 1998; Larsen et al., 1998).

3. RESULTS AND DISCUSSION

3.1 Characteristics of storm events

Three storm events on 15 November, 17 November and 26 November 2015 were collected at the studied site for assessing the highway stormwater runoff quality. The rainfall depths for these storm events were ranged from 5.0 mm to 22.0 mm and the rainfall intensities were ranged from 5.0 mm/hr to 23.9 mm/hr. The maximum rainfall depth and intensity occurred on 26 November 2015. Table 1 presents the characteristics of each monitored storm event.

Table 1. Monitored storm events at the studied site

Event	Rainfall depth (mm)	Duration (hr)	Intensity (mm/hr)	Runoff volume (m^3)	Antecedent dry day (day)
15 November 2015	13.0	1.17	11.1	3452.1	1
17 November 2015	5.0	1.0	5.0	623.7	1
26 November 2015	22.0	0.92	23.9	4040.7	3

3.2 Highway stormwater runoff quality

A total of 19 stormwater samples were collected during these three storm events. The event mean concentration (EMC) was calculated for each water quality parameter during each storm event and the results are summarized in Table 2. The EMCs for COD, DO, pH, TSS and turbidity were 38.5 mg/L, 9.48 mg/L, 7.9, 86.4 mg/L and 33.8 NTU, respectively. The highway runoff quality in this study is categorized as class III based on Department of Environment Malaysia's water quality index classification which required extensive treatment for water supply. The mean EMC for COD in this study is comparable with the findings obtained by Kim et al. (2007) at the roadway and parking lots in Korea. However, this result is relatively lower than EMC_{COD} of 73 mg/l obtained by Salleh et al. (2013) in Gombak highway, Malaysia. In addition, The EMC of TSS in this study is also comparatively lower than the EMC_{TSS} (215 mg/L) in the study by Salleh et al. (2013). The rainfall characteristics were observed that had a direct influence on the EMC value of COD, TSS and turbidity. Higher rainfall depth and runoff volume on event 26 November 2015 had diluted the EMC values of pollutants.

Table 2. Event mean concentrations for each water quality parameter.

Event	Number of samples	COD (mg/l)	DO (mg/l)	TSS (mg/l)	Turbidity (NTU)	pH
15 November 2015	5	14.30	9.42	-	15.39	-
17 November 2015	4	54.85	10.50	87.87	51.11	7.28
26 November 2015	10	46.24	8.75	85.00	35.08	8.53
	Mean	38.47	9.48	86.44	33.86	7.90

- Data not available

Table 3. Water quality index classification according to Department of Environment Malaysia.

Parameter	Unit	Class				
		I	II	III	IV	V
Ammoniacal nitrogen	mg/l	<0.1	0.1-0.3	0.3-0.9	0.9-2.7	>2.7
Biochemical oxygen demand	mg/l	<1	1-3	3-6	6-12	>12
Chemical oxygen demand	mg/l	<10	10-25	25-50	50-100	>100
Dissolved oxygen	mg/l	>7	5-7	3-5	1-3	<1
pH	-	>7	6-7	5-6	<5	>5
Total suspended solid	mg/l	<25	25-50	50-150	150-300	>300

3.3 First flush analysis

The pollutographs for water quality parameters were plotted in order to assess the transport mechanism of pollutant during the storm event. Figure 2 presents the examples of pollutographs for water quality parameters on event 26 November 2015. From the pollutographs, it can be seen that the peak concentration of pollutant tends to occur prior to the peak flow of storm event. Higher concentrations of pollutant were observed at the initial part of stormwater runoff and decreases gradually toward the end of storm event. First flush analysis was carried out for each water quality parameter in every storm event. Figure 3 shows the plots of normalized cumulative mass against normalized cumulative flow for every pollutant. Values above the 1:1 line indicate the occurrences of first flush. It is observed that COD, TSS and turbidity show the first flush effects in this study. The TSS showed the strongest first flush effect on event 26 Nov 2015 in the study. This observation may be due to the accumulation of dust and dirt from vehicles that deposited on road surfaces during the three dry days' period and flushed away by high stormwater runoff volume on 26 Nov 2015. Similarly, COD also showed strong first flush effect on event 26 Nov 2015. Based on these findings, we suggest that the longer antecedent dry days and greater rainfall intensity will cause stronger first flush effect on stormwater pollutant at highway site. In general, the average strengths of first flush for stormwater pollutant at highway site in this study are TSS > COD > turbidity > DO.

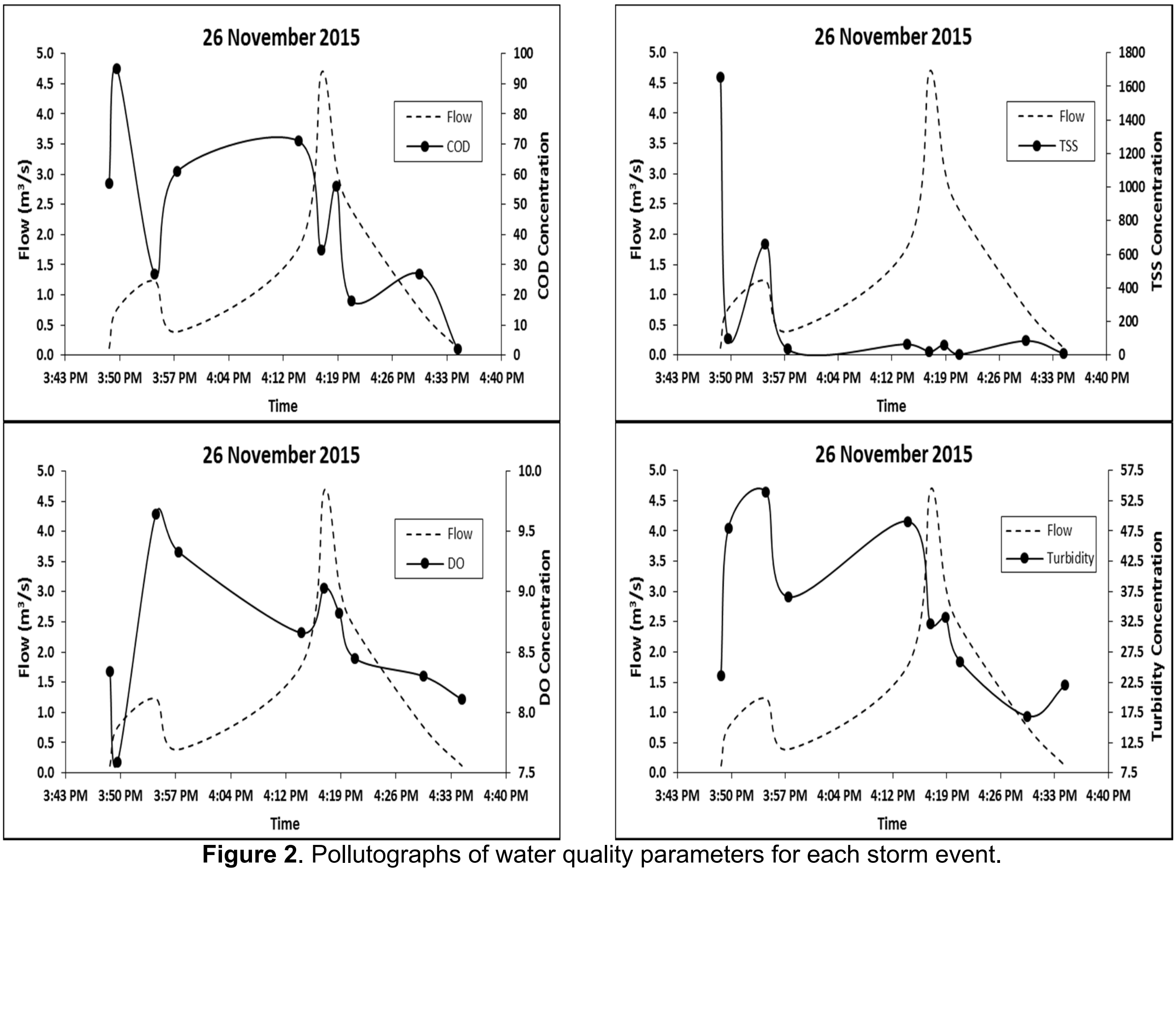

Figure 2. Pollutographs of water quality parameters for each storm event.

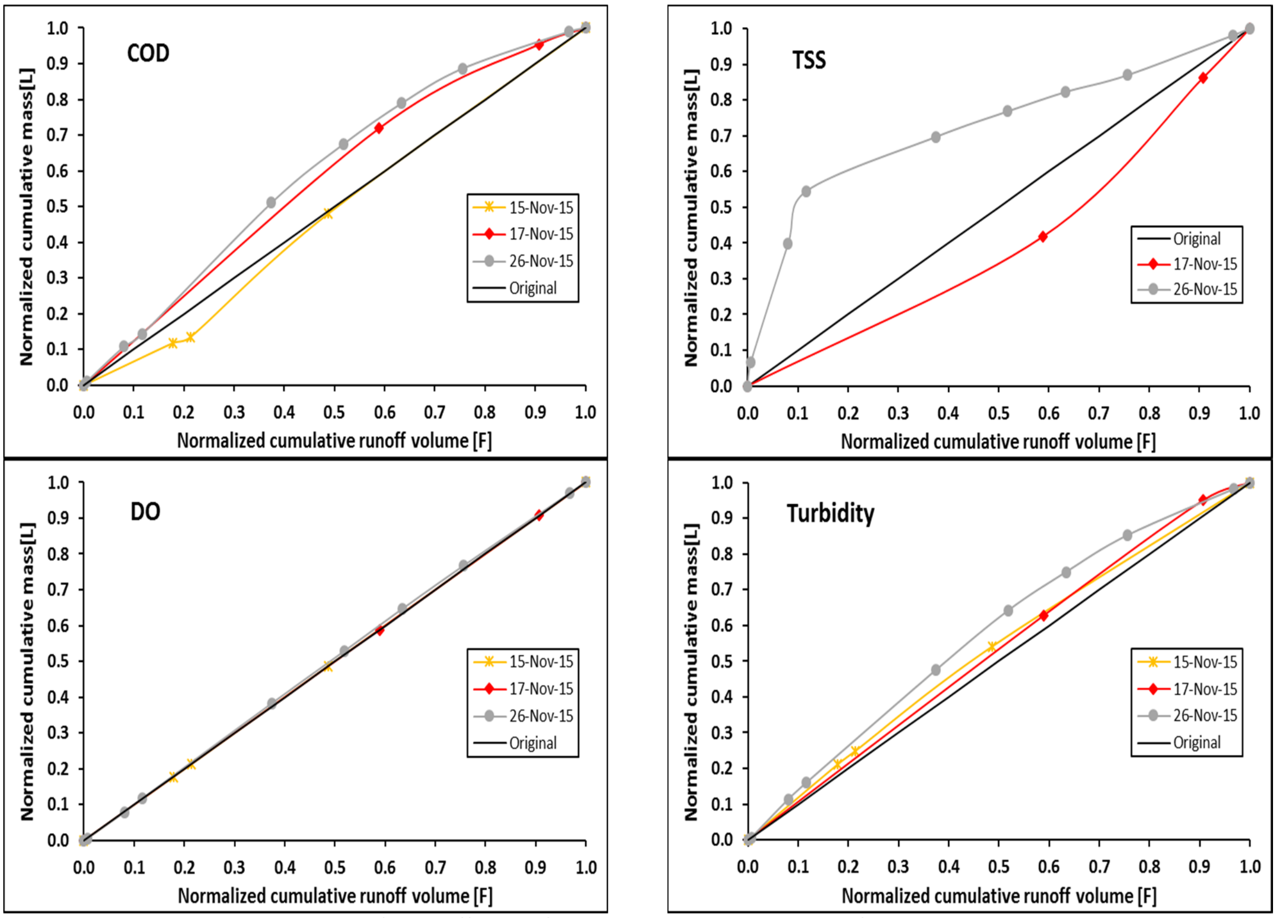

Figure 3. First flush effects of water quality parameters for each storm event.

3 CONCLUSIONS

This study had monitored three storm events at a highway site in Kajang, Selangor, Malaysia. Event mean concentration and first flush analysis were carried out to determine the stormwater quality from highway and to assess the transport mechanism of pollutants during storm event. The findings showed that EMCs for COD, DO, pH, TSS and turbidity were 38.5 mg/L, 9.48 mg/L, 7.9, 86.4 mg/L and 33.8 NTU, respectively. The highway runoff quality in this study is categorized as class III based on Department of Environment Malaysia's water quality index classification which required extensive treatment for water supply. TSS and COD both show strong first flush effects in this study. The results suggested that initial treatment is required to reduce the pollutant loadings in highway stormwater runoff.

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