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Physicochemical characteristics of streams in Bukit Timah Nature Reserve, Singapore

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ABSTRACT. Spatial and temporal surveys were conducted to better understand the physicochemical characteristics of the streams in Bukit Timah Nature Reserve (BTNR). A total of 87 survey stations were selected along ten streams for an in-situ water quality study conducted in June 2018. Temporal investigation, including in-situ and ex-situ samplings, was conducted from late November 2017 to July 2018 for Fern Valley and Jungle Fall streams. The in-situ physicochemical parameters included pH, Dissolved Oxygen (DO), Conductivity, Oxidation-Reduction Potential (ORP), Total Dissolved Solids (TDS), Turbidity, Salinity, and Temperature. Water samples were collected for further analysis of Total Suspended Solids (TSS), anions, cations, elements, Total Organic Carbon (TOC), Total Nitrogen (TN) and Total Phosphorus (TP). Water discharge was calculated as stream cross-sectional area multiplied by water velocity. Groundwater samples (down to maximum 2 m) were collected at upstream and downstream locations in Fern Valley and Jungle Fall catchments and analysed for water chemistry. Seventy-five soil samples (surface and subsurface) were collected to investigate the hydrogeomorphic conditions of the catchments in an attempt to understand the influence of hillslopes on water quality within the stream channel. Physicochemical baselines of the streams in Bukit Timah Hill were established, the data suggesting that stream temperature, TDS, salinity, the amount of TOC, TP, anions and cations vary within their expected natural ranges. Some parameters including DO and conductivity are slightly lower than expected, which may not be favorable for large aquatic animals. Some issues needing further investigations include low stream pH in Jungle Fall and Seraya streams as well as the significantly high concentration of Cd, Sb and Se in all streams. Follow-up actions are recommended to further investigate the drivers and monitor the effect of stream acidification, the causes and effects of high concentration of Cd, Sb and Se, as well as possible stream rehabilitation measures leading to improvement of water quality.

Keywords. Acidification, freshwater, soil chemistry, water quality, hill stream, headwater

Introduction

The physicochemical characteristics of streams and the ways in which they function are determining factors of aquatic ecosystem health (Dudgeon, 2011). Many aquatic organisms in streams are affected by even small changes in water chemistry and habitat (e.g., Bere & Tundisi, 2011). Physicochemical functions include the interaction of physical and chemical processes to create the basic water quality conditions of the stream including physical parameters such as temperature, dissolved oxygen, conductivity, pH, turbidity, and chemical parameters etc., as well as to facilitate nutrient (e.g. organic carbon) transformation and transport cycles. These parameters provide both direct and indirect indications of stream condition and the stream's ability to support biological communities. Understanding what is expected of these parameters in a given stream, based on the reference conditions and what the stream actually demonstrates, requires a comprehensive physicochemical stream assessment (Harman et al., 2012).

Although the aquatic biodiversity in the streams of Bukit Timah Nature Reserve (BTNR) has been comparatively well studied, the water quality of these streams has never been thoroughly assessed. Available information on water quality of the area is limited to a few parameters that have mostly been measured in-situ during biodiversity surveys. In the past decade, several studies on water quality of streams in Bukit Timah have all focused specifically on documenting stream acidification in Jungle Fall stream (Phang, 2009; Huang, 2011; Ng et al., 2015b).

The objectives of this study were to provide an account of the physicochemical characteristics of the streams in Bukit Timah hill through field and laboratory investigation, together with the available up-to-date information including published literature and unpublished student theses and internal reports; to compare the baselines against benchmark references to evaluate the physicochemical functions that the streams are currently performing; and to recommend steps forward.

Materials and Methods

Both spatial (Table 1) and temporal surveys were conducted in the attempt to better understand the physicochemical characteristics of the streams. For the spatial investigation, 87 survey sites were selected along ten surveyed streams for ex-situ water quality studies (Table 1, Fig. 3–5 in Cai, 2019). Three sampling replicates were conducted at each survey site, with the sampling period concentrated in the months of May and June 2018 to minimise the effects of seasonal/temporal variability. The month of May and June is regarded as the intermonsoon and beginning of the Southwest Monsoon period, with rainfall slightly lower or close to monthly average for the year. All sampling was conducted in fine weather conditions except for a few additional samplings specifically taken to understand the impact of wet weather conditions. The latter were not used to represent points for comparison. Water samples from 20 of the 87 sites (Table 2) were collected for ex-situ analysis. The points were chosen corresponding to the at-a-reach stream channel morphology sampling (described by Cai, 2019). The sampling sites were taken to represent water quality in the chosen reach of the stream channel, without further distinguishing the influence of inflows from side channels entering at intermediate positions between sampling points. Temporal investigation, including in-situ and ex-situ samplings, was conducted from late November 2017 to July 2018 for two streams, namely Fern Valley stream and

Table 1. Physical parameters (means, n=3 readings per location per paramater) in various streams in and adjacent to Bukit Timah Nature Reserve, Singapore. Sampling locations are shown in Fig. 3–5 in Cai, 2019.

	Site	**Temp. ˚C**	**pH**	**DO %**	**DO mg/L**	**EC µS/cm**	**TDS mg/L**	**Salinity ppt**	**ORP mV**	**Turbidity FNU**
Fern Valley	FV1	26.78	5.38	21.83	1.76	67.33	33.67	0.03	29.67	18.90
	FV2	26.68	5.57	20.27	1.63	78.33	51.33	0.04	42.70	20.50
	FV3	26.61	5.67	18.00	1.45	69.00	34.00	0.03	40.37	18.65
	FV4	26.27	4.88	17.40	1.41	65.00	32.00	0.03	115.97	20.55
	FV5	26.16	5.12	20.20	1.63	-	-	-	174.70	17.37
	FV6	26.12	4.98	19.35	1.57	62.50	31.50	0.03	143.90	26.12
	FV9	26.30	5.40	53.63	4.33	67.33	33.67	0.03	-22.10	16.30
Taban Valley	TB1	25.78	5.89	17.93	1.45	18.67	9.33	0.00	89.80	22.80
	TB2	26.42	5.06	19.23	1.55	68.00	33.67	0.03	190.97	24.03
	TB4	26.39	4.47	20.30	1.64	73.33	36.33	0.03	259.47	18.23
	TB5	26.13	4.44	18.43	1.50	69.00	34.67	0.03	256.77	23.07
Lasia Stream	LS1	26.75	6.47	16.70	1.33	120.67	60.67	0.06	24.93	23.07
	LS2	26.73	6.60	16.20	1.30	127.33	63.67	0.06	20.10	2.59
	LS3	26.60	5.41	16.07	1.29	51.00	25.33	0.02	75.13	23.67
	LS4	26.54	5.63	18.57	1.50	48.00	24.00	0.02	110.23	21.75
	LS5	26.52	5.64	18.87	1.52	36.33	19.67	0.02	128.40	57.80
	LS7	26.85	6.16	16.87	1.35	95.00	47.33	0.04	28.53	22.23
	LS8	26.95	6.24	17.33	1.37	101.00	50.67	0.05	49.93	22.37
	LS9	26.70	5.70	17.37	1.40	106.33	53.00	0.05	70.57	21.97
	LS10	26.92	5.82	17.43	1.40	85.33	42.67	0.04	81.23	23.20
	LS12	26.45	4.49	19.40	1.57	17.67	9.00	0.01	251.50	22.13
	LS13	26.45	5.22	16.27	1.31	51.67	25.67	0.02	135.00	22.35
	LS16	26.43	4.78	16.43	1.32	55.67	27.67	0.02	183.73	26.17
	LS17	26.37	4.55	17.57	1.42	63.33	31.67	0.03	204.13	21.23
	LS18	26.26	4.47	17.40	1.40	80.67	40.00	0.04	214.43	18.83
	LS19	26.22	4.24	18.37	1.48	87.00	45.00	0.04	254.90	-
	LS22	26.25	4.65	16.83	1.36	56.00	28.00	0.03	208.97	-
	LS23	26.60	5.05	19.77	1.58	7.00	4.00	0.00	192.97	17.93
Catchment Stream	CS1	27.04	5.66	18.57	1.48	55.00	27.67	0.02	94.63	23.33
	CS2	26.97	5.37	18.73	1.50	45.33	22.67	0.02	146.20	23.93

Table 1. Continuation.

	Site	**Temp ˚C**	**pH**	**DO %**	**DO mg/L**	**EC µS/cm**	**TDS mg/L**	**Salinity ppt**	**ORP mV**	**Turbidity FNU**
Catchment Stream	CS3	26.95	5.67	17.50	1.40	48.00	25.67	0.02	106.03	22.67
	CS4	26.19	4.87	18.90	1.53	33.50	16.50	0.02	139.10	69.47
	CS5	26.34	4.97	18.73	1.51	35.33	18.00	0.01	137.53	21.67
	CS6	26.36	4.78	18.43	1.49	53.00	26.33	0.02	155.13	33.90
	CS8	26.33	4.81	17.97	1.45	63.33	32.00	0.03	151.40	23.03
	CS9	26.32	4.58	18.13	1.47	63.33	31.67	0.03	168.80	-
	CS10	26.30	4.53	20.57	1.66	17.00	9.00	0.01	193.37	-
	CS11	26.29	4.44	19.33	1.56	6.33	3.33	0.00	185.93	21.87
	CS13	26.36	4.34	16.73	1.35	76.00	37.67	0.03	176.37	23.10
	CS15	26.29	4.56	16.13	1.30	61.67	30.67	0.03	154.80	23.60
	CS18	26.08	4.70	20.60	1.67	32.67	16.00	0.01	208.90	22.25
	CS19	26.11	5.28	19.43	1.57	42.67	21.33	0.02	158.37	22.53
	CS20	26.12	5.31	18.13	1.47	47.33	23.33	0.02	149.00	23.80
	CS22	26.15	5.08	16.57	1.34	74.33	37.33	0.03	150.07	26.77
	CS24	26.20	4.65	18.00	1.46	54.67	27.67	0.03	177.20	21.30
Wallace Stream	W1(D)	27.04	6.01	40.27	3.21	74.67	37.00	0.03	-22.20	181.67
	W1(W)	25.99	6.17	72.20	5.87	63.67	33.00	0.03	11.40	46.73
	W16	26.67	5.12	42.17	3.38	59.00	30.67	0.03	117.17	26.10
	W18	26.73	5.14	41.87	3.35	52.33	26.33	0.02	119.20	25.00
	W20	26.50	4.71	43.00	3.46	61.33	30.67	0.03	150.10	31.30
	W22	26.29	4.65	51.80	4.18	69.00	34.33	0.03	132.97	23.80
	W25	26.29	4.59	57.93	4.68	23.00	11.50	0.01	147.73	24.05
Dairy Farm	DF1(D)	27.17	6.77	40.70	3.24	154.00	77.00	0.07	-43.10	58.70
	DF1(W)	25.82	6.77	72.30	5.90	113.00	56.33	0.05	-7.37	24.67
	DF4	26.65	6.02	22.87	1.85	53.33	27.00	0.02	2.70	19.30
	DF6	26.87	6.06	20.10	1.61	60.33	30.67	0.03	42.17	22.00
	DF8	26.72	5.33	20.17	1.62	50.33	25.33	0.02	190.50	24.70
	DF10	26.89	5.33	21.13	1.69	18.00	8.67	0.01	151.70	31.20
	DF13	26.57	4.47	24.73	1.99	12.00	6.00	0.00	279.87	27.30
	DF15	26.89	6.45	19.20	1.54	87.00	43.33	0.04	-8.37	21.23

Table 1. Continuation.

	Site	Temp. ˚C	pH	DO %	DO mg/L	EC µS/cm	TDS mg/L	Salinity ppt	ORP mV	Turbidity FNU
Seraya Stream	SR2A	26.60	4.69	18.67	1.49	44.00	22.00	0.02	207.10	26.63
	SR2B	26.90	4.97	18.97	1.51	45.67	22.67	0.02	204.13	27.93
	SR3	26.51	4.42	19.80	1.59	55.00	27.33	0.02	235.57	23.40
	SR4	26.58	4.49	18.63	1.50	64.33	32.00	0.03	236.13	21.73
	SR6	26.29	4.32	19.03	1.53	59.67	30.00	0.03	251.67	28.20
	SR7	26.21	4.31	21.43	1.72	15.33	9.33	0.01	266.63	28.45
Jungle Fall	JF1	25.97	4.50	25.40	2.06	49.33	24.67	0.02	184.20	18.50
	JF2	25.95	4.52	28.27	2.28	62.00	31.00	0.03	176.33	16.90
	JF3	26.09	4.51	29.87	2.41	42.67	23.00	0.02	201.73	20.63
	JF4	26.09	4.44	28.90	2.33	52.00	25.67	0.02	197.33	26.80
	JF5	26.13	4.56	31.73	2.55	-	-	-	232.83	27.45
	JF6	26.17	4.50	29.00	2.33	-	-	-	245.17	49.10
	JF7	26.16	4.35	27.83	2.24	57.67	28.67	0.03	290.00	29.75
Asas Stream	AS1	26.96	6.48	66.50	5.33	170.67	85.67	0.08	-22.17	25.63
	AS2	26.79	6.34	66.13	5.32	172.00	85.67	0.08	-30.87	22.60
	AS4	26.81	6.46	67.03	5.39	157.67	80.67	0.07	-39.43	26.93
	AS5	27.22	6.63	65.43	5.22	194.00	97.00	0.09	-54.93	28.80
	AS6	27.54	6.85	60.27	4.75	191.33	95.67	0.09	-89.73	29.17
	AS7	27.80	7.06	38.90	3.08	276.33	138.00	0.13	-154.53	28.70
Rail Corridor	RC1	26.48	6.66	28.97	2.34	116.33	58.00	0.05	26.60	22.70
	RC3	26.36	5.60	27.10	2.19	52.00	26.00	0.02	7.40	-
	RC5	26.14	4.81	26.37	2.14	62.00	30.67	0.03	138.57	18.85
	RC7	26.23	4.76	26.03	2.11	50.33	25.00	0.02	165.73	16.80
	RC8	26.20	4.77	24.40	1.98	66.00	33.33	0.03	173.73	15.97
	RC9	26.22	4.76	21.60	1.75	70.33	35.00	0.03	177.77	15.95
	RC12	26.76	6.05	21.27	1.70	55.00	27.33	0.03	65.77	20.20
	RC13	28.12	5.60	54.13	4.24	49.33	26.00	0.02	-4.90	13.00

Table 2. Water chemistry in streams within and adjacent to Bukit Timah Nature Reserve, Singapore. Sample locations are abbreviated as given in Table 1. Units for TOC, TN, TP, Na^+, NH_4^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, SO_4^{2-} are mg/L. Units for the other parameters (concentrations of elements) are µg/L. BDL: below detection limit.

Sample	**TOC**	**TN**	**TP**	**Na^+**	**NH_4^+**	**K^+**	**Mg^{2+}**	**Ca^{2+}**	**Cl^-**	**SO_4^{2-}**	**Al**	**Ba**	**Ca**	**Cd**
RC13	2.29	2.9	0.41	3.31	BDL	2.09	0.70	1.39	3.44	2.10	91	147	1263	29
RC9	0.28	1	0.25	0.92	0.0566	0.88	0.48	5.25	2.58	5.78	45	56	7384	29
CS1	1.30	0.8	0.4	2.35	0.0392	2.01	0.80	5.62	4.00	2.54	78	106	4742	27
CS10	3.13	4.1	0.71	3.76	0.0423	2.93	1.18	2.92	4.59	2.42	156	198	2086	30
CS20		4.3	0.23	3.83	BDL	3.23	1.38	3.01	3.90	3.03	158	195	2229	27
FV1		1.7	0.42	3.62	BDL	2.59	0.83	4.74	3.71	3.59	46	156	3690	29
FV9		3.1	0.29	1.94	BDL	1.88	0.73	2.05	3.52	0.74	55	187	1535	30
DF1		1.2	0.52	3.80	0.0168	2.25	0.76	4.33	3.51	3.41	63	93	3153	29
DF13	2.04	3.8	0.43	3.77	BDL	2.03	0.78	1.60	5.77	0.58	179	199	1101	27
SR1	2.18	3.4	0.56	2.18	0.0021	1.76	0.87	1.23	3.65	0.67	252	160	1345	28
SR6	2.47	3.8	0.33	1.67	0.0113	1.78	0.93	1.10	3.23	0.79	357	164	1316	30
JF2	2.59	3	0.36	1.98	BDL	1.36	0.70	1.04	3.73	1.06	447	114	1167	29
JF6	2.33	3.5	0.22	2.08	0.0025	1.51	0.82	1.08	3.84	0.65	570	121	1207	28
LS16	2.41	3.3	0.29	2.43	BDL	2.01	0.64	1.26	3.99	3.33	124	205	1699	29
LS9	0.77	2.9	0.41	3.78	BDL	2.33	0.90	14.67	2.96	9.50	69	57	12910	30
LS12	2.22	2.1	0.43	1.19	BDL	0.95	0.55	2.97	1.61	1.35	115	47	827	27
TB1	0.74	3.8	0.51	1.77	0.0023	1.55	0.65	5.86	3.18	4.31	106	148	6592	30
WL18	1.95	3.9	0.3	2.34	BDL	2.55	0.93	2.11	3.23	2.75	102	183	1498	27
AS7	4.06	2.2	0.22	8.77	0.2125	4.49	0.96	33.50	8.21	10.96	44	96	34200	30
AS1	1.83	2	0.56	4.12	0.0255	2.49	0.84	20.70	3.80	13.55	40	79	17080	26

Sample	**Co**	**Cr**	**Cu**	**Fe**	**K**	**Mg**	**Mn**	**Na**	**Ni**	**Pb**	**Sb**	**Se**	**Sr**	**Ti**	**V**	**Zn**
RC13	27	44	29	50	2152	651	93	3794	22	45	42	62	44	33	46	52
RC9	27	42	30	67	309	395	51	1701	21	41	41	91	51	31	47	65
CS1	29	43	34	219	2117	718	68	3066	26	51	51	54	56	33	46	46
CS10	24	43	29	71	2950	1053	113	4030	28	36	39	93	55	30	48	54
CS20	28	41	24	85	3361	1244	54	4027	22	41	53	91	52	32	50	48
FV1	27	43	33	70	2736	724	54	4169	23	38	46	56	52	30	47	53
FV9	29	43	27	46	3536	900	34	4454	25	44	30	48	51	31	48	48
DF1	25	43	30	147	2213	561	67	4256	24	35	44	BDL	47	32	46	53
DF13	29	43	34	46	2619	872	116	5664	26	50	65	52	49	32	45	55
SR1	25	43	29	58	1874	1051	111	2817	25	60	38	93	50	32	46	49
SR6	26	44	28	66	2101	1357	123	2523	23	44	52	117	48	31	48	51
JF2	27	42	27	47	1363	881	76	2895	22	56	54	46	46	31	45	51
JF6	26	43	30	76	1603	1085	82	2908	23	52	53	50	47	30	47	50
LS16	27	43	31	44	2415	769	93	3479	22	40	64	44	48	30	46	53
LS9	27	44	25	66	2038	767	47	3532	26	38	68	81	126	32	46	49
LS12	28	43	27	62	322	250	42	1066	25	52	50	41	37	31	45	46
TB1	27	43	29	105	2048	685	86	3077	27	43	43	65	53	30	48	66
WL18	27	44	27	48	2847	839	109	2817	25	46	68	99	50	31	49	53
AS7	26	45	24	52	5311	827	395	10740	25	46	57	88	148	32	48	44
AS1	27	44	33	53	2202	640	102	4002	27	44	53	93	77	32	48	53

Jungle Fall stream (Fig. 1–2), which are historically better studied and are assumed to be more or less representative of the hydrogeomorphic characteristics of streams in BTNR. The period of study took into account the seasonality of Singapore's intermonsoonal climate (Rahman & Tay, 1991) to cover wet and dry periods. In-situ physicochemical parameters, including pH, Dissolved Oxygen (DO), Oxidation-Reduction Potential (ORP), Total Dissolved Solids (TDS), Salinity, and Temperature were recorded using a HANNA 9829 Multiparameter at each site.

To investigate the temporal variation of physicochemical parameters, regular sampling was conducted in Fern Valley and Jungle Fall, at a total of five locations (two in the upper and lower sections of Jungle Fall stream, and three in the upper, middle and lower sections of Fern Valley stream) (Fig. 1). Water samples were collected at these locations and brought back within a few hours to Geolab, Department of Geography, National University of Singapore for further analysis of Total Suspended Solids (TSS), anions, cations, elements, Total Organic Carbon (TOC), Total Nitrogen (TN) and Total Phosphorus (TP). Approximately 600 ml of stream water was collected in a clean acid-washed bottle at each site. In-situ stream velocity was measured using a HACH FH950 flowmeter (Marsh-McBirney CO, USA), and water quality (Temperature, DO, Conductivity, TDS, Salinity and pH) were measured using a YSI Professional Plus Multiparameter Instrument. Water discharge was calculated as stream cross-sectional area multiplied by stream velocity. Groundwater samples were collected from several wells (down to maximum 2 m depth) at the upper and lower stream locations in Fern Valley and Jungle Fall catchments and analysed for water chemistry.

Total Suspended Solids (TSS) were measured using EPA method 160.2 (US EPA, 1983). It is the dry mass of suspended solids derived from one litre of water and remaining on a clean filter paper, measured after drying in an oven at 60°C until reaching constant mass (usually after 24h). For anions, cations and elemental analysis, water samples were filtered through a 0.45 µm-pore size filter paper (Whatman) Replace with and either kept in a freezer (for anions and cations) or acidified and kept at 4°C (for elements). No filtration is needed for Total Nitrogen (TN), Total Phosphorus (TP) and Total Organic Carbon (TOC); instead, these samples were frozen until analysis. Anions and cations were analysed by Dionex ICS-5000 (Thermo Fisher Scientific); elements by Inductively Coupled Plasma Atomic Emission Spectroscopy 8300 (ICP-OES) (Perkin Elmer); Nitrogen and Phosphorus by Lico 690 Spectra Colorimeter (Hach); and TOC by Vario Cube TOC analyser (Elementar).

In total, 75 soil samples (52 from Fern Valley and 23 from Jungle Fall catchments), among them 65 from surface soils and ten from subsurface soils), were collected (Fig. 2) to investigate the hydrogeomorphic conditions of the catchments and to better understand the influence of hillslopes on the water quality of the stream channels within them. The sampling strategy for surface soils was to cover as much of the catchments' area as possible taking into account physical constraints on human access. Subsurface soils were collected near water stations (Fig. 1) at 1 m and 1.8 m depth. At each sampling location, approximately 300 g of soil was collected using a stainless steel spade, or a soil auger for subsurface soils, and stored in a fresh zip-lock bag. In between samplings, equipment was washed thoroughly with stream water. Analysed soil parameters were bulk density, particle size distribution, TOC, pH, and elements.

Soil bulk density was determined using a 98 cm^3 aluminium cylinder (Bashour & Sayegh, 2007). Samples were dried in an oven at 105°C until reaching constant weight (usually after 24hrs). The bulk density was calculated as the ratio of soil dried mass to volume of soil. Particle size distribution was determined from the ASTM D422 (2016) standard test method which utilises a hydrometer and Stoke's Law (Blake & Steinhardt, 2008). Total Organic Carbon was determined using Vario Cube TOC analyser (Elementar) following the removal of inorganic carbon via fumigation (Harris et al., 2001). In the determination of soil moisture at field capacity, 30 g of ground soil was placed in open silver-foil capsules (6 × 6 × 12 mm) and 50 µl of deionised water was added to the capsule. To remove carbonates, the sample was placed in a desiccator for acid fumigation (using 100 ml 37% HCl) for 6 hours (Harris et al., 2001). The capsule (together with soil) was dried, weighed, packed and analysed for TOC. Soil pH was measured with a pH meter (Orion 3 star) after the fine grains (< 2 mm) had been mixed with water (soil/water ratio of 1:2.5) and shaken for 2 hours (Van Reeuwijk, 1992). Element concentrations were analysed using the microwave-assisted EPA 3051a method (US EPA, 2007). Pulverised samples of 0.5 ± 0.001g were digested with 9 ml of 65% HNO_3 and 3 ml of 37% HCl in a microwave digester (E = 1000W; temp = 180°C) for a total of 55 minutes (Milestone, 2009). After cooling, the digested solutions were centrifuged at 2500 rpm for 10 minutes. The supernatant was decanted and diluted five-fold for trace metal analysis and 100-fold for macro element analyses, via ICP-OES.

Results and Discussion

1. *Physicochemical baselines of streams in Bukit Timah*

Results of the spatial survey are presented in Table 1. The ten streams originating in BTNR range from only 250 to 1100 m in length (Cai, 2019), downstream of which they flow into the concretised surface drainage system of urban Singapore and they lie within an elevation of between 158 and 37 m above sea level (Cai, 2019). There are few reports on the physicochemical characteristics of small lowland streams in the Southeast Asian region, most studies having been either on large rivers, or on small headwaters at considerable elevations. We are therefore forced to make comparisons with some of the literature on Central and South American streams.

1.1 *Temperature*

1.1.1 *General synopsis.*

Temperature affects the metabolic rates and hence the growth and development times of aquatic organisms. Each organism has its own range of temperature within which it can survive. Other than the effects on organisms, temperature also affects other properties of water such as DO, concentration

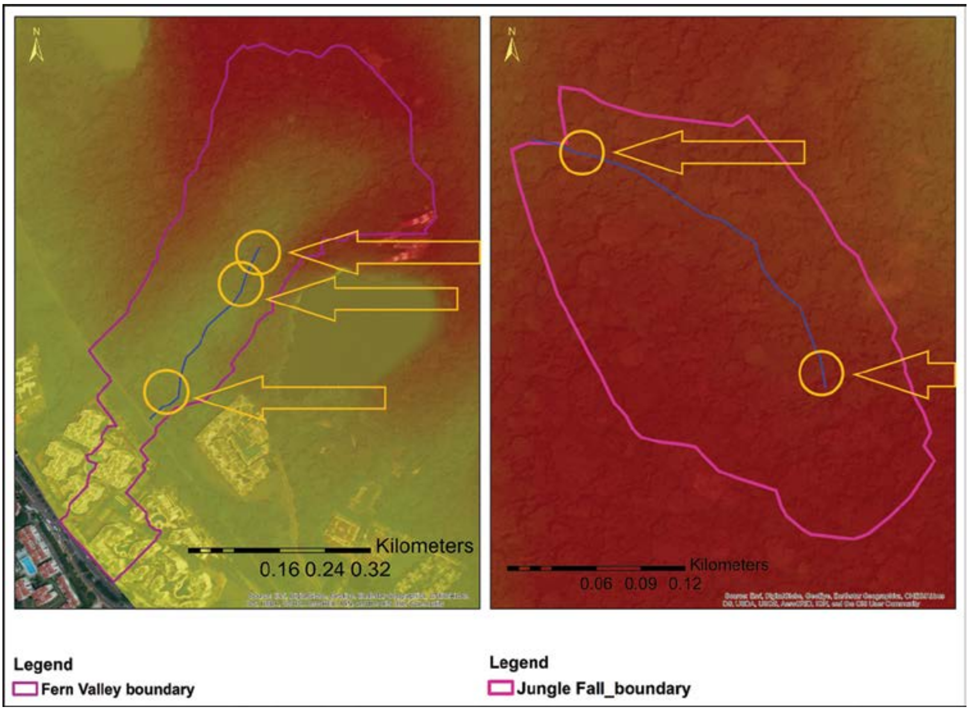


Fig.1. Temporal water sampling stations in Fern Valley and Jungle Fall, Bukit Timah Nature Reserve, Singapore.

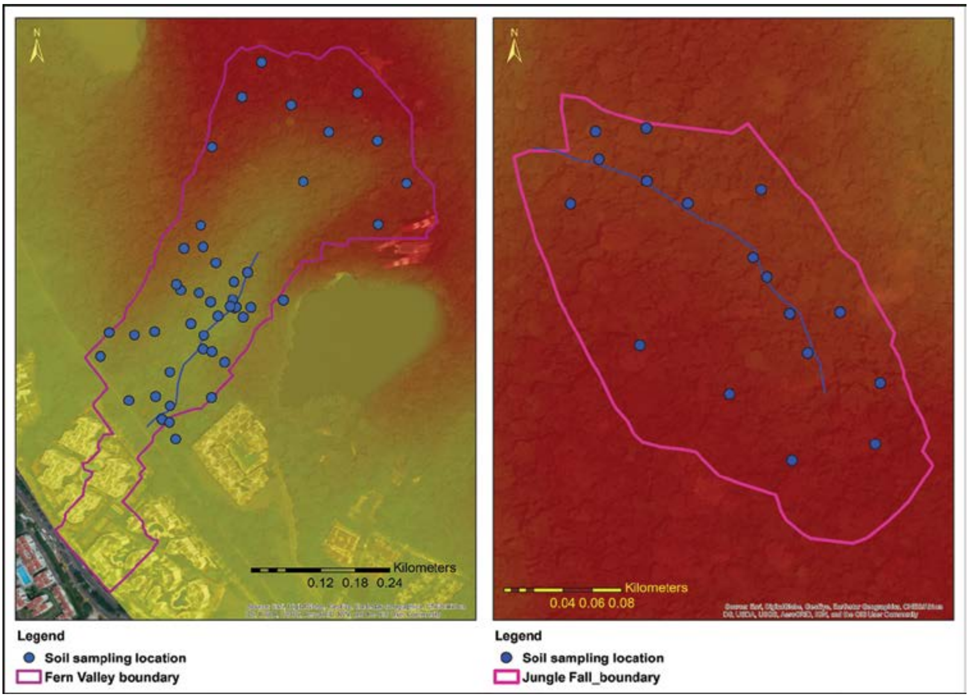


Fig. 2. Soil sampling locations at Fern Valley, and Jungle Fall.

of nutrients and the viscosity of the water. Warm water usually has low DO and thus increases the rate of biochemical reactions in water bodies that eventually affect the fate of pollutants. Tropical headwater stream temperature in general is subject to diel fluctuation, following daily air temperature variation (Dudgeon, 2011). Headwater streams usually have lower water temperatures compared to larger rivers in the lowlands (Ortiz-Zayas et al., 2005; Dudgeon, 2011).

1.1.2 *BTNR streams*.

Streams in Bukit Timah, although short, with a mean temperature of 26.55°C (ranges 25.96 to 29.03°C), also follow this pattern as their upper reaches always have lower temperatures than the lower reaches, except for Jungle Fall and Asas streams (Table 1, Fig. 3). The temperature difference, however, is small, probably due to the short distance between stream survey points. There is no obvious temperature difference between the streams in BTNR. In general, their water temperature varies within expected values of tropical low latitude, low elevation streams in humid regions, which typically have a mean temperature of about 27°C, and range from 25–29°C (Dudgeon, 2011: 9). The headwaters of streams at higher elevations and higher latitudes have lower temperatures than Bukit Timah streams, for instance Rio Mameyes and Quebrada Prieta in Puerto Rico (mean daily temperature ranges from 22 to 24°C and 20 to 24°C, respectively) (Crowl et al., 2001; Ortiz-Zayas et al., 2005), Rio das Mortes catchment, Brazil (14.9°C to 19.1°C) (dos Santos Rosa et al., 2013) and various streams in Puerto Rico (from 23.84 to 28.46°C) (Burgos-Caraballo et al., 2014).

1.1.3 *Fern Valley.*

In Fern Valley, the stream temperature ranges from 24.6 to 26.4°C (Fig. 4). One outlier reading gave a temperature of 27.7°C at the middle stream on February 6th 2018. The readings were all taken in the morning and the two-degree range reflects natural temperature variation in the survey period. On any given day, the temperature difference between the upper and middle stream is negligible and not significant, but both are cooler than the lower stream. This is in agreement with the aforementioned temperature trend in tropical streams (Ortiz-Zayas, 1999; Dudgeon, 2011). The differences in water temperature between the upper, middle and lower sites are too small to expect any differences in biological activities, at least for temperature-driven processes, which, in general, are doubled for every 10°C increase in temperature (Caissie, 2006). There is no obvious trend of temperature within the survey period. Interestingly, stream temperature is 1.5–2°C higher than the historical data of 23–24.5°C measured in Bukit Timah by Douglas (1967).

1.1.4 *Jungle Fall.*

For Jungle Fall, spatial information was compared only between the upper and lower parts of the stream. The stream temperatures range from 24.9 to 26.7°C (Fig. 5), similar to those from Fern Valley. Both spatial and temporal surveys reveal

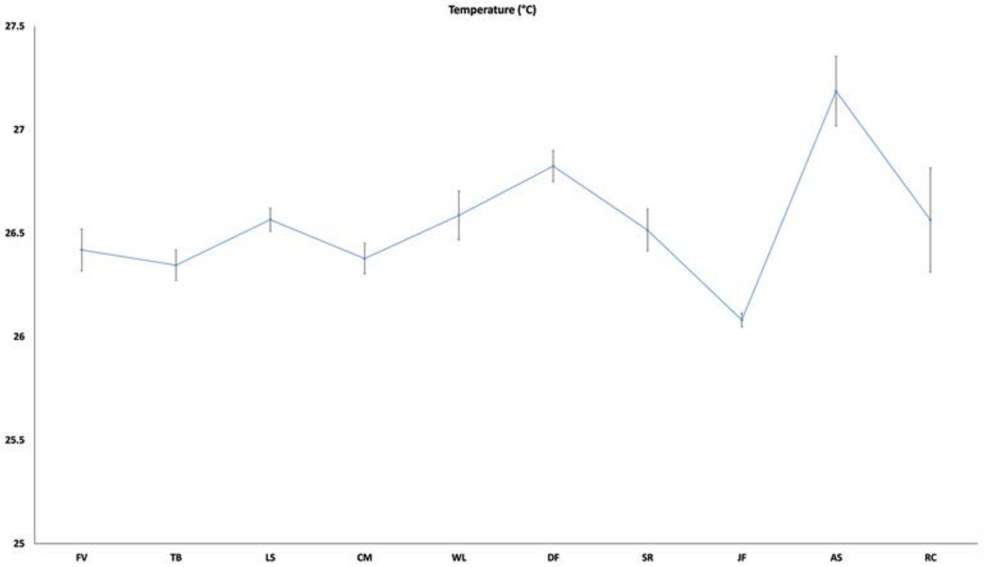


Fig. 3. Temperature (Mean±SE) at various survey streams, Bukit Timah Nature Reserve, Singapore.

significantly lower temperature in the lower than in the upper stream. There is no obvious trend for temperature in Jungle Fall during the surveyed period. The current temperatures are about 2°C higher than historical values of 23–24.5°C (Douglas, 1967).

1.2. *Oxidation-Reduction Potential (ORP)*

1.2.1 *General synopsis.*

Oxidation reduction potential (ORP) measures water's cleanliness and its ability to break down contaminants. The ORP reading indicates the capability of water either to release or accept electrons from chemical reactions. When a system tends to accept electrons, it is an oxidising system, and release of electrons indicates a reducing system. ORP values are used much like pH values to determine water quality. Just as pH values indicate a system's relative state for receiving or donating hydrogen ions, ORP values characterise a system's relative state for gaining or losing electrons. ORP values are affected by all oxidising and reducing agents, not just the acids and bases that influence pH measurement.

1.2.2 *BTNR streams.*

The streams in BTNR display a wide range of ORP, from -65.28 mV (Asas stream) to 233.45 mV at Seraya stream and 218.23 mV at Jungle Fall stream (Table 1; Fig. 6). The majority (n=6) of readings in the streams of BTNR are between 90 to 200 mV which indicates the occurrence of oxidising conditions. The ranges of ORP are lower as compared to cool mountain streams in Wyoming, USA (Tronstad et al., 2016) where "oxidation-reduction potential indicated that oxidising conditions occurred in most streams (>200 mV)"; but much higher than those headwater streams of Yangtze River which show ORP varying from -77.1 to -134.2 mV with an average of -88.88 mV, indicating an anoxic water surface (Qu et al., 2015). With an average value of -65.28 mV, Asas stream seems to be very different from all the other streams and the stream water shows reducing conditions.

1.3. *Dissolved Oxygen (DO)*

1.3.1 *General synopsis.*

DO depends on water temperature. The solubility of oxygen in water increases as temperature decreases and concentrations can also change throughout the course of a day based on respiration rates of algae. Concentrations below 5 mg/L may adversely affect function and survival of biological communities, and below 2 mg/L can lead to death of fish that are not adapted to such conditions. Saturated DO in tropical streams is usually low, for example, saturated oxygen concentration ranges from 7.6 to 8.1 mg/L (mean 7.9 mg/L) for low latitude and elevation, humid zone streams (Dudgeon, 2011).

1.3.2 *BTNR streams.*

Bukit Timah streams have low DO, mostly less than 3 mg/L (or less than 30% saturated). Some streams, however, have higher DO, ranging from 3.21 to 5.87 mg/L (Wallace stream) or 3.08 to 5.39 mg/L (Asas stream) (Table 1, Fig. 7). Some sites along streams are abnormally high in DO such as at Fern Valley upstream (FV9), Wallace stream (W1 wet season), Dairy Farm (DF1 wet season), Seraya upstream (SR7) and Rail Corridor stream (RC13). These sites have specific conditions leading to the high DO (e.g. either near an outlet/spring or reading taken under wet conditions). Compared to other tropical streams, those in Bukit Timah have lower DO than Água Limpa (8.6 mg/L), Correias (9.0 mg/L) and Chaparrals (7.6 mg/L) which are natural streams in an acidic, Fe and Mg rich, nutrient poor catchment in Brazil (dos Santos Rosa et al., 2013). Other headwater streams, such as those in a humid tropical and seasonal climate at São Francisco catchment, Brazil (Nova Ponte (DO 7.5±1.16 mg/L), Três Marias (DO 7.7±2.9 mg/L), Volta Grande (DO 8.4±3.2 mg/L) and São Simão (DO 7.6±1.7 mg/L) (Ferreira et al., 2017), and the streams in the Turabo watershed, Puerto Rico (DO from 4.36–8.10 mg/L) (Burgos-Caraballo et al., 2014) also have higher DO than those from Bukit Timah. This suggests that streams in Bukit Timah could be slightly unfavourable to some aquatic fauna, especially large fishes (Fondriest Environmental, 2013).

1.3.3 *Fern Valley.*

In Fern Valley, from June to July 2018, the DO sensor malfunctioned, thus the readings in these months were not reliable. Despite a large variation, from 15.4 to 53.9% saturation (or equivalent to 1.26 to 4.42 mg/L), the majority of readings in Fern

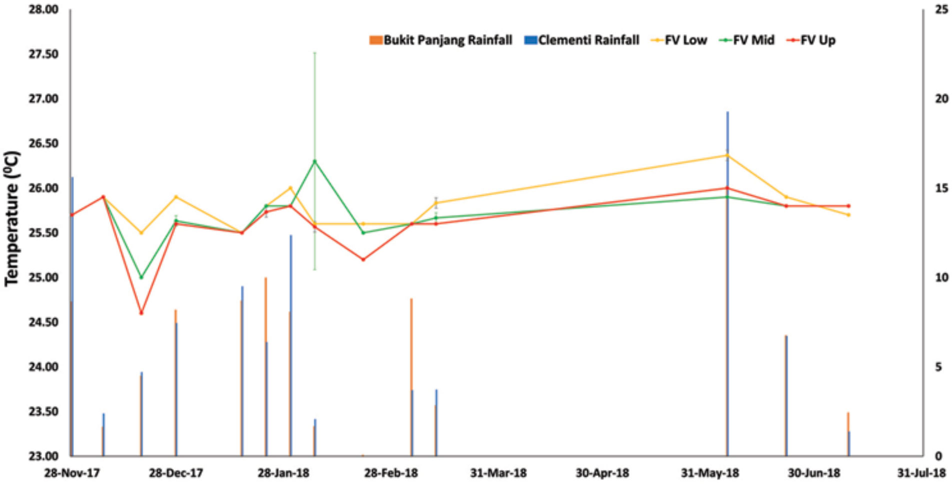


Fig. 4. Fern Valley stream water temperature and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

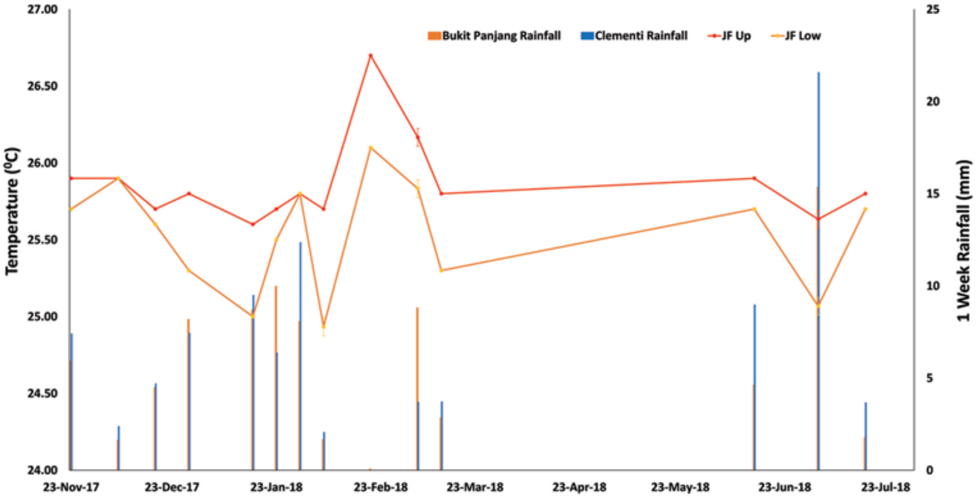


Fig. 5. Jungle Fall stream water temperature and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

Valley are lower than 40% saturation (Fig. 8). Again, this is expected for a low latitude, low elevation, humid zone tropical stream (Dudgeon, 2011). DO evinced a decreasing trend from 28 Nov 2017 to 13 Mar 2018 (except one reading on 16 Jan 2018). The high reading on 16 Jan 2018 (during the temporal survey) and 16 June 2018 (during the spatial survey at site FV9) could be an anomaly. Again, no significant differences were observed between stream locations. Similar to other Bukit Timah streams, Fern Valley had much lower DO compared to tropical headwaters globally.

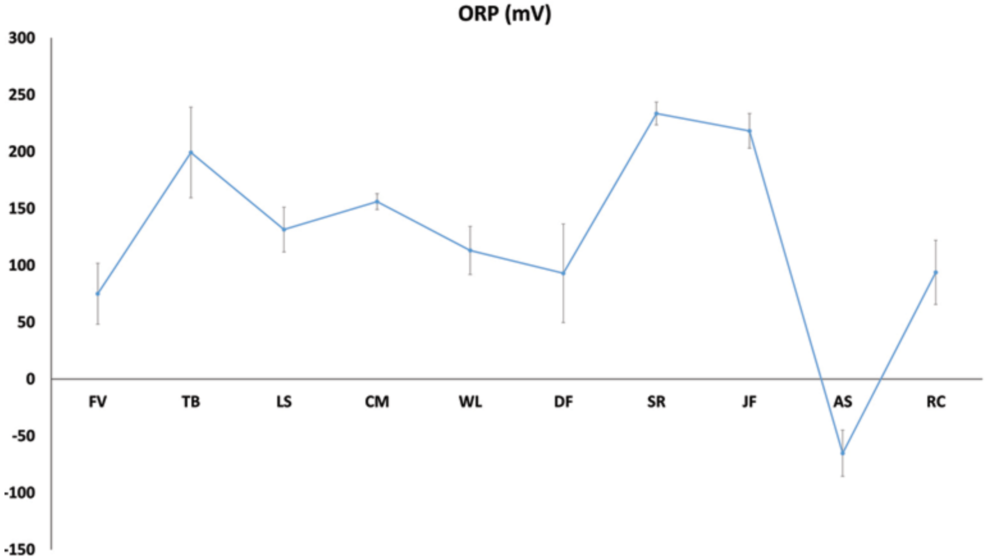


Fig. 6. Oxidation-reduction potential (ORP) (Mean±SE) at various survey streams.

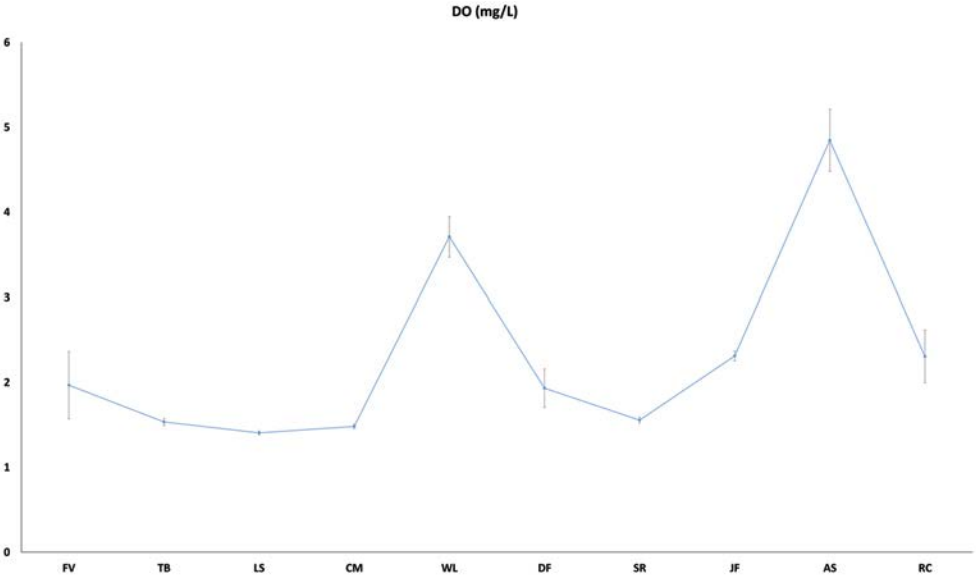


Fig. 7. Dissolved oxygen (DO) (Mean±SE) at various survey streams.

1.3.4 *Jungle Fall.*

Jungle Fall stream DO fluctuates from 12.4 to 53.1%, equivalent to 1.01 to 4.38 mg/L (Fig. 9) and was again similar to readings from Fern Valley (Fig. 8) (omitting readings in June and July for reasons explained previously). Our spatial survey results (25.4 to 31.73%) lie within the range of variation. It is worth noting that DO in Fern Valley and Jungle Fall streams shows a similar pattern of decrease (Fig. 8–9) and both readings are lower than in other tropical headwater streams. There is no clear difference in DO between the two surveyed sites in Jungle Fall stream.

1.4. *Conductivity*

1.4.1 *General synopsis.*

Conductivity is an important parameter because it directly relates to the amounts of dissolved ions in water (Davie, 2008).

1.4.2 *BTNR streams.*

Differing patterns of conductivity were evident in several of the streams at BTNR (Table 1; Fig. 10). Conductivity in the Fern Valley stream was fairly constant. Although small, the Taban stream has much lower conductivity at the outlet compared to the other streams. The Wallace stream has an opposite trend in conductivity measurements compared to Taban, the lowest conductivity being observed at the upper stream. In the Rail Corridor stream, on the contrary, conductivity is highest at the outlet. For the Dairy Farm stream, conductivity is high at its outlet and decreases upstream. Conductivity in the Lasia stream is difficult to explain since it is high at the upper stream and slightly lower at the confluence but becomes high again at the outlet. Both Seraya and Asas streams have low conductivity downstream and increase towards the headwaters. In the Catchment stream, in the southern tributary conductivity increases upstream, whereas there is no obvious pattern for the northern tributary. Compared to other tropical streams, Bukit Timah streams have much lower conductivity than small, lowland streams in Costa Rica (mean 300 µS/cm, range from 239-403 µS/cm) and Ecuadorian Eastern Cordillera (from 26 to 249 µS/cm) (Dudgeon, 2011).

1.4.3 *Fern Valley.*

In Fern Valley Stream, conductivity was similar in samples from the upper and middle reaches and in both it was significantly lower than in the lower reach of the stream (Fig. 11). The values ranged from 48 to 56 µS/cm and are comparatively low in all three sites in Fern Valley. Compared to results during the spatial survey (ranging from 62.50 to 78.33 µS/cm), conductivity data taken during the temporal survey is slightly lower. Although much lower than in other tropical headwaters, Fern Valley stream's conductivity is comparable to that from tropical rivers in forested and lightly disturbed agricultural areas (28 to 53 µS/cm) in Brazil (Bere & Tundisi, 2011). It is also comparable to the upper part of the main stream at Springleaf – a site in Singapore that acts as a buffer to Nee Soon freshwater swamp forest catchment, of high conservation importance – where conductivity ranges from 43 to 69 µS/cm (Y. Cai, unpublished data). This result suggests that conditions in Fern Valley stream are natural and probably reflect an undisturbed condition.

1.4.4 *Jungle Fall.*

Conductivity in Jungle Fall stream was in the range 51–67 µS/cm (Fig. 12), slightly but significantly higher than the values from Fern Valley. Within the stream, the upper reach has significantly higher conductivity and TDS than the lower reach. It is evident that, like Fern Valley, Jungle Fall stream is relatively unpolluted given its low conductivity in comparison with Springleaf and other tropical headwater catchments.

1.5. *Total dissolved solids (TDS)*

1.5.1 *General synopsis.*

Total dissolved solids (TDS) represent the total concentration of dissolved substances in water and are made up of inorganic salts as well as a small amount of organic matter. Some examples of inorganic solids are minerals like calcium, magnesium, chlorides and nitrates. If there is a high concentration of dissolved salts in the water, many forms of aquatic life will be affected. Total dissolved solids reflect similar patterns to conductivity because they are interdependent (Walton, 1989; Thirumalini & Joseph, 2009). From a toxicological viewpoint, the higher the TDS is, the greater the chance of the water being contaminated.

1.5.2 *BTNR streams.*

Despite low conductivity (Table 1; Fig. 13), TDS in the Bukit Timah streams ranges from 1–139 mg/L, with an average of 36.35 mg/L, and is comparable to other tropical streams such as Nova Ponte (TDS 15.2±11.8 mg/L), Três Marias (TDS 41.1±33.5 mg/L), Volta Grande (TDS 19.8±23.9 mg/L) and São Simão (TDS 38.6±31.5 mg/L) (Ferreira et al., 2017), and to Upper Araguari River Basins, Brazil, an area with mainly metamorphic rock and agricultural land use (TDS 15.2±11.8 mg/L) (Ferreira et al., 2014). TDS in Bukit Timah streams is much lower than in a series of headwater streams in Turabo watershed, a catchment dominated by forest cover in its upper part, in Puerto Rico (TDS from 76.6–353.8 mg/L) (Burgos-Caraballo et al., 2014). It is interesting that TDS in Bukit Timah streams is lower than the world average TDS of 100 mg/L (Meybeck, 1981). However, TDS in Asas stream is significantly higher compared to all the other streams in BTNR, indicating its unhealthiness for aquatic life.

1.5.3 *Fern Valley.*

The TDS levels in Fern Valley stream was in the range 29.9–35.7 mg/L (Fig. 14), comparable to levels in the tropical headwater streams mentioned above but lower than the global average TDS for rivers of 100 mg/L (Meybeck, 1981). Interestingly, TDS readings for streams in Bukit Timah during the 1960s were similar (28.8 mg/L) (Douglas, 1967) to those found today. Fern Valley TDS is slightly lower than

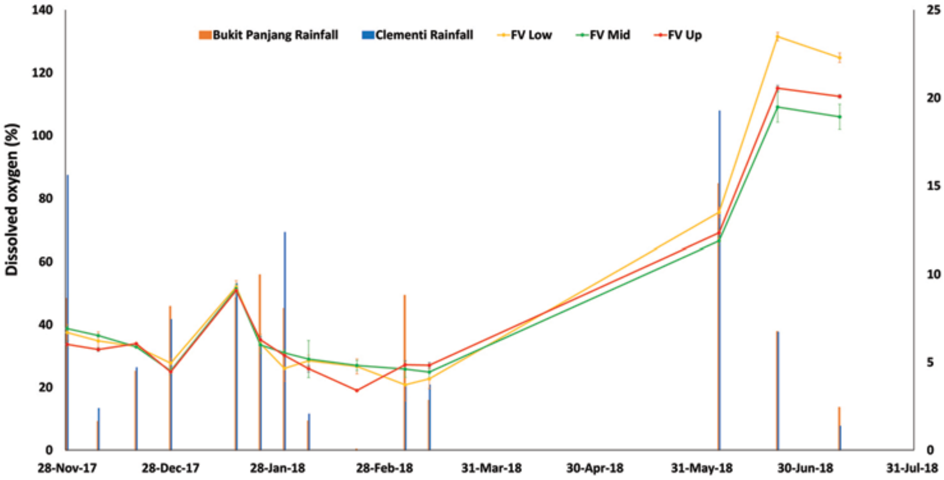


Fig. 8. Fern Valley stream water dissolved oxygen (DO) and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

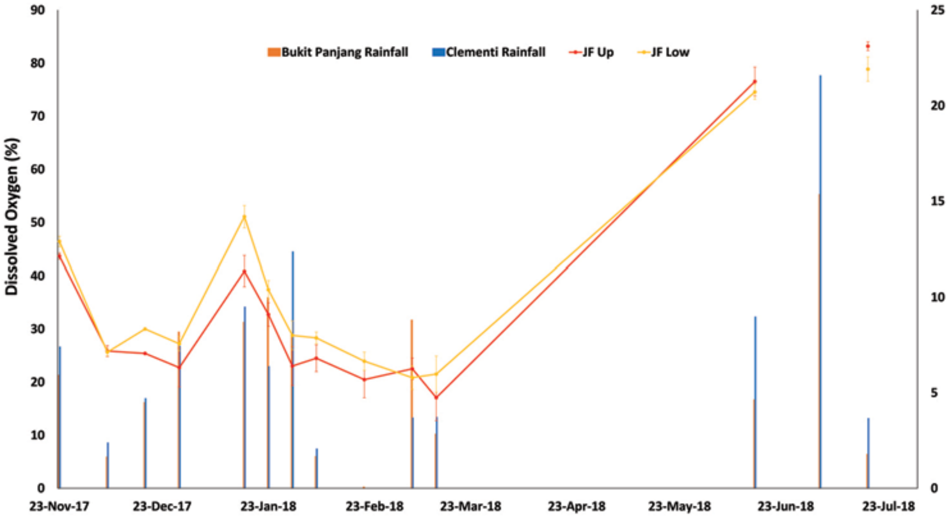


Fig. 9. Jungle Fall stream water Dissolved Oxygen (DO) and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

Springleaf stream (40–80 mg/L) and Dermawan stream near Bukit Gombak (~65–90 mg/L, unpublished data). Within-stream variation in TDS, like temperature and conductivity, is significantly greater in the lower reach than it is in the middle and upper reaches.

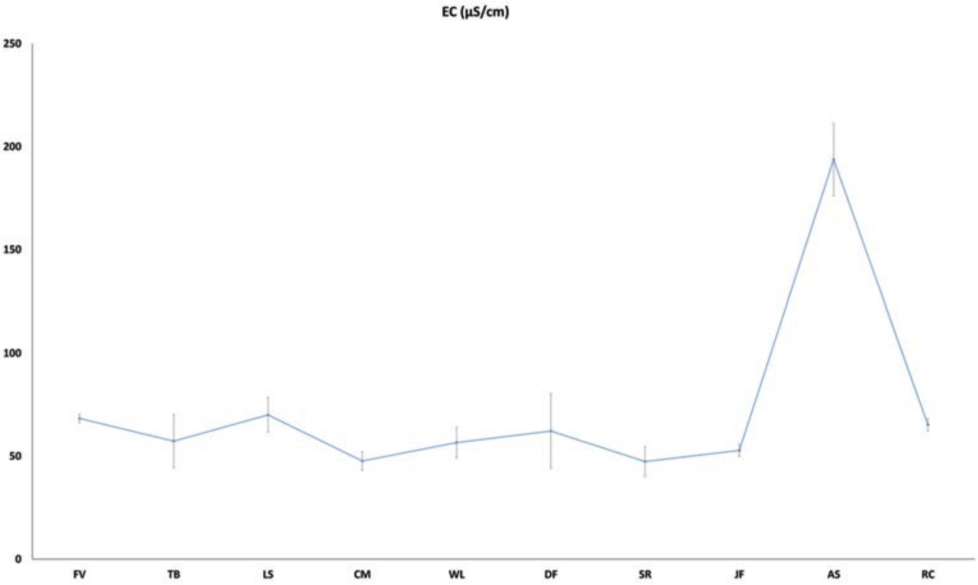


Fig. 10. Conductivity (EC) (Mean±SE) at various survey streams

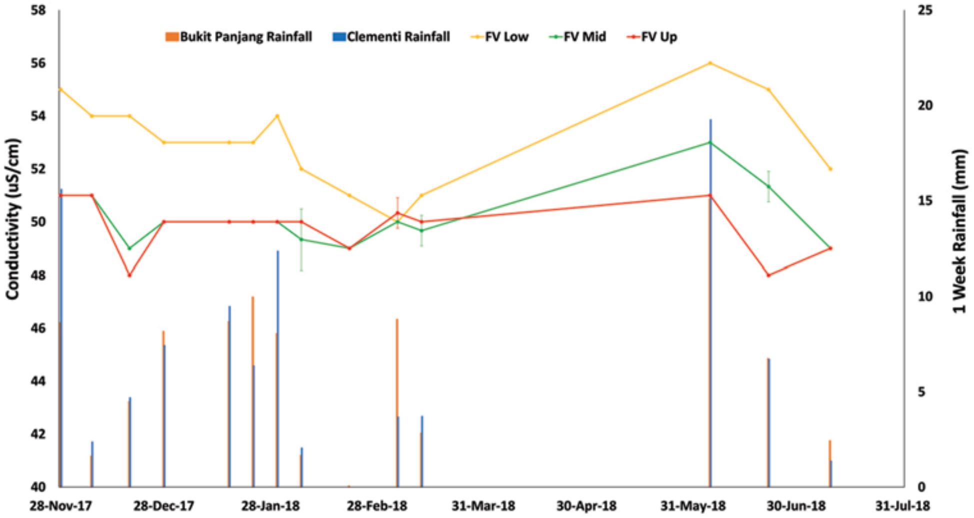


Fig. 11. Fern Valley stream water conductivity and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

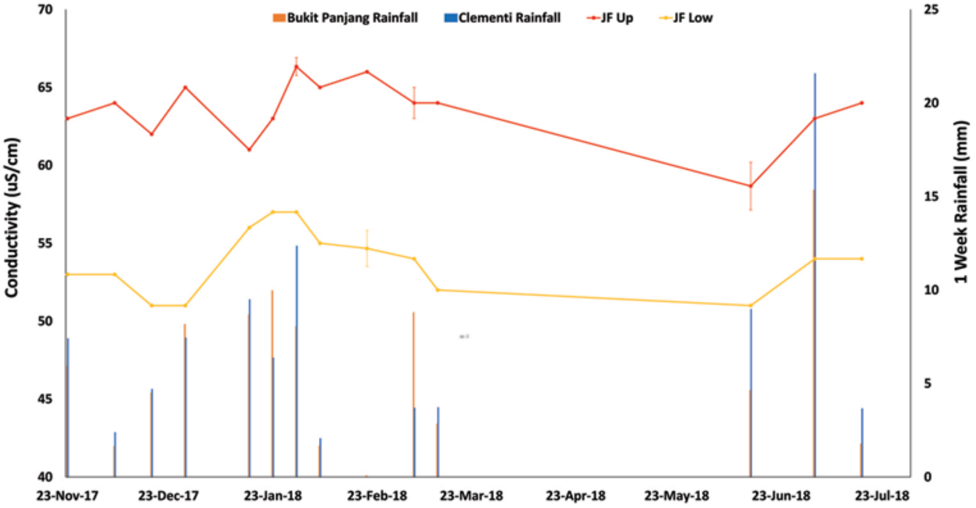


Fig. 12. Jungle Fall stream water conductivity and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

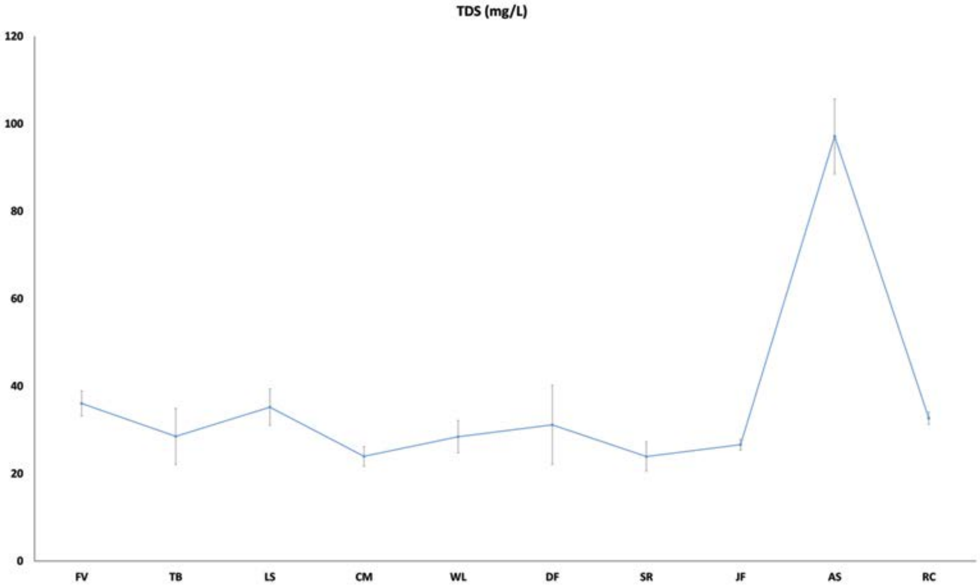


Fig. 13. Total Dissolved solids (TDS) (Mean±SE) at various survey streams

1.5.4 *Jungle Fall.*

TDS values in Jungle Fall stream was in the range 32.5–42.9 mg/L (Fig. 15), slightly but significantly higher than those from Fern Valley. TDS in the upper reach is higher than in the lower reach, which is opposite to the situation in Fern Valley stream.

1.6. *Turbidity and total suspended solids (TSS)*

1.6.1 *General synopsis.*

Turbidity gives an indication of the clarity of water and is influenced by the amount of suspended materials in the water column. It is the measure of how suspended particles in water will affect its clarity. Aquatic animals are generally not directly affected by high turbidity but by the environmental changes that are linked to turbidity such as reduced dissolved oxygen (Starkey & Karr, 1984). Submerged aquatic plants in the deeper parts of streams would be affected by turbidity as turbid water would reduce the penetration of sunlight into the water. Total Suspended Solids (TSS) are particles that are larger than 2 µm found in the water column (Fondriest Environmental, 2014). Most suspended solids consist of inorganic materials. Turbidity measurements here are given in Formazin Nephelometric Units (FNU), a measure of scattered light at 90 degrees from the incident light beam, using an infrared light source according to the International Standards Organisation (ISO) 7027 method.

1.6.2 *BTNR streams.*

In BTNR, mean values of turbidity for various streams are from 17.64±0.89 FNU (Rail Corridor stream) to 29.49±3.6 FNU (Wallace stream), and the overall average value for all stream reaches is 24.39 FNU (Table 1; Fig. 16).

1.6.3 *Fern Valley.*

Nearly all TSS measurements at Fern Valley were zero (Fig. 17), in agreement with the clear water observed. TSS paralleled the low observed turbidity (also zero for most samples; data not shown). Compared to TDS, the stream’s TSS is considerably lower.

1.6.4 *Jungle Fall.*

Similar to Fern Valley, most of the TSS readings for Jungle Fall stream are zero (Fig. 18) and, in general, lower than TDS.

1.7. *Salinity*

1.7.1 *General synopsis.*

Salinity of the water refers to the dissolved ions concentration in the water. Generally, salinity increases as the stream flows downstream. The salinity of a stream would affect the plants and animals in the stream as most of the freshwater adapted species are unable to maintain their internal ionic balance in saline water. Fresh water is typically defined as having a salinity of less than 0.05 ppt.

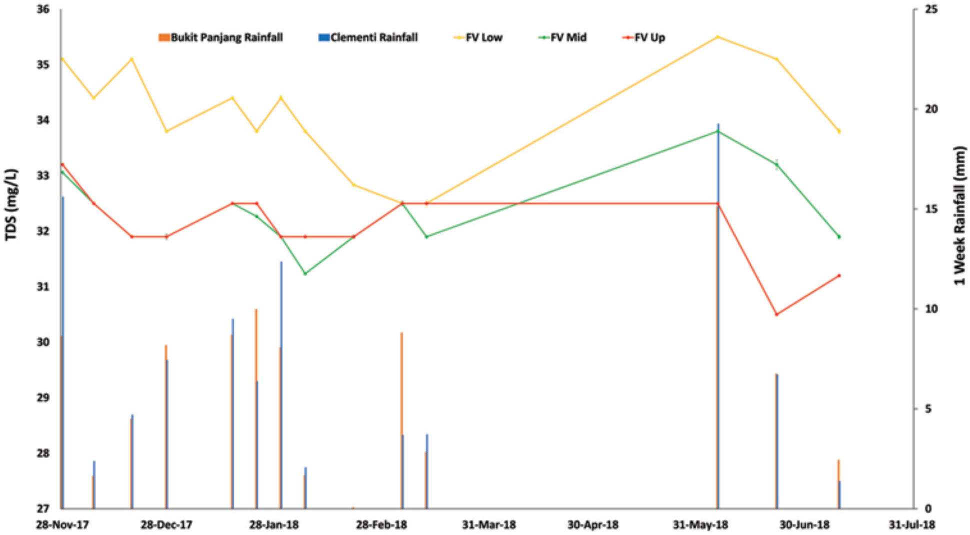


Fig. 14. Fern Valley stream water Total Dissolved solids (TDS) and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

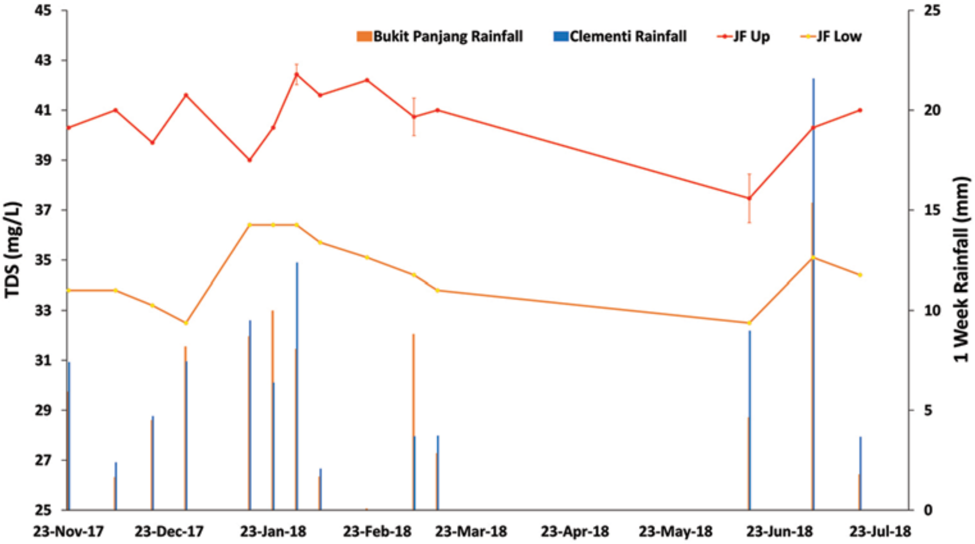


Fig. 15. Jungle Fall stream water Total Dissolved Solids and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

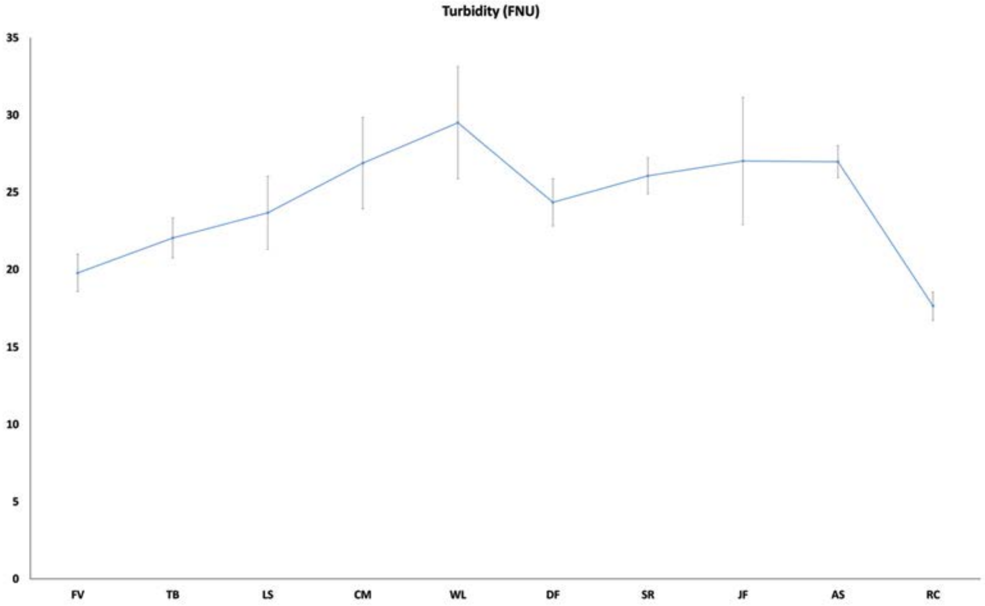


Fig. 16. Turbidity (Mean±SE) at various survey streams

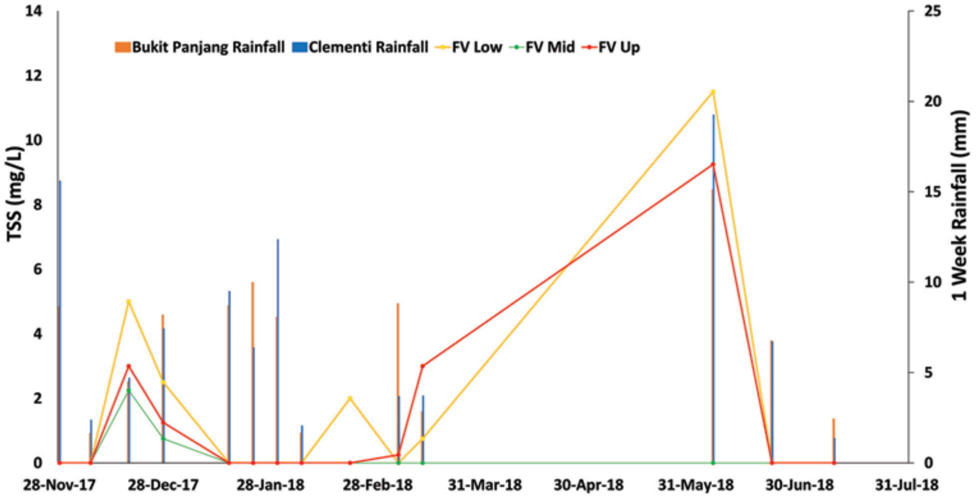


Fig. 17. Fern Valley stream water Total Suspended solids (TSS) and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

1.7.2 *BTNR streams.*

For salinity (ppt), Bukit Timah streams show very low values. For 78 readings from nine of the streams, there were only three salinity readings above 0.05 ppt (two for Lasia stream and one for Dairy Farm); but for Asas stream all six readings were in the range 0.07 to 0.13 ppt with a mean of 0.09 ppt (Table 1; Fig. 19). Salinity can reach 30 ppt or higher in streams subject to tidal influence (Wolanski, 1986; Jennerjahn et al., 2004). Among all streams in BTNR, the higher salinity in Asas stream is probably owing to its link to the Singapore Quarry.

1.7.3 *Fern Valley and Jungle Fall.*

Salinity in Fern Valley is low and constant (0.02ppt) since there is no tidal influence. Jungle Fall stream showed a small difference in salinity between the upper (0.03 ppt) and lower reaches (0.02 ppt) although they are within the range of natural fresh water, as expected.

1.8. *Stream acidity (pH)*

1.8.1 *General synopsis.*

Stream acidity (pH) is a measure of the amount of free hydrogen ions in the water and neutral levels have a pH of 7. Watercourse pH is usually slightly alkaline, with pH slightly greater than 7 but with ranges from 6 to 9. Stream pH has implications for the availability of calcium and other elements, particularly for crustaceans, molluscs and other aquatic organisms.

1.8.2 *BTNR streams.*

Among all stream parameters, pH is the best studied in Bukit Timah streams. The oldest available literature reported pH from 6.0–6.3 in Bukit Timah but the stream name was not mentioned (Douglas, 1967). The best-studied stream is Jungle Fall stream (Phang, 2009; Huang, 2011; Yeo, 2014; Ng et al., 2015b). All of these studies indicated low stream pH in Jungle Fall. In detail, stream pH readings at specific locations in Jungle Falls were 4.34; 4.25; 4.94 (Phang, 2009; Huang, 2011). Yeo (2014) measured pH along the stream for 10 weeks and found the pH level to be from 2.96 to 4.53 (median 3.97) whereas Ng et al. (2015b) reported a pH of 4.5±0.2. In our surveys, water acidity varies among streams and is particularly low in Jungle Fall (pH from 4.35 to 4.56) and Seraya stream (4.31 to 4.97) (Table 1; Fig. 20). The streams with higher pH are Fern Valley (4.88 to 5.67), Taban (4.44 to 5.89), Lasia (4.24 to 6.60), Catchment (4.34 to 5.67), Wallace (4.59 to 6.17), Dairy Farm (4.47 to 6.77), Asas (6.34 to 7.06) and Rail Corridor stream (4.76 to 6.66) (Table 1). It is worth noting that stream pH is low in the upstream reaches and is increasingly higher in the lower reaches, except for Asas stream. The high pH in the lower reach could be due to acidic groundwater, percolating through acidic soils in Bukit Timah (Zhao et al., 1994), being neutralised by streambed substances and earth banks (e.g. soil base cations) (Yeo, 2014) as it flows downstream.

Compared to other tropical headwater streams, with the exception of Jungle Fall and Seraya, Bukit Timah streams show pH values lower than or comparable to natural forested sites such as Água Limpa (pH 6.5), Correias (6.7), Chaparrals (7.1), Brazil (dos Santos Rosa et al., 2013), but lower than small, lowland streams in the moist tropical forests of Costa Rica (7.7 to 8.2) (Lorion and Kennedy, 2009), Upper Araguari Basin, Brazil (6.9±0.46) (Ferreira et al., 2014), lower than four hydrologic units in a humid tropical and seasonal climate in the São Francisco catchment, Brazil, i.e. Nova Ponte (6.89±0.46), Três Marias (7.7±0.5), Volta Grande (7.1±1.8) and São Simão (6.8±0.5) (Ferreira et al., 2017), and lower than a series of streams in Turabo watershed, Puerto Rico (pH from 7.04 to 8.00) (Burgos-Caraballo et al., 2014). Low stream pH in Bukit Timah is expected to occur naturally given the acidic Bukit Timah granite rock and its derived soils (Ives, 1977; Zhao et al., 1994).

As mentioned above, the location of the earliest pH readings, 6.0–6.3 by Douglas (1967) is unknown. The nearby Hindhede lake has nearly neutral pH, from 7.7 to 7.85 (Lim, 1997).

1.8.3 *Fern Valley.*

Our observations reveal that Fern Valley stream pH ranges from 4.71 to 5.87 (Fig. 21). There was no obvious trend in pH during our survey period, nevertheless the lower reach is always higher than the middle and upper reaches. There is no statistical difference between the upper and middle reaches. This pattern was also observed for streams in other catchments nearby, e.g. Nee Soon freshwater swamp forest catchment (Nguyen et al., 2018b) and Springleaf stream (unpublished data). As explained earlier, it is believed that stream pH is low in the upstream reach because water washes over or flows through acidic soil before emerging to the surface and is then progressively neutralised by alkaline substrates while travelling downstream. In addition, our results suggest that there has been a slight decrease in stream pH compared to those readings in the 1960s (Douglas, 1967).

1.8.4 *Jungle Fall.*

Stream acidification in Jungle Fall has long been documented (Phang, 2009; Ho, 2009; Tan, 2010; Huang, 2011; Oon, 2012; Yeo, 2014; Ng et al., 2015b). Our temporal survey revealed Jungle Fall stream pH varies from 3.90 to 4.42 (Median 4.21±0.11) (Fig. 22). In general, pH from our observations is somewhat higher compared to the study by Yeo (2014) but lower than Ng et al. (2015b). Interestingly, our observations indicate lower stream pH at the upper compared to the lower reach, which contradicts the findings by Yeo (2014). The contradiction possibly reflects seasonal variation (our study period was from 23 Nov to 17 Jul while Yeo's was from 23 Aug to 26 Oct).

The Singapore freshwater crab *Johora singaporensis* Ng, 1986, is listed on the International Union for Conservation of Nature (IUCN) Red List of Threatened Species as critically endangered and regarded as one of the top 100 threatened species in the world (Ng et al., 2015a). It was thought that this crab could already be extinct

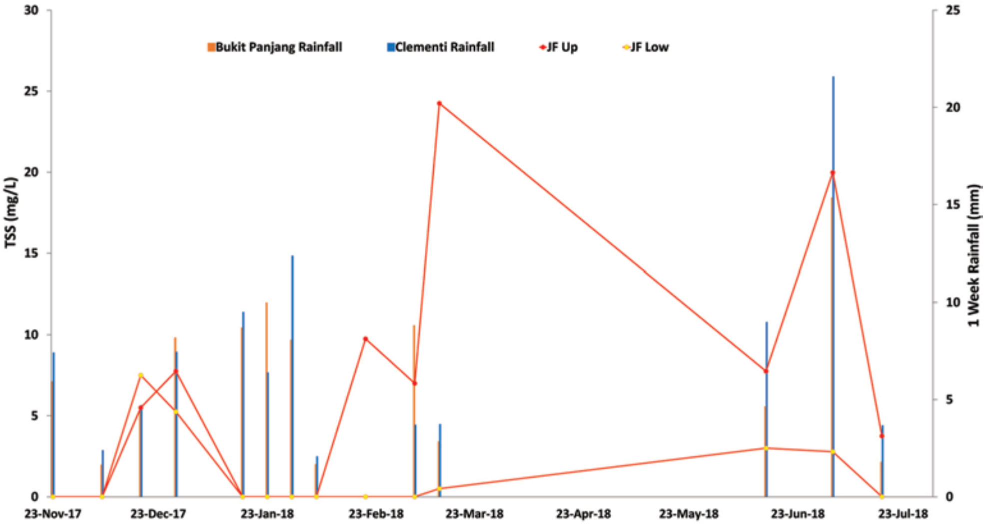


Fig. 18. Jungle Fall stream water Total Suspended Solids and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

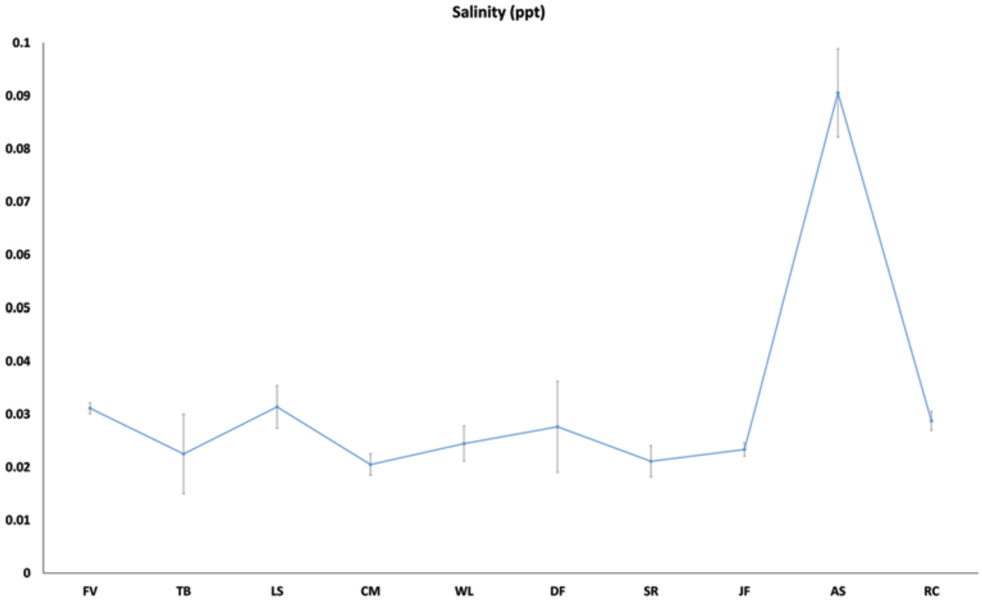


Fig. 19. Salinity (Mean±SE) at various survey streams

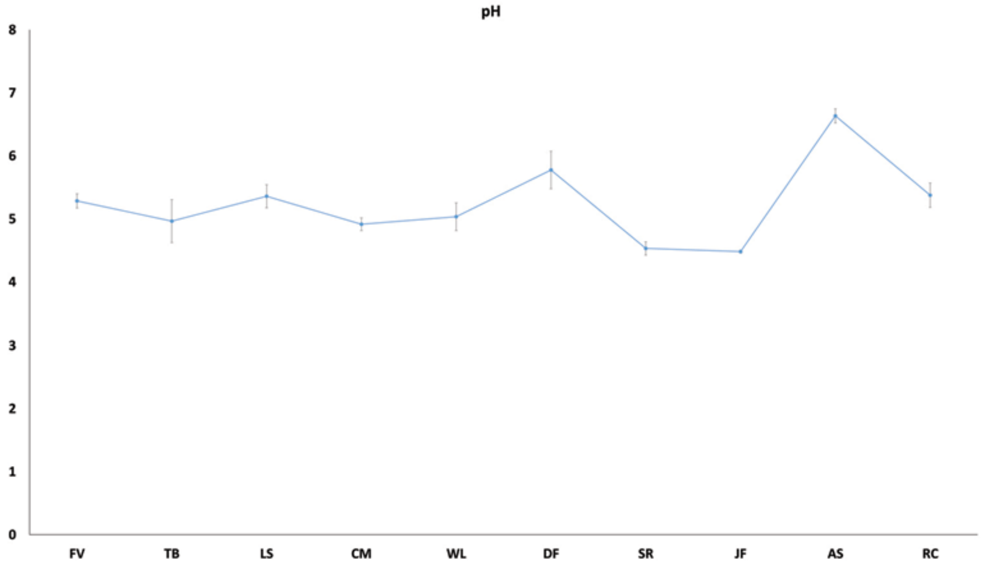


Fig. 20. pH (Mean±SE) at various survey streams

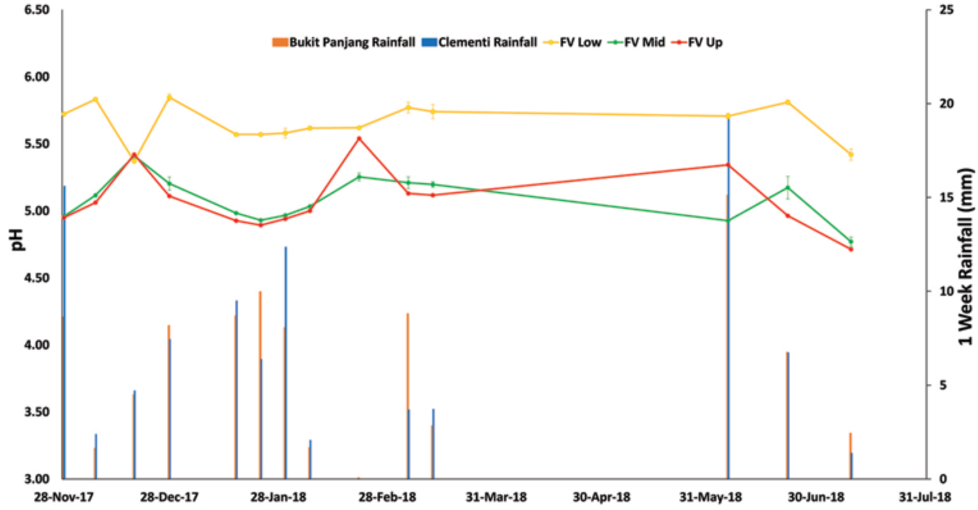


Fig. 21. Fern Valley stream water pH and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

in the reserve (Tan et al., 2010); its extinction in Jungle Fall stream has since been confirmed but its presence in other BTNR streams has been documented (Khoo et al., 2019). The suspected reasons for its decline include the acidification of water along with the loss of forest cover, aquatic pollution and the lowering of the water table (Tan et al., 2010; Esser et al., 2008). The issue of acidification is complicated as streams in

BTNR are also naturally acidic, as the bedrock of the reserve is granite which provides low buffer capacity, and decomposition of organic matter in the humid forest floor of hill slopes as well as litter within the stream channel produces natural organic acids that lower the water pH. Oon (2012) described results from a stream-water chemistry monitoring programme that was established at Jungle Fall stream in 2005. She found that stream-water pH can decrease by 0.2 to 0.3 pH units following storm events that flush organic acids from the litter into the stream. However, human induced acidification has also been suspected at Jungle Fall stream (Oon, 2012). Through the analysis of diatom communities as well as trace metal concentration in Jungle Stream, Oon (2012) showed that the stream sediments contain a record of atmospheric contamination in the area. The trace metal peak found at 15 cm depth in sediments may correspond to the mid to late 1960s when Singapore was undergoing rapid industrialisation and pollution controls were not yet in place, resulting in raised levels of atmospheric pollution and contamination."

The pH values examined for five (FV Up, FV Mid, FV Low, JF Up and JF Low) sampling stations in Jungle Fall and Fern Valley seem to be negatively correlated to the one-week rainfall (Fig. 21–22), with about two weeks lag time period. Stream pH increased during dry weather in December 2017, February and June/July 2018, and significantly decreased when rainfall was higher. A similar trend has been reported by Small et al. (2012) who analysed 14 years of monthly observations from 13 sampling stations in eight tropical streams in lowland Costa Rica. Stream pH increased during the 4-month dry season and declined throughout the wet season. The magnitude of the seasonal pH decline was greatest following the driest dry seasons. Their results show tight coupling between rainfall, terrestrial and aquatic ecosystems in the tropics.

Stream acidification in Singapore is not completely understood. A long-term monitoring plan for a better understanding of pH in BTNR streams is thus needed. Compared to the nearby Fern Valley, stream pH in Jungle Fall is significantly lower, with a median difference of ~0.92 pH units. The large difference (pH value is a logarithmic scale) suggests different factors controlling pH of the two streams, despite their proximity.

1.9. *Water chemistry*

Water samples from specific locations in Fern Valley, Taban, Lasia, Catchment, Wallace, Dairy Farm, Seraya, Jungle Fall, Asas and Rail Corridor streams were collected to understand their chemical composition. The variables analysed include TOC, TN, TP, anions, cations and elements. The results are presented in Table 2.

TOC in Bukit Timah streams ranges from 0.28 to 4.06 mg/L, slightly lower than the typical range between 3 and 10 mg/L in most tropical stream waters (Lewis et al., 2006). Compared to other tropical streams, TOC in Bukit Timah is similar to those from R. Icacos, (1.93 mg/L - sum of particulate organic carbon and dissolved organic carbon), Q. Sonadora (2.54 mg/L) and Q. Toronja (1.55 mg/L), all forested catchments in Puerto Rico (McDowell & Asbury, 1994). Total Nitrogen and TP in Bukit Timah are in the range 0.8–4.3 mg/L (median 3.05 mg/L) and 0.22–0.71 mg/L (median 0.41 mg/L) respectively. Total Nitrogen is slightly higher than that from headwater streams in Puerto Rico (ranging from 0.17 to 2.39 mg/L) (Burgos-Caraballo et al., 2014), Upper Araguari Basin (0.05±0.01 mg/L) and Upper São Francisco Basin (0.24±0.98 mg/L), Brazil (Ferreira et al., 2017), whereas TP seems to be in the expected natural range compared to the sum of particulate and dissolved phosphorus in South America (sum less than 1 mg/L) (Dudgeon, 2011: 18). For anions and cations, the Bukit Timah median NH_4^+ is 0.02 mg/L, fairly similar to those from Água Limpa (0.017 mg/L) and Chaparrals (0.023 mg/L) (dos Santos Rosa et al., 2013), R. Icacos, (0.014 mg/L), Q. Sonadora (0.011 mg/L) and Q. Toronja (0.011 mg/L) (McDowell & Asbury, 1994), but lower than Correias (0.174 mg/L) (dos Santos Rosa et al., 2013). Chloride (Cl^-) in Bukit Timah varies from 1.21 to 8.21 mg/L, lower than 16 tropical headwater streams in Puerto Rico (6.58 to 35.16 mg/L); Sulphate (SO_4^{2-} (0.58 to 13.55 mg/L) is, however higher than these streams (0 to 3.63 mg/L) (Burgos-Caraballo et al., 2014). For Na^+ (0.92-8.77 mg/L, median 2.39 mg/L), K^+ (0.88-4.49 mg/L, median 2.02 mg/L), Mg^{2+} (0.48-1.38 mg/L, median 0.81 mg/L) and Ca^{2+} (1.04 – 33.50 mg/L, median 2.94 mg/L), Bukit Timah streams are similar to streams surveyed by Burgos-Caraballo et al. (2014) in terms of K^+ (0.14 to 2.90 mg/L), but lower in Na^+ (7.68 to 30.82 mg/L), Mg^{2+} (2.33 to 21.44 mg/L) and Ca^{2+} (9.42 to 28.55 mg/L). Compared to R. Icacos stream (Na^+ 5.07 mg/L; K^+ 0.51 mg/L; Mg^{2+} 1.2 mg/L and Ca^{2+} 3.33 mg/L), Bukit Timah contains slightly lower Na^+, higher K^+, similar Mg^{2+} and Ca^{2+}. In comparison with Q. Sonadora stream (Na^+ 4.36 mg/L; K^+ 0.22 mg/L; Mg^{2+} 1.4 mg/L and Ca^{2+} 2.22 mg/L), Bukit Timah is lower in Na^+, higher in K^+, lower in Mg^{2+} and slightly higher in Ca^{2+}. Compared to Q. Toronja stream (Na^+ 7.52 mg/L; K^+ 0.28 mg/L; Mg^{2+} 4.42 mg/L and Ca^{2+} 6.27 mg/L), Bukit Timah has lower Na^+, higher K^+, lower Mg^{2+} and Ca^{2+} (McDowell & Asbury, 1994). These comparisons suggest that Bukit Timah streams contain considerable amounts of TN, SO_4^{2-} and K^+, but are low in Na^+ and Cl^-. Other parameters seem to vary within their expected natural ranges.

In terms of elements, dissolved metal concentration (0.45µm filtered – Whatman® glass microfibre) is comparable to a local site in Bukit Gombak (Nguyen et al., 2018a) and within international threshold guidelines, i.e. United States Environmental Protection Agency (US EPA), Canadian Council of Ministers of the Environment (CCME), Australia and New Zealand Default guideline values (DGV). Element concentrations in BTNR streams can be compared with Singapore and WHO criteria for drinking water (Table 3). In detail, Ca, Mg and Sr in Bukit Timah streams are significantly lower than a stream in Bukit Gombak only 1.5 km from BTNR. Differences in rocks and soil types could be the reason. In Bukit Timah, acidic granite rock and soil (Ives, 1977; Lee & Zhou, 2009) reduce stream water pH whereas basic Gombak Norite rock and its derived soil (Lee & Zhou, 2009) maintain higher stream pH, as reflected in higher concentrations of alkaline elements (e.g. Ca, Mg and Sr). The concentrations of other metals, except for Mn and Ba, are fairly similar between Bukit Timah and Bukit Gombak streams (Table 3). Compared to international threshold guidelines, elements in Bukit Timah streams fluctuate within expected natural ranges (and do not exceed the threshold guidelines), except for Cd, Sb and Se. While Cd is almost one order of magnitude higher than these thresholds, Sb is about two times higher and Se is from 1.5 to 20 times higher depending on

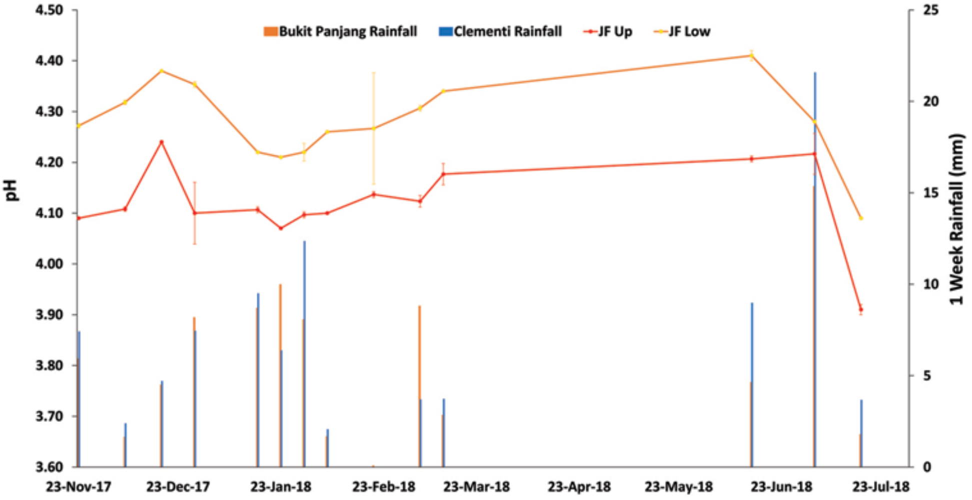


Fig. 22. Jungle Fall stream water pH and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

the compared criterion. Although Cd, Sb and Se concentrations are high, we also observed high Cd and Sb in Bukit Gombak stream (Nguyen et al., 2018a). The possible anthropogenic sources for high concentration of these elements in Bukit Timah is from World War II and historical quarry activities. Bukit Timah was a wartime munitions storage site, not an actual battle field (James Tann, 2013 – pers. comm.), and, although E.J.H. Corner was shocked by the amount of spent artillery materials left in the forest after the war, most was collected and removed thereafter (Davison & Chew, 2019). The influence of quarry activities was more prolonged, from the 1900s to the 1990s (Davison & Chew, 2019), but was not investigated in our study. Therefore, the reason for high Cd, Sb and Se in these streams is uncertain.

1.10 *Comparison of water chemistry in Fern Valley and Jungle Fall*

Water chemistry is important for aquatic life. In terms of elemental concentration, among 26 elements analysed, we only discuss elements showing reliable results in these two streams (21 in total, including Al, As, Ba, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Mo, Ni, Pb, Sb, Se, Sr, Ti, V and Zn) (Table 4). Of these, the following discussion considers only 14 elements for which extensive information is available (Cd, Cr, Cu, Ni, Pb, Zn, Ca, Ba, Mn, V, Co, Sb, Al and Fe). Given the limited number of samples, statistical analysis was employed only for external comparison (between streams) and not internal comparison (between different sites within a stream). Median ± Median Absolute Deviation (MAD) of these elements are presented in Table 4. In the following discussion we compare BTNR results with five sets of water quality guidelines: CCME (Canadian Council of Ministers for Environment, 2007), DGV (Default Guideline Values of Australia and New Zealand) (Water Quality Australia, 2014), Singapore drinking water quality guidelines (Public Utilities Board, 2018), United States Environmental Protection Agency (US EPA, 2004), and WHO (World Health Organisation, 2011). It is essential to bear in mind that the various guidelines were developed for different purposes, in different climatic, physical, chemical and biological background conditions, for different uses of water. Furthermore, BTNR streams are tiny compared with the total volume of water in Singapore or in the other countries concerned. Therefore, readings for a single element in a single sample from BTNR that fall above or below any particular guidelines must be interpreted very cautiously.

Fern Valley and Jungle Fall elemental concentrations are distinct from each other, especially for concentration of Al (50±16 µg/L for Fern Valley and 633.5±67 µg/L for Jungle Fall), Ba (188±14 and 109±18 µg/L respectively), Ca (1625±27.9 and 1239±124 µg/L respectively), K (3175±156 and 1393±118.5 µg/L respectively), Mg (876±47 and 937±60 µg/L respectively) and Sr (45±9 and 41±8 µg/L respectively). In comparison, while Fern Valley has significantly higher concentrations of Ba, Ca, K and Sr, Jungle Fall had higher concentrations of Al and Mg (Table 4). Interestingly, high amounts of Al and Mg – elements associated with stream acidification by releasing hydrogen ions through hydrolysis reaction (Grosjean et al., 2005; Franzoni et al., 2011; Zou et al., 2013) – and low amounts of alkaline elements, i.e. Ba, Ca, K and Sr, in Jungle Fall stream explain its low pH. In fact, the concentration of Al in Jungle Fall is almost one order of magnitude higher than EPA guidelines for aquatic life (Brooke & Stephan, 1988) (Table 4).

There is no difference in concentration of potentially toxic elements (e.g. As, Cd, Co, Cr, Cu, Ni, Pb, Sb, Zn) between Fern Valley and Jungle Fall streams, which may suggest negligible anthropogenic disturbance. This is further supported by the comparison between Fern Valley and Jungle Fall versus international water quality guidelines. Nineteen of 21 elements are either lower than one of the five guidelines (EPA, CCME, DGV, WHO and Singapore) or within natural ranges (Table 4). In detail, except for the remarkably high Al concentration causing low pH in Jungle Fall stream, Arsenic (As) concentration is much lower than EPA (150µg/L) and DGV (94µg/L) guidelines though it is higher than CCME guidelines (5 µg/L). Barium in both catchments is 4 to 8 times lower than WHO and Singapore guidelines whereas Ca is almost two orders of magnitude lower. Cobalt and V are two to five times lower than CCME guidelines for irrigation purposes although V is much higher than DGV guidelines. Chromium and Mo are from 2 to 3 times lower compared to these guidelines although Cr is much higher than DGV guidelines. While Cu median concentration is higher than CCME and DGV guidelines, it is much lower than the other guidelines. Iron, Ni, Mo and Mn were also low compared to these criteria, except for Ni that exceeds the DGV guidelines. Lead, given the large MAD, is comparable to the WHO and Singapore guidelines, lower than EPA but much higher than CCME and DGV guidelines. Zinc concentrations are lower than EPA but higher than CCME and DGV guidelines. Cadmium, Sb and Se, however, exceeded these guidelines (Table 4). While median concentrations of Sb and Se were only slightly above the guidelines, Cd is much higher than all criteria. Indeed, given the large MADs, it is most likely that Sb and Se are still within the guidelines' threshold. Cadmium and Se medians,

Table 3. Median elemental concentrations (µg/L) in streams within and adjacent to Bukit Timah Nature Reserve, Singapore, in comparison with streams in Bukit Gombak, versus five national or international guidelines. See text for abbreviations and references to guidelines.

	Cd	**Cr**	**Cu**	**K**	**Ni**	**Pb**	**Zn**	**Ca**	**Ba**	**Mg**
Bukit Gombak (Median±MAD)	26 ±2	55 ±2.5	28.5 ±5.03	-	33 ±9.56	40.9 ±5.6	44 ±2.76	13875 ±1015	54.8 ±1.31	5292 ±228
US EPA	1.8	74a,e	5.2-1290		470	65	120			
CCME	0.09a		2b		25b	1b	30	100000c		
DGV	0.4	3.3	1.8	-	13	5.6	15	-	-	-
Singapore	3	50	2000		70	10			700	
WHO	3	50	2000		70	10			700	
Bukit Timah (Median)	29	43	29	2177	25	44	51.5	1892.5	147.5	798

	Sr	**Mn**	**V**	**Co**	**Sb**	**Se**	**Ti**	**Na**	**Al**	**Fe**
Bukit Gombak (Median±MAD)	89.5 ±2.5	33.3 ±3.26	51 ±10	34 ±1	42 ±10.2	84 ±17	24 ±1.4	-	79 ±23	80.5 ±28.5
US EPA						3.1			87	1000
CCME		200c	100c	50c		1				300
DGV	-	2500	6	-	9	18	-		0.8	-
Singapore		400			20	10			100-200	
WHO					20	40			100d	
Bukit Timah (Median)	50.5	84	47	27	51.5	65	31	3505.5	104	64

Legend: a. Chronic; b. For water hardness of 50 mg/L $CaCO_3$; c. For irrigation purposes; d. Screening values; e. Chromium (III)

Table 4. Water chemistry (Median ± MAD) of Fern Valley and Jungle Fall streams, Bukit Timah Nature Reserve, Singapore. Units in µg/L.

		Al	**As**	**Ba**	**Ca**	**Cd**	**Co**	**Cr**	**Cu**	**Fe**	**K**
Fern Valley	Median	50	35	188	1625	21	38	44	23.4	26.5	3175
	MAD	16	7	14	279	1.7	3.9	0.9	5.1	18	156
Jungle Fall	Median	633.5	33	109	1239	22.5	32	42.5	22	25	1393
	MAD	67	15	18	124	3.3	6.9	1.5	8	15	118.5
EPA		87	150^b			1.8		$74^{a,b}$	5.2-1290	1000	
CCME			5		100000^c	0.09^b	50^c		2^d	300	
Singapore		100-200		700		3		50	2000		
WHO		100^e		700		3		50	2000		
DGV		0.8	94	-	-	0.4	-	3.3	1.8	-	-

		Mg	**Mn**	**Mo**	**Ni**	**Pb**	**Sb**	**Se**	**Sr**	**Ti**	**V**	**Zn**
Fern Valley	Median	876	60	18	27	36	23	28.5	45	31	43	48.7
	MAD	47	14	13.1	5	10.5	20	15	9	0.3	6	1.3
Jungle Fall	Median	937	73	18	24.5	27.1	40.6	29	41	31	36.5	49
	MAD	60	13.5	10	3.5	15	17.4	13	8	0.3	8	1.7
EPA					470	65		3.1				120
CCME			200^c	73	25^d	1^d		1			100^c	30
Singapore			400	70	70	10	20	10				
WHO					70	10	20	40				
DGV		-	2500	34	13	5.6	9	18	-	-	6	15

Legend: a. Chromium (III); b. chronic; c. for irrigation purposes; d. for water hardness of 50 mg/L CaCO$_3$; e. screening values. See text for abbreviations and references to guidelines however, are significantly higher than EPA, CCME (for Cd, Se) and WHO/Singapore/DGV guidelines (for Cd). Interestingly, a high concentration of Cd was also observed in Dermawan stream, flowing through alkaline, Gombak Norites derived soil in Bukit Gombak (Nguyen et al., 2018a), a different soil type from the acidic Jungle Fall soil (Ives, 1977), suggesting that high Cd in these streams could be from outside sources. However, the source of Cd in the current data is inconclusive and more work needs to be done on this matter.

For K, Mg, Sr and Ti, there are no available guideline concentrations for the protection of aquatic life. Thus, their values are compared qualitatively to others from different regions. Potassium is an essential element. A study in the United Kingdom found average K concentration in drinking water of 2.5 mg/L (Powell et al., 1987) which is comparable to Fern Valley and Jungle Fall streams (3.175±0.156 and 1.393±0.118 mg/L, respectively). Magnesium concentration in untreated water could be as high as several tens mg/L (Hofman et al., 2006), which is much higher than those of Fern Valley and Jungle Fall. Strontium in rivers is considered low if its concentration is less than 0.5 mg/L (Skougstad & Horr, 1960) and, in general, river water average Sr concentration is ~50 µg/L (Lenntech, 2018). Thus, Fern Valley and Jungle Fall streams contain comparatively low Sr. For Ti, our reported concentrations are 31±0.3 and 36.5±8 µg/L in Fern Valley and Jungle Fall, respectively, lower than the world's typical surface water concentration (ranges from 0.0 to 1180 µg/L) (Linnik & Zhezherya, 2015).

It is also noteworthy that many Fern Valley and Jungle Fall stream elemental concentrations (Al, Cd, Co, Cr, Cu, Ni, Pb, Sb, Se, V and Zn), although low, are significantly higher than the Australian and New Zealand freshwater default guideline values (DGVs) (Table 3, Table 4). However, DGVs may not be as relevant as other criteria given that Australia and New Zealand are isolated islands in the southern hemisphere. DGVs are usually much lower than the other guidelines (except for Mn), for greater protection of their enclosed systems.

2. *Correlation between rainfall and stream's parameters*

To evaluate the study site conditions prior to the actual fieldwork date, same-day rainfall data may not be representative of the "wet" or "dry" conditions of the catchment. In fact, we did not find a correlation between daily rainfall and the stream's parameters (data not shown). Weekly rainfall data are more likely to be representative. Therefore, we calculated average daily rainfall data for the week prior to the actual field date (herein referred as "1-week rainfall data") and compared these data with the parameters measured on the site (Fig. 4–22) to understand the impacts of rainfall on streams.

Limited studies have shown positive correlations between rainfall and TSS, NO_3^-, PO_4^{3-}, TP, TP, TN, salts and sediment. Prathumratana et al. (2008) reported the relationship of climatic and hydrological parameters to surface water quality in the lower Mekong River, and Lintern et al. (2018) reported the key factors influencing spatial differences in stream water quality. However, in our study, we observed no correlations between rainfall and these parameters. Instead, we observed positive correlation between 1-week rainfall data with Conductivity and TDS at Fern Valley lower stream and middle streams for both rain gauge stations (Fig. 11, Fig. 14). This observation must not lead to the erroneous notion that TDS and Conductivity in Fern Valley stream are driven by salt spray (containing ions) concentrated in rainfall from the ocean, because salinity during the entire study period was low and constant (0.2 ppt). Instead, it suggests that rainfall may enhance dissolution loss from the catchment soils. Other studies, however, have reported a negative correlation between rainfall and Conductivity (Prathumratana et al., 2008).

Interestingly, there is a positive correlation between stream temperature and rainfall in Fern Valley low stream which could be due to the influence of prevailing weather during these periods. Rainfall and water discharge were also positively correlated at Jungle Fall lower stream, but not at Fern Valley, suggesting that rainfall possibly impacts water temperature more in smaller rather than larger catchments (in this case the Jungle Fall catchment (~7 ha) is much smaller than Fern Valley catchment (~22 ha)). Additionally, there are positive correlations between rainfall and Ca concentration at Fern Valley lower and middle streams; negative correlations between rainfall and NO_3^- concentration at Fern Valley lower reach and Jungle Fall upper reach, which are contradictory to observations in the vast Mekong River (Prathumratana et al., 2008). Although TSS in Fern Valley and Jungle Fall is very low (most of the time TSS = 0 mg/L), significantly high TSS readings at Fern Valley lower reach and upper reach were concurrent with high rainfall on 5 June 2018 (Fig. 17 & 23). This correlation has also been reported in other studies (Prathumratana et al., 2008; Lintern et al., 2018) as rainfall induced runoff carries more particulate matter, leading to high TSS. High rainfall is linked to higher stream discharge, as observed in Jungle Fall discharge at the lower reach (Fig. 24).

It is worth noting that although some correlations were observed, the influence of rainfall on a stream's parameters need to be carefully interpreted given the relatively low numbers of observations and locations that reveal any statistically significant correlations. More observations are thus needed to clearly demonstrate and explain these correlations.

3. *Influence of water discharges to stream's dissolved and suspended loads*

Table 5 presents Fern Valley and Jungle Fall stream water quantity parameters i.e. water discharge, total dissolved and suspended loads. Within the studied periods (from 28 Nov 2017 to 10 Jul 2018 for Fern Valley and from 23 Nov 2017 to 17 Jul 2018 for Jungle Fall), stream water discharge was much higher in Fern Valley (3.41 to 25.38 L/s) compared to Jungle Fall (2.19 to 3.11 L/s), which is related to their respective catchment sizes. This results in higher total dissolved and suspended loads in Fern Valley despite the two streams having fairly similar TDS and TSS. Total dissolved load in Fern Valley fluctuated from 4.01 to 30.35 tonnes/year, roughly 4.5 times higher than those from Jungle Fall, which ranged from 2.48 to 3.93 tonnes/year. Similarly, total suspended load in Fern Valley (averaged at 0.83 tonnes/year) is also high compared to Jungle Fall (averaged at 0.31 tonnes/year). In general, both Fern Valley

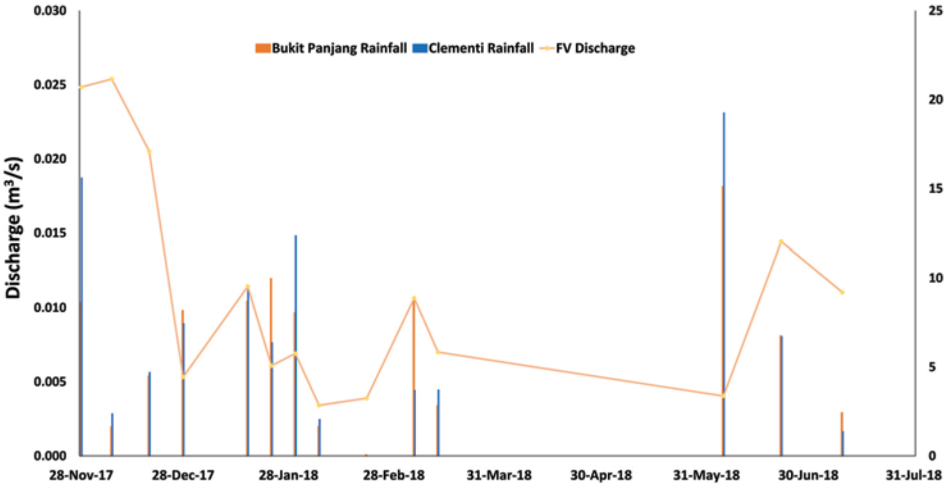


Fig. 23. Fern Valley stream discharge and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

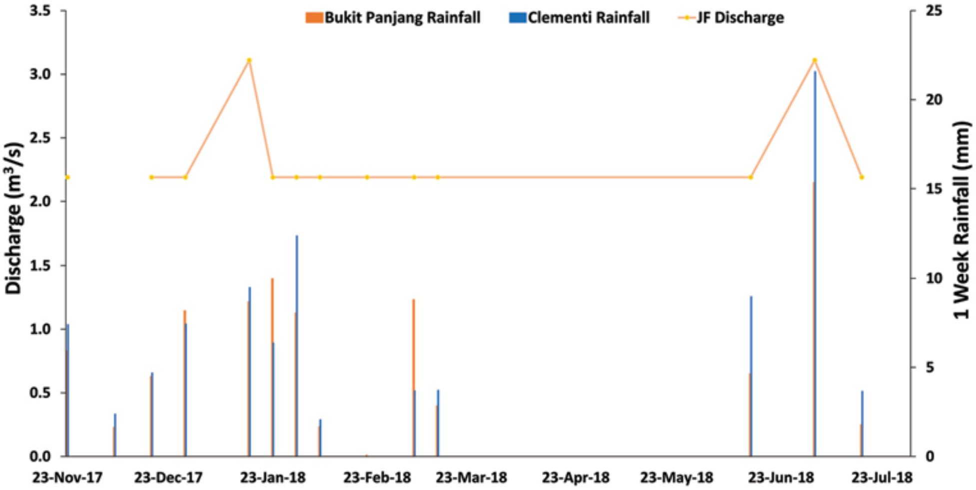


Fig. 24. Jungle Fall stream discharge and 1-week rainfall data at two nearest rain gauge stations (Clementi and Bukit Panjang).

and Jungle Fall stream discharges are low compared to streams within and nearby the Central Catchment Nature Reserve, Singapore, e.g. Nee Soon (estimated discharge of <50 L/s to > 400 L/s) (Tropical Marine Science Institute, 2016); Springleaf (34 to 578 L/s during baseflow condition – unpublished data). However, Fern Valley stream discharge is higher than that from Dermawan stream, Bukit Gombak (ranging from 3.2 to 15 L/s) (Nguyen et al., 2018a). Total dissolved load always occupies a higher proportion than total suspended load in both Fern Valley and Jungle Fall, which is similar to observations in Nee Soon (Nguyen et al., 2018b) and Springleaf (unpublished data), suggesting in terms of material movement, that elements in these catchments are mainly lost from the catchment through dissolution. This unique property is opposite to most streams globally, especially the top 20 largest rivers in the world (Dudgeon, 2011).

4. *Association between groundwater and stream water chemistry*

Together with rainfall, groundwater input is one of the main sources of stream water. As mentioned above, the influences of rainfall on stream characteristics in the two catchments are not obvious given the limited significant correlations among parameters. Thus, groundwater could be the main unseen driving factor in these two streams. We, therefore, collected groundwater samples from several wells (down to maximum 2 m depth) at upstream and lower stream locations in Fern Valley and Jungle Fall catchments and analysed their water chemistry. Comparisons between groundwater and stream water chemistry (pH, TDS, conductivity, Cl^-, SO_4^{2-}, NO_3^-, and elemental concentration) are illustrated in Fig. 25 to 48. Groundwater parameters in general show greater fluctuation compared to stream water parameters. A possible reason for the large variation of groundwater parameters is that water samples were collected from more than one well and not measured on site (groundwater data were measured in GEOLAB a few hours after collection from the field). The fact that groundwater and nearby stream water have the same order of magnitude for all variables(in most cases having fairly similar readings) suggests that localised groundwater is the most important source of stream water in Bukit Timah. Additionally, it is worth noting that except for Fern Valley's lower reach, groundwater pH is always higher than the stream's pH (Fig. 25, Fig. 37). This suggests that other factors play a role in lowering the pH in both streams. Also, SO_4^{2-} in the groundwater is higher than that in the stream water of both streams (Fig. 29, Fig. 41); NO_3^- in the Fern Valley groundwater is much lower than that in the stream water (Fig. 30).

Therefore, there is some evidence concerning the relative contributions of rainfall and groundwater to the streams' properties in both catchments. However, with available data it is difficult to uncover the main driving factors of these streams. The following section provides further evidence to link the streams' characteristics with those of the soil.

5. *Soil properties of catchment slopes and their impact on stream water quality*

Soil acidity (pH), bulk density (g/cm^3), particle size distribution and TOC are among the most widely studied soil characteristics. They play important roles in soil health and indirectly affect soil hydrology. These soil parameters are usually interrelated. For example, soil acidity influences the amount of available nutrients for plant species (Lambers et al., 1998; Watmough & Dillon, 2003). Soil acidity is a cause of nutrient loss (Brady & Weil, 2002) leaving behind nutrient poor soils such as found in the widespread Rengam series soils in the Central Catchment Nature Reserves (Ives, 1977; Nguyen, 2018b). Soils with high organic matter, and thus high total

Table 5. Total Dissolved Solids (TDS) and Total Suspended Sediments (TSS) load in Fern Valley and Jungle Fall streams, Bukit Timah Nature Reserve, Singapore.

	Date	Discharge (L/s)	TDS (mg/L)	TSS (mg/L)	Total Dissolved Load (tonnes/yr)	Total Suspended Load (tonnes/yr)
Fern Valley	28/11/2017	24.84	35.1	0	30.31	
	12/7/2017	25.38	34.4	0	30.35	
	18/12/2017	20.52	35.1	5	25.04	3.57
	28/12/2017	5.32	33.8	2.5	6.25	0.46
	16/01/2018	11.43	34.4	0	13.68	
	23/01/2018	6.08	33.8	0	7.14	
	30/01/2018	6.91	34.4	0	8.26	
	2/6/2018	3.41	33.8	0	4.01	
	20/02/2018	3.89	32.5	2	4.40	0.27
	3/6/2018	10.64	32.5	0	12.02	
	13/03/2018	7.00	32.5	0.75	7.91	0.18
	5/6/2018	4.04	35.5	9.25	4.99	1.30
	22/6/2018	14.43	30.5	0	15.30	0.00
	10/7/2018	11.04	31.2	0	11.98	0.00
Jungle Fall	23/11/2017	2.19	33.8		2.58	
	12/7/2017	2.19	33.8		2.58	
	18/12/2017	2.19	33.2	7.5	2.53	0.57
	28/12/2017	2.19	32.5	5.25	2.48	0.40
	16/01/2018	3.11	36.4		3.93	
	23/01/2018	2.19	36.4		2.77	
	30/01/2018	2.19	36.4		2.77	
	6/2/2018	2.19	35.7		2.72	
	20/02/2018	2.19	35.1		2.67	
	6/3/2018	2.19	34.4		2.62	
	13/03/2018	2.19	33.8	0.5	2.57	0.04
	14/6/2018	2.19	32.5	3	2.47	0.23
	3/7/2018	3.11	35.1	2.78	3.80	0.30
	17/7/2018	2.19	34.4		2.62	

organic carbon, usually have low acidity due to the decomposition of humic materials which release functioal groups capable of attracting and dissociating H^+ (Fageria & Nascente, 2014).

5.1 *General soil variables of Fern Valley*

Fern Valley's basic soil properties are presented in Table 6. Soil acidity, ranging from pH 3.65 to 8.33, median 4.38, is considered typical for a forested area whose soil pH ranges from less than 3 to more than 5 (McCauley et al., 2009). It is interesting that soil acidity is high (i.e., low pH value) at the upper catchment and is lower at the lower catchment. Soil bulk density varies between 0.41 to 1.15 g/cm^3, median 0.8 g/cm^3, also typical for forest soils. Again, bulk density tends to be high at the lower catchment where soil is more compacted. Soil TOC ranges from 0.11 to 4.56% and is high at the upper and lower catchment. Soil type varies within the catchment, from clay soil to fine sandy soil (sand, silt and clay percentages are from 19.05 to 90.23%, 3.75 to 34.6% and 0.78 to 46.45%, respectively). Soil particle size distribution shows no obvious trend within the catchment.

5.2 *Element in the soils of Fern Valley*

Median and MAD of elements in Fern Valley are presented in Table 7. Given the scarcity of soil elemental data in Singapore, only Cr, Cu, Mn, Pb and Zn data are thoroughly discussed. Soil Cr (8.34±6.54 mg/L) varies within a wide range (0.96 to 47.56 mg/L). It is, however, lower than other natural and disturbed Singapore sites in Nee Soon and MacRitchie (Table 7). Also, Fern Valley soil Cr is lower than international threshold guidelines (Table 7). Similar to Cr, widely fluctuating soil Cu (26.28±11.88 mg/L) is considered higher than in natural sites but could be considered similar to those from contaminated sites. Compared to international threshold guidelines, Cu is similar to TEC and Eco-SSL, but much lower than PEC. In general, Mn (16.74±8.28 mg/L) and Pb (11.22±8.76 mg/L) are lower than contaminated sites in Singapore and below international threshold guidelines. Zinc (15.6±10.68 mg/L) is lower than natural and disturbed lands as well as international threshold guidelines.

It is worth noting that, given the high MAD, Fern Valley soils likely contain site-specific enrichment. Maximum values of As (43.08 mg/L), Cd (6.6 mg/L), Mn (250 mg/L), Mo (67.56 mg/L) and Sn (17.4 mg/L) are all higher than threshold guidelines (Table 7). In detail, compared to the highest value of any international threshold guideline in Table 7, four out of 43 locations, accounting for ~9% of samples, have higher As; 13 out of 26 (50%) have higher Cd; 7% have higher Mn; 20% have higher Mo, and 14% have higher Sn. The high concentration of these elements in the surface soil might imply contamination, especially in the case of Cd. The simplest calculation of enrichment factor (EF), the concentration ratio between surface and subsurface soil (e.g. down to 1.8 m deep), was therefore calculated to evaluate soil contamination. In general, pollution from outside sources would be expected to be concentrated near the surface, leading to high EF. For As, Mn and Mo, the number of sites with EF > 4 (moderately enriched) are 7, 9 and 3, respectively. These sites are located near manmade features, e.g. concrete trails, residential

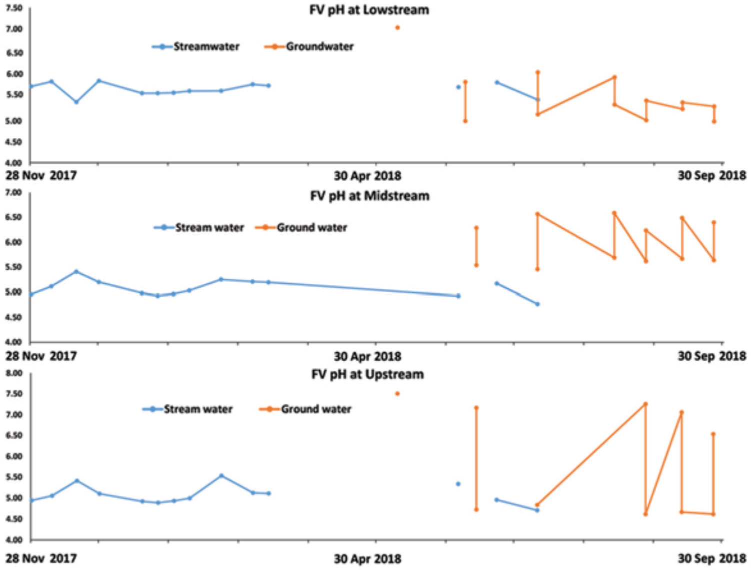


Fig. 25. pH in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

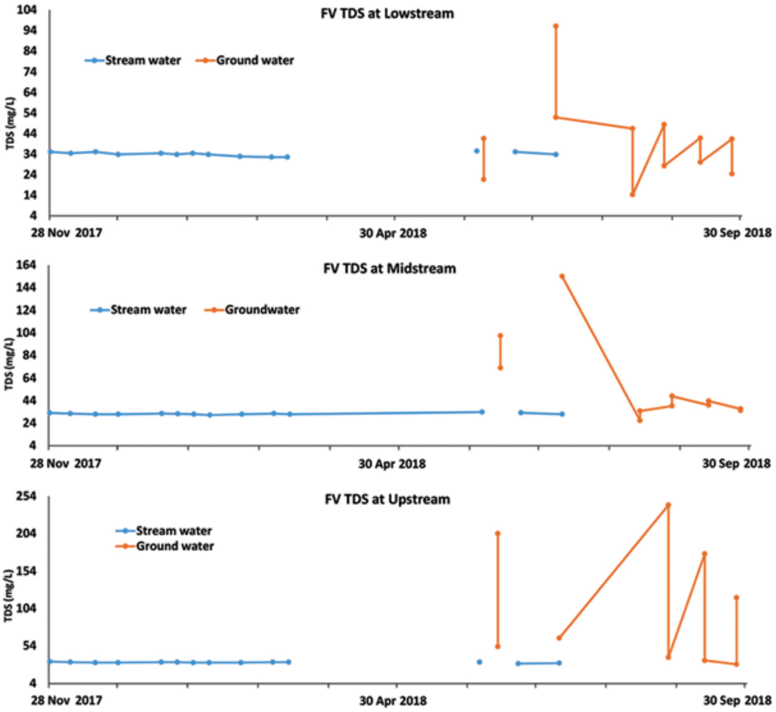


Fig. 26. TDS in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

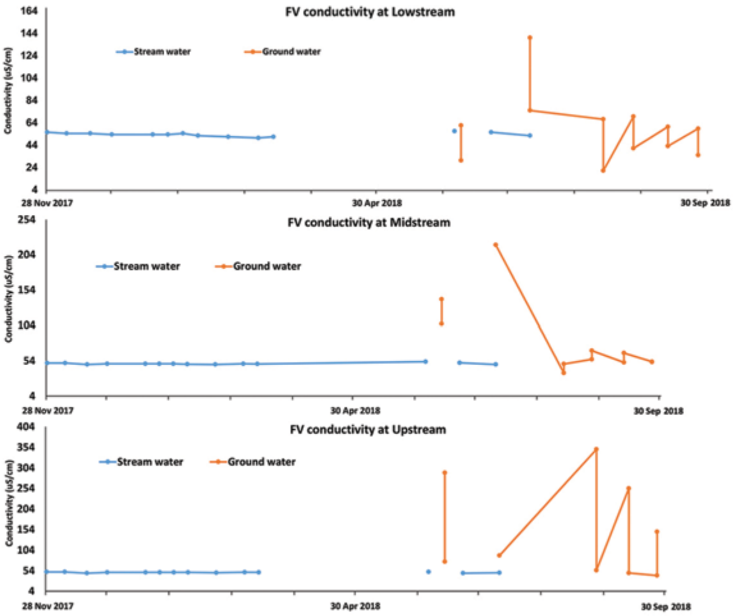


Fig. 27. Conductivity in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

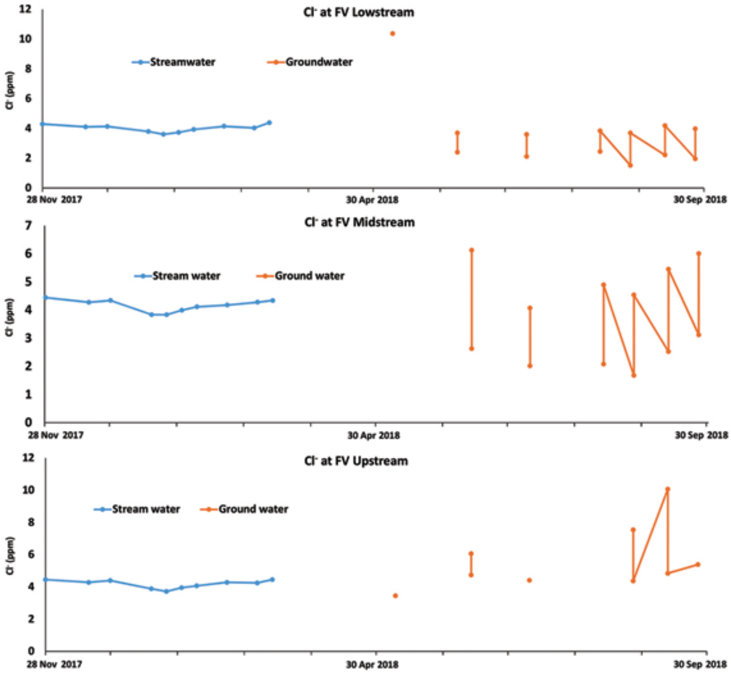


Fig. 28. Chloride in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

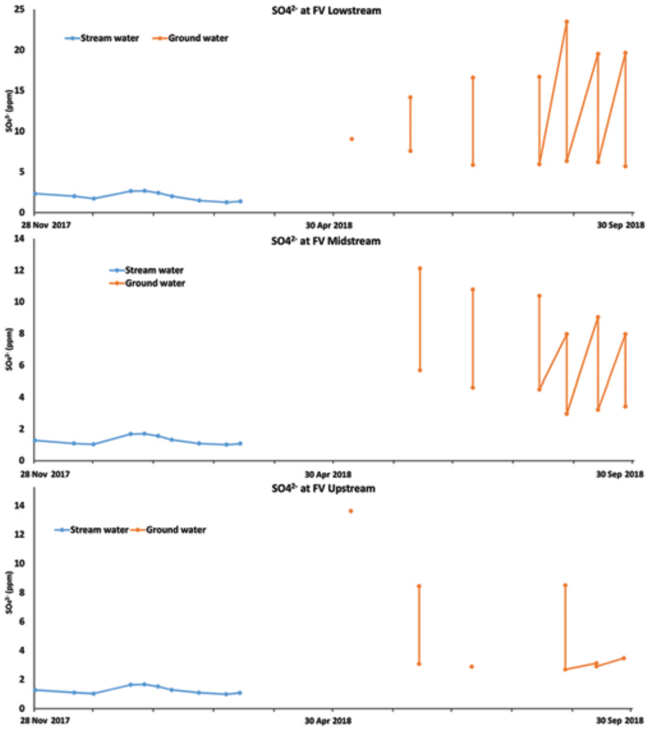


Fig. 29. Sulphate in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

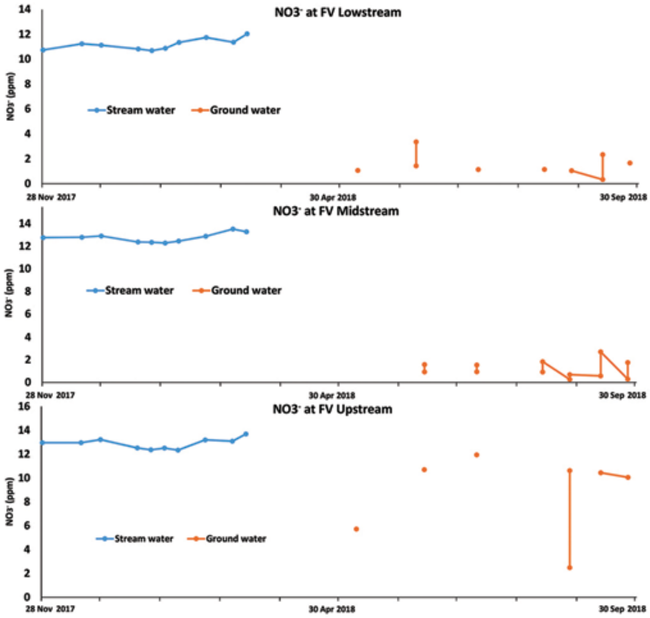


Fig. 30. Nitrate in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

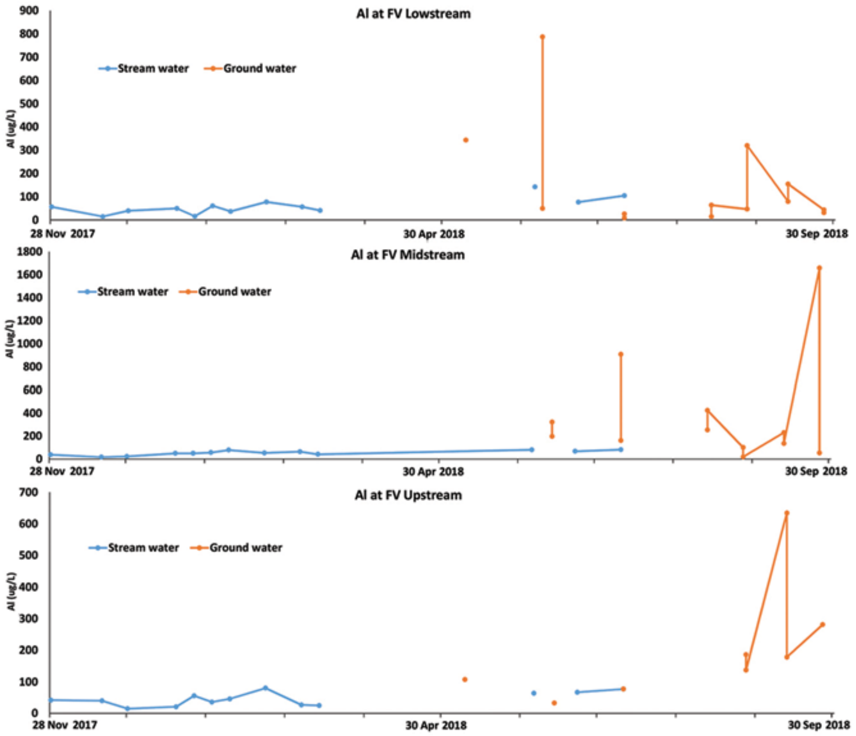


Fig. 31. Aluminum in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

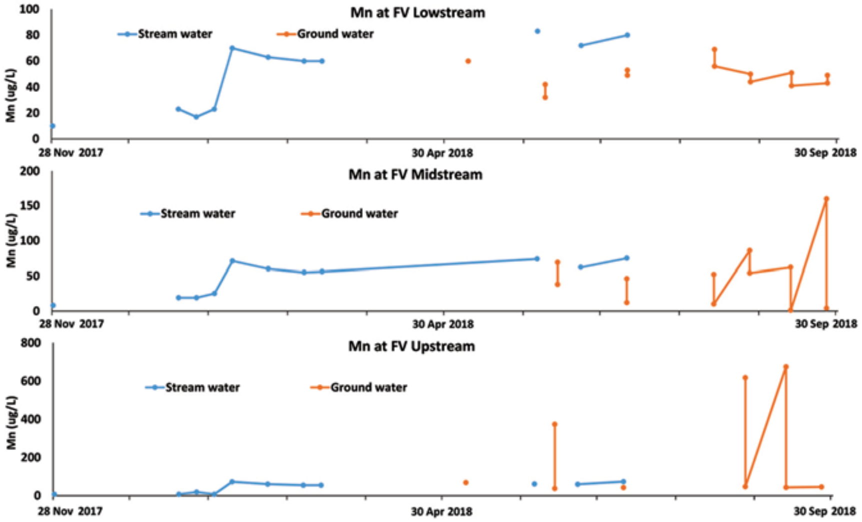


Fig. 32. Manganese in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

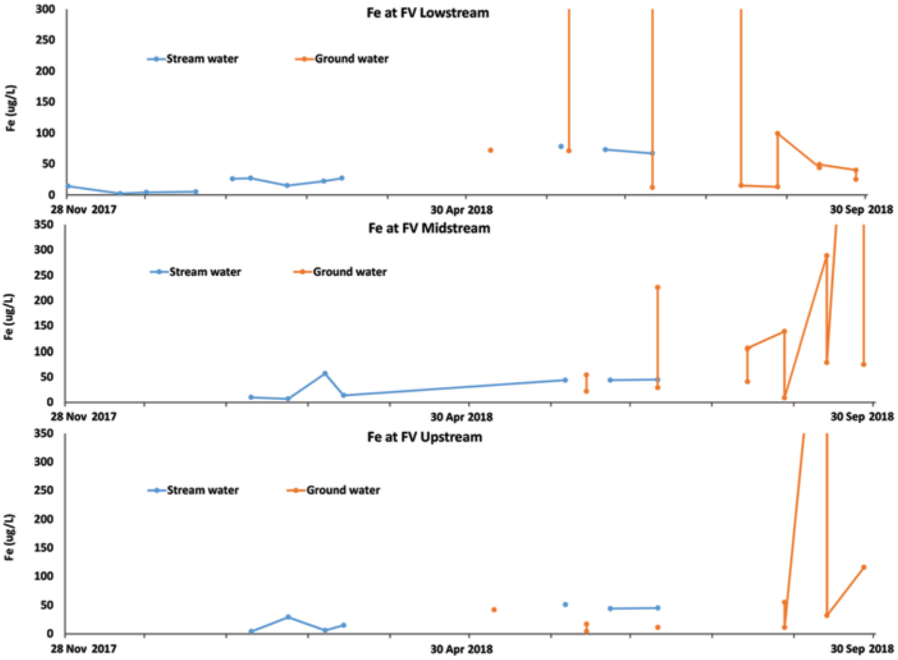


Fig. 33. Iron in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

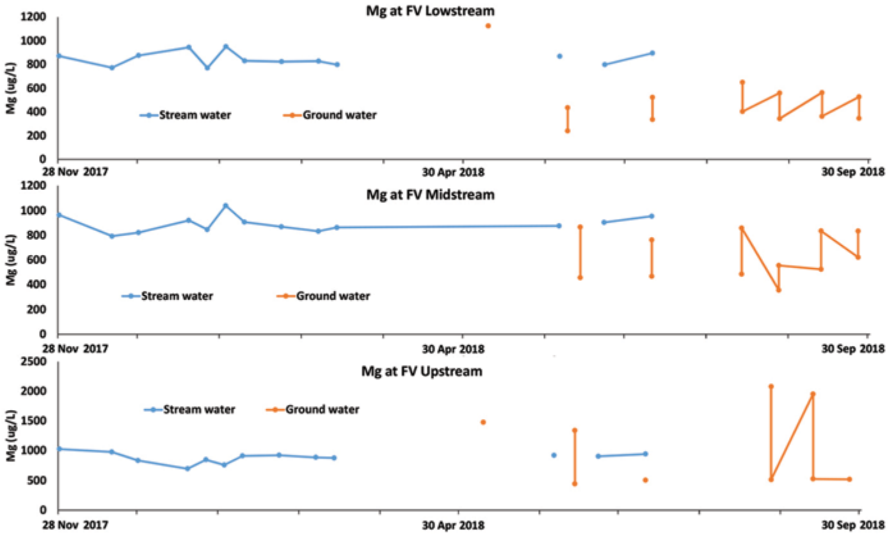


Fig. 34. Magnesium in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

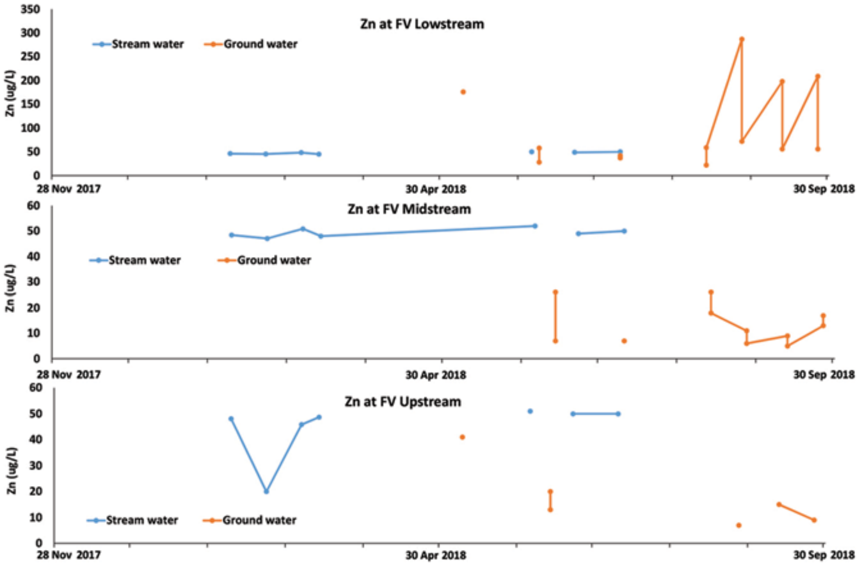


Fig. 35. Zinc in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

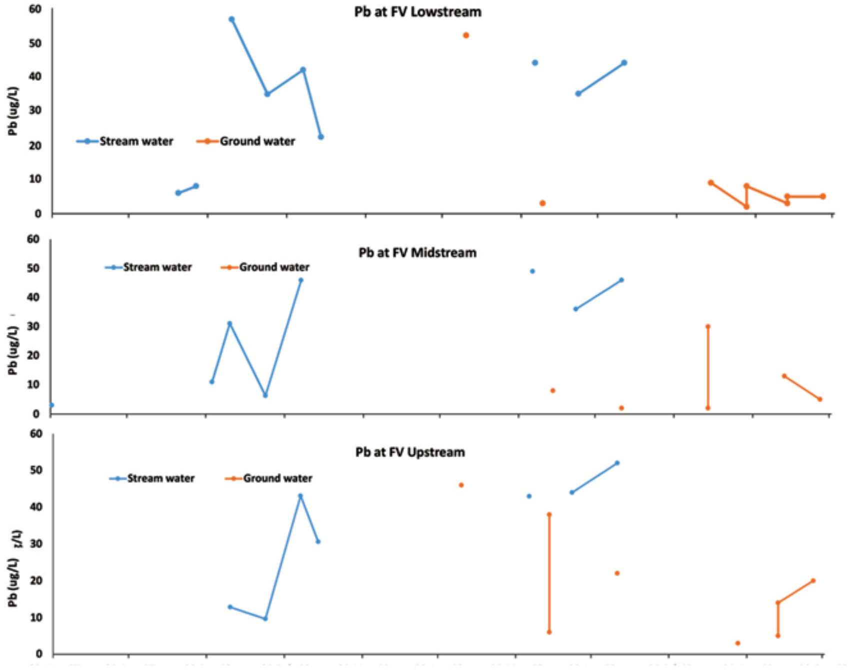


Fig. 36. Lead in Fern Valley stream water and ground water at Lower, Middle and Upper streams.

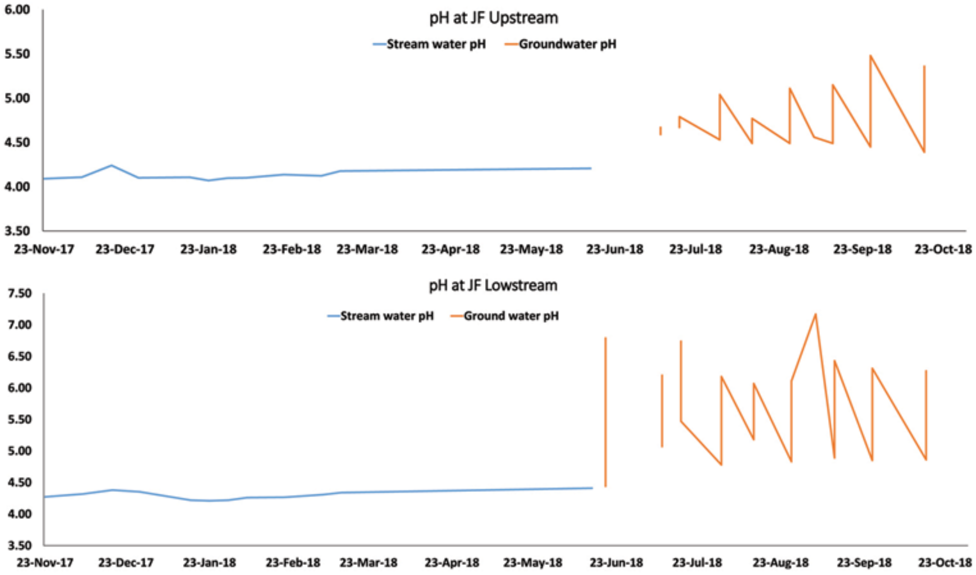


Fig. 37. pH in Jungle Fall stream water and ground water at Lower and Upper streams.

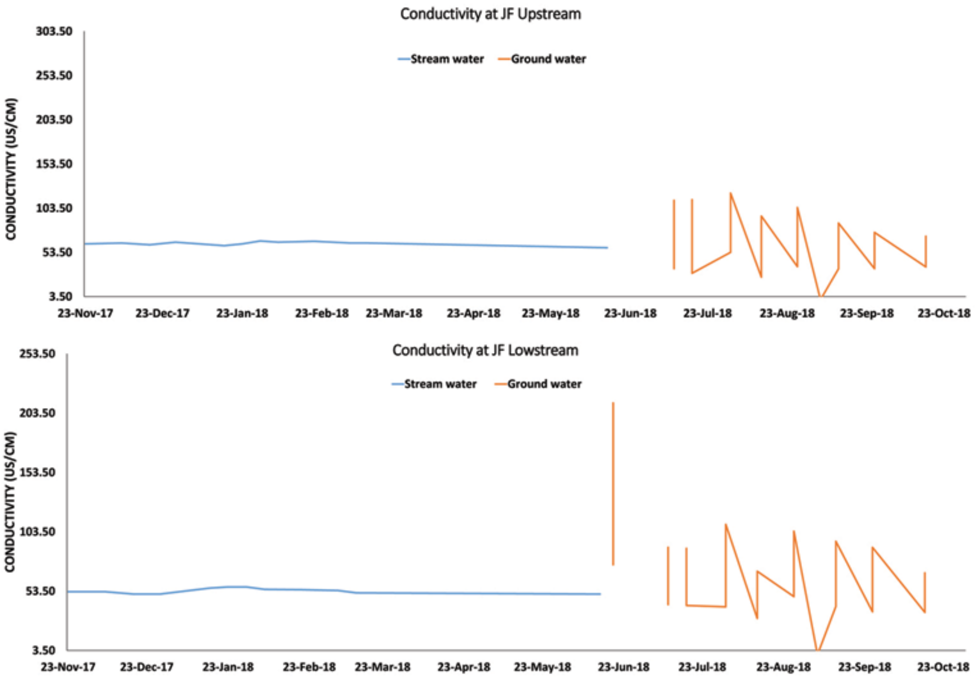


Fig. 38. Conductivity in Jungle Fall stream water and ground water at Lower and Upper streams.

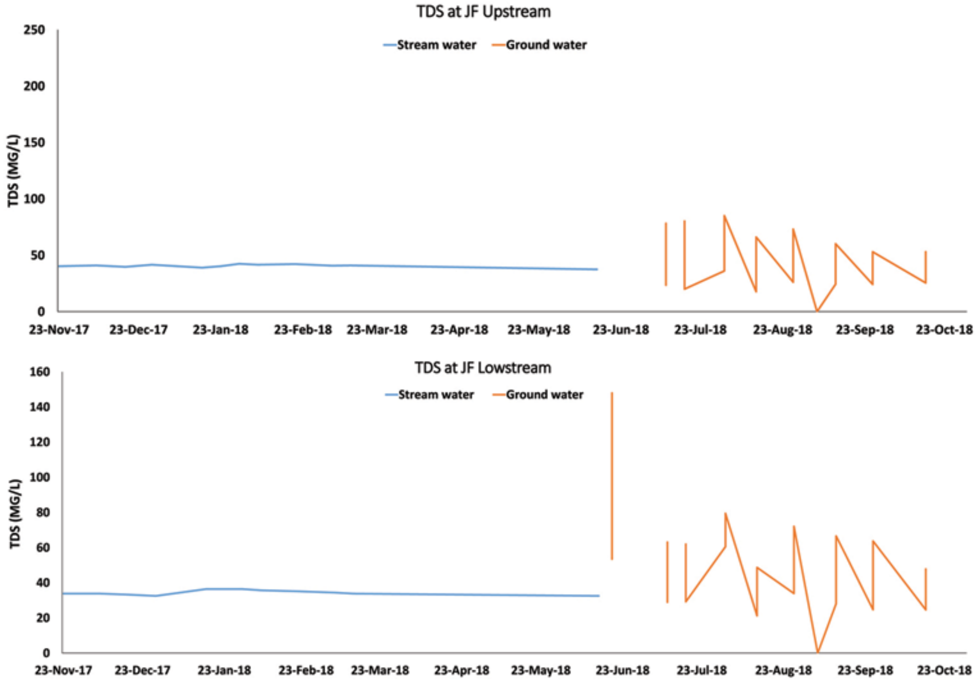


Fig. 39. TDS in Jungle Fall stream water and ground water at Lower and Upper streams.

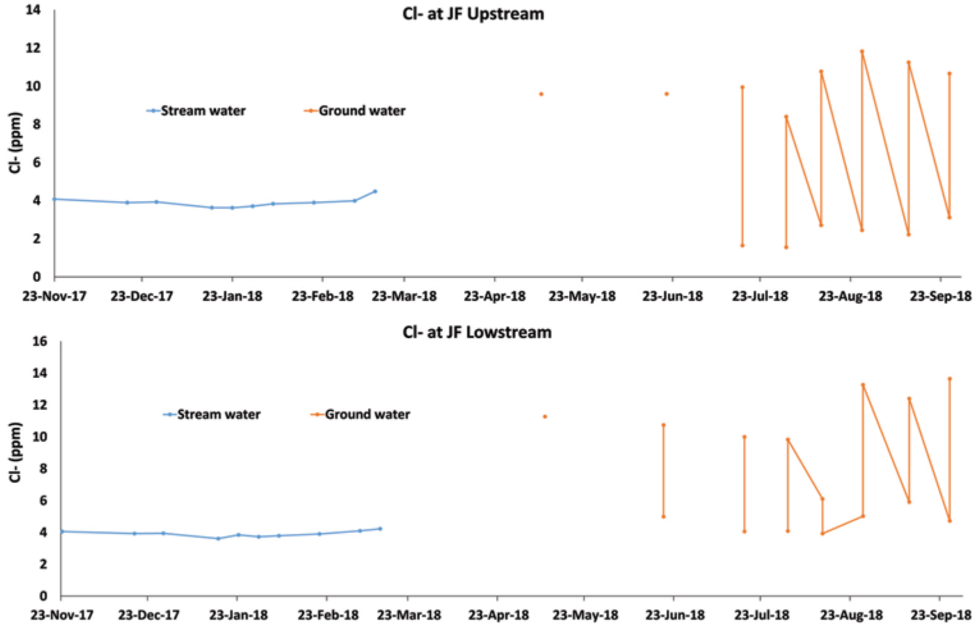


Fig. 40. Chloride in Jungle Fall stream water and ground water at Lower and Upper streams.

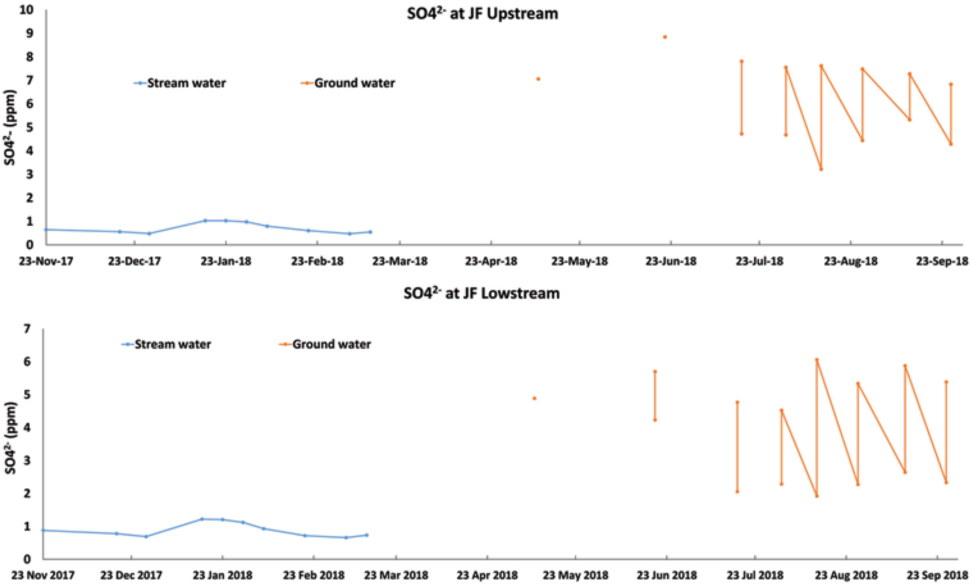


Fig. 41. Sulphate in Jungle Fall stream water and ground water at Lower and Upper streams.

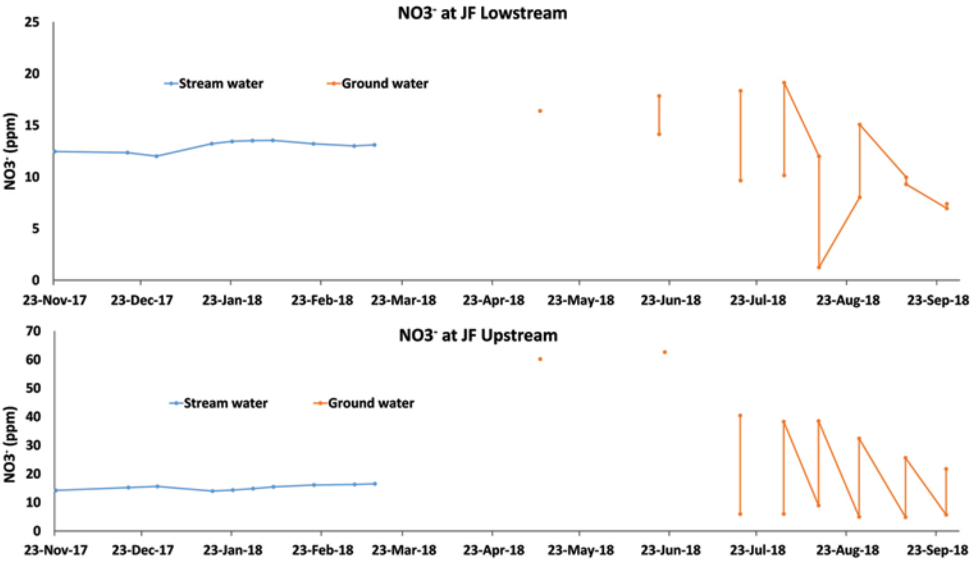


Fig. 42. Nitrate in Jungle Fall stream water and ground water at Low and Up streams.

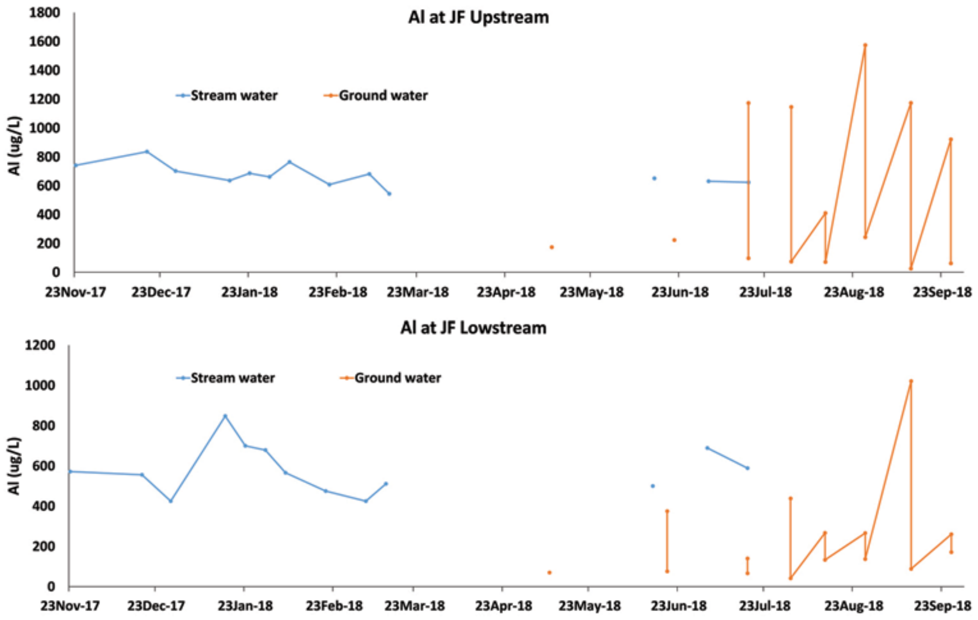


Fig. 43. Aluminium in Jungle Fall stream water and ground water at Lower and Upper streams.

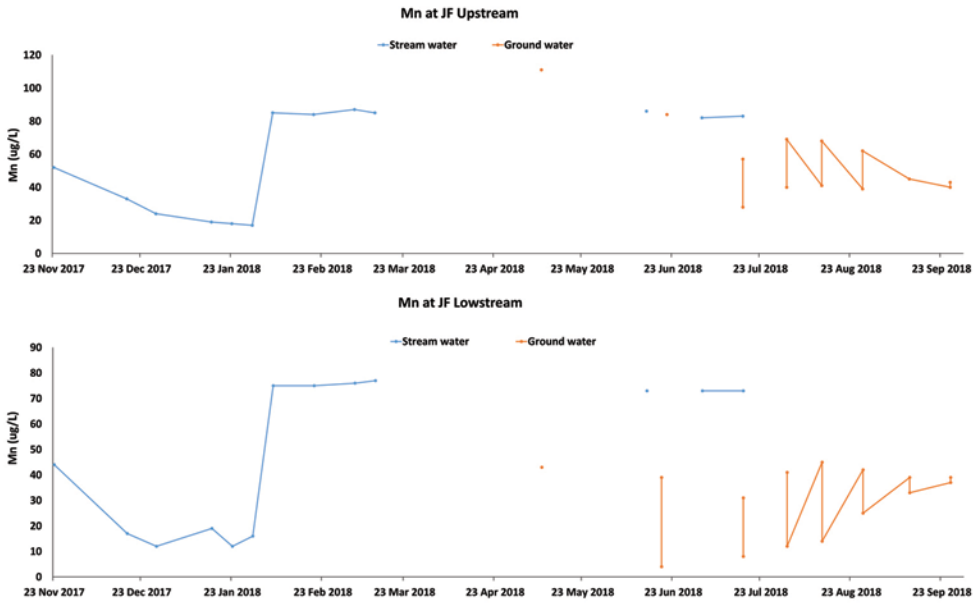


Fig. 44. Manganese in Jungle Fall stream water and ground water at Lower and Upper streams.

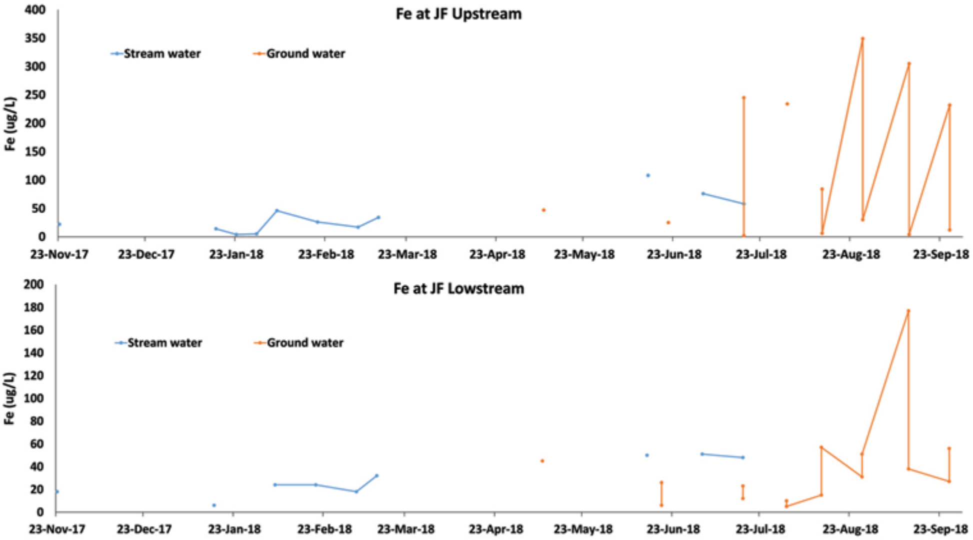


Fig. 45. Iron in Jungle Fall stream water and ground water at Lower and Upper streams.

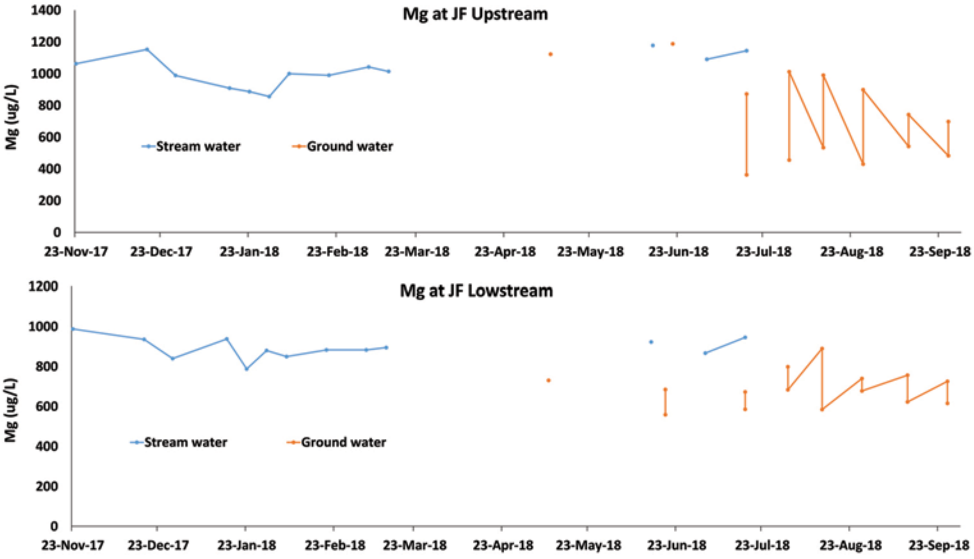


Fig. 46. Manganese in Jungle Fall stream water and ground water at Lower and Upper streams.

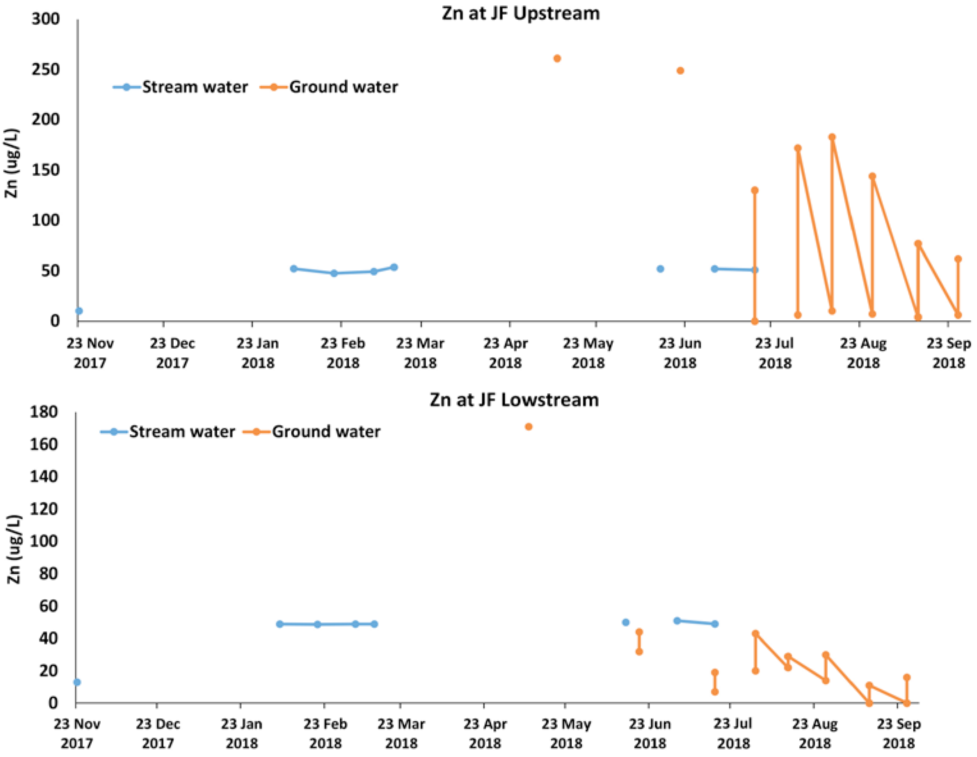


Fig. 47. Zinc in Jungle Fall stream water and ground water at Lower and Upper streams.

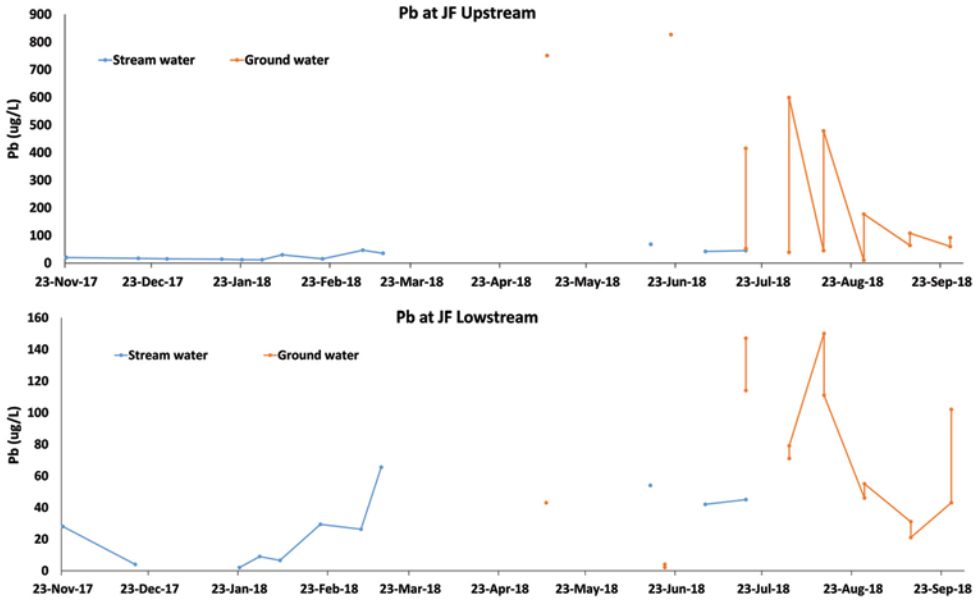


Fig. 48. Lead in Jungle Fall stream water and ground water at Lower and Upper streams.

Table 6. Basic soil properties in Fern Valley catchment, Bukit Timah Nature Reserve, Singapore. Sampling locations are shown in Fig. 5A.

Sample ID	pH	Bulk Density (g/cm^3)	TOC (%)	Sand (%)	Silt (%)	Clay (%)
FV1	5.41	0.62	3.05	19.05	34.5	46.45
FV10	4.54	1.10	0.77	83.03	8.38	8.59
FV11	4.25	0.83	2.63	58.19	6.14	35.67
FV12	4.02	0.89	1.67	69.47	16.3	14.23
FV13	3.88	0.69	2.70	74.93	22.41	2.66
FV14	5.01	0.99	0.70	78.1	11.15	10.75
FV15	5.19	0.84	1.05	77.16	13.25	9.59
FV16	5.35	0.89	0.71	90.23	8.99	0.78
FV17	4.27	0.88	1.26	74.68	12.24	13.08
FV18	4.28	0.88	0.96	81.24	3.75	15
FV19	4.08	0.67	1.26	74.72	10.43	14.85
FV2	5.96	0.97	1.27	78.54	7.02	14.44
FV20	4.17	0.71	1.22	80.63	8.12	11.25
FV21	3.93	0.78	1.41	74.03	8.23	17.74
FV22	3.94	0.61	2.76	64.77	27.4	7.83
FV23	4.06	1.15	1.28	65.19	9.83	24.98
FV24	4.23	1.02	0.94	65.7	14.59	19.71
FV25	4.21	0.75	1.15	83.35	5.83	10.82
FV26	4.44	1.14	0.50	84.54	6.26	9.2
FV27	4.18	1.06	1.00	69.63	7.69	22.68
FV28	4.33	1.10	0.90	76.52	8.33	15.15
FV29	4.59	0.76	0.82	71.04	9.92	19.03
FV3	4.70	0.83	2.39	38.44	34	27.56
FV30	4.20	0.63	0.78	65.04	21.8	13.16
FV31	8.13	0.73	2.09	85.71	9.05	5.24
FV32	7.31	0.73	1.49	88.5	5.98	5.52
FV33	7.84	0.80	1.84	77.84	11.68	10.47
FV34	3.65	0.41	4.45	49.29	14.82	35.88
FV35	3.92	0.82	1.54	62.09	12.32	25.58
FV36	3.96	0.64	1.82	64.51	13.29	22.2
FV37	3.80	0.70	2.54	60.9	28.64	10.46
FV38	3.73	0.59	3.56	41.61	21.2	37.2
FV39	4.13	0.78	1.17	64.43	9.35	26.22

Table 6. Continuation.

Sample ID	pH	Bulk Density (g/cm^3)	TOC (%)	Sand (%)	Silt (%)	Clay (%)
FV4	4.06	1.00	0.88	79.14	7.29	13.57
FV40	3.82	0.55	3.79	59.09	7.36	33.54
FV41	3.80	0.52	3.24	60.3	9.61	30.09
FV42	3.82	0.56	2.33	76.49	12.39	11.11
FV43	3.87	0.69	1.96	61.08	12.84	26.07
FV5	5.17	1.14	0.57	80.4	5.9	13.7
FV6	5.43	1.13	1.19	75.54	5.87	18.59
FV7	5.38	0.92	2.96	24.7	34.6	40.7
FV8	6.94	0.87	2.47	86.78	5.24	7.98
FV9	6.22	0.80	2.12	83.65	8.05	8.31
FV46 (1m)	6.86	-	0.19	58.94	26.28	14.78
FV46	8.33	-	1.18	85.57	10.14	4.29
FV45	4.84	-	0.68	57.81	25.31	16.87
FV44 (1.8m)	5.14	-	4.56	47.78	21.28	30.95
FV44	5.27	-	0.58	66.34	20.19	13.46
FV46 (1.8m)	5.85	-	0.41	65.07	11.53	23.41
FV45 (1.8m)	5.93	-	0.27	56.61	25.34	18.05
FV44 (1m)	5.28	-	0.52	55.9	20.58	23.52
FV45 (1m)	5.02	-	0.11	83.32	12.56	4.12

Table 7. Elemental concentration in Fern Valley and Jungle Fall soils (unit in ppm unless otherwise stated).

		Al (%)	**Fe (%)**	**Na**	**As**	**Ba**	**Ca**	**Cd**	**Co**	**Cr**	**Cu**	**Mg**	**Mn**	**Mo**	**Ni**	**Pb**	**Sb**	**Sn**	**Sr**	**Ti**	**V**	**Zn**
Fern Valley	Median	3.46	0.83	139.20	7.92	16.19	99.96	3.12	0.72	8.34	26.28	103.56	16.74	3.24	2.40	11.22	2.04	2.88	1.68	126.18	10.20	15.60
	MAD	1.21	0.40	39.72	4.68	9.17	50.88	2.70	0.60	6.54	11.88	42.54	8.28	1.68	1.80	8.76	1.68	1.68	1.20	39.72	3.66	10.68
	Min	1.51	0.29	12.00	0.60	3.12	33.12	0.12	0.00	0.96	3.72	47.40	7.20	0.12	0.24	0.00	0.12	0.12	0.48	53.52	2.88	0.24
	Max	9.14	2.84	1097	43.08	90.72	24612	6.60	5.73	47.56	116.76	1369	250.0	67.56	16.94	95.52	12.00	17.40	24.60	267.4	32.04	320.7
Jungle Fall	Median	5.02	1.12	88.80	10.32	13.32	43.92	5.28	3.96	8.32	16.92	59.64	11.64	3.36	4.38	8.05	6.36	4.44	3.12	92.04	13.44	13.80
	MAD	2.27	0.31	31.20	2.28	1.80	8.16	0.24	0.12	1.40	1.38	15.61	3.00	1.56	0.62	6.85	2.35	0.77	0.24	22.80	3.36	4.47
	Min	1.35	0.13	9.60	2.39	1.80	35.40	0.12	0.25	0.48	11.76	29.52	3.48	0.36	0.12	0.24	0.72	1.92	0.24	48.48	2.16	0.72
	Max	9.32	1.43	194.40	35.88	22.80	508.80	5.88	4.45	10.32	27.24	177.02	16.44	6.24	5.76	23.64	9.84	5.40	4.56	148.73	18.36	20.88
Undisturbed lands																						
MacRitchie	Natural area									14	15		58			28						65
Nee Soon	FUC									7	5		38			13						23
Nee Soon	FLC									18	12		160			18						33
Disturbed lands																						
MacRitchie	Industrial area									47	47		146			71						268
Nee Soon	ML									35	44		248			56						77
MacRitchie	Mix disturbance									28	83		83			32						124
Nee Soon	VDL									23	16		188			24						43

Table 7. Continuation.

	Al (%)	Fe (%)	Na	As	Ba	Ca	Cd	Co	Cr	Cu	Mg	Mn	Mo	Ni	Pb	Sb	Sn	Sr	Ti	V	Zn
International thresholds																					
TEC (MacDonald, 2000)				9.79			0.99		43.4	31.6				22.7	35.8						121
PEC (MacDonald, 2000)				33			4.98		111	149				48.6	128						459
Eco-SSL (USA)[a]					300				26	28		220		38	11					7.8	46
CCME (Canada)[b]				5.9	750		0.6	40	37.3				5	45	35	20	5			130	123

Legend: SD. Standard Deviation; a Minimum values for screening purpose; b Minimum values; FUC: Forest Upper Catchment; FLC: Forest Lower Catchment; ML: Military Lands; VDL: Variably Disturbed Lands. TEC: threshold effect concentration, PEC: probable effect concentration. Undisturbed and disturbed lands from Nguyen et al. (2019).

areas, old quarry and tower (Fig. 49), suggesting these sites could be affected by anthropogenic disturbance. For Cd and Sn, since their concentrations at 1.8 m are below the detectable limit, EF could not be calculated.

The Cd in soil and water clearly indicate a high Cd concentration in Fern Valley. Future studies need to focus more on this issue since Cd is a toxic element to organisms and human (Nasu & Kugimoto, 1981; Silverberg, 1976; Moore & Ramamoorthy, 2012), but bearing in mind that the water volume of the stream is tiny compared with Singapore's total water supply.

5.3 *General soil variables of Jungle Fall catchment*

Jungle Fall's basic soil properties are presented in Table 8. Jungle Fall soil acidity ranges from pH 3.61 to 5.02, median 4.11, again considered typical for a forested area (McCauley et al., 2009). Unlike Fern Valley, in Jungle Fall sites with high soil pH are located along the main stream (Fig. 50). Soil bulk density varies between 0.31 to 1.10 g/cm^3, median 0.68 g/cm^3, fairly similar to that from Fern Valley. Soil TOC ranges from 0.31 to 6.81%, slightly greater than TOC in Fern Valley. Soil type also varies within the catchment, from sandy clay loam to fine sandy soil. Particle size fractions are coarser compared to Fern Valley soil (sand, silt and clay percentages are from 52.08 to 92.49%, 3.5 to 44.62% and 0.72 to 31.57%, respectively). Similar to pH, the sand fraction mostly accumulates along the main stream. Basic soil properties in both Jungle Fall and Fern Valley suggest that soil in Bukit Timah is acidic, sandy and nutrient poor, agreeing with investigations by Ives (1977) and Lee & Zhou (2009) on the Bukit Timah granite and its derived soils.

5.4 *Elements in the soils of Jungle Fall*

Jungle Fall soil Cr (median 8.32±1.40 mg/L) varies across a wide range (0.48 to 10.32 mg/L) and is comparable to that of Fern Valley. Copper (average 16.92±1.38 mg/L, ranging from 11.76 to 27.24 mg/L) in Jungle Fall is lower than in Fern Valley and fairly similar to natural local sites but much lower than those from contaminated local sites. Compared to international threshold guidelines, Jungle Fall Cu is in the "safe zone". Manganese (11.64 ±3.00 mg/L), Zn (13.80±4.47 mg/L) and Pb (8.05±6.85 mg/L) are all lower than in natural and contaminated lands in Singapore as well as international threshold guidelines. It is evident that soil in Jungle Fall has lower Na, Ba, Ca, Cu, Mg, Mn, Pb and Ti concentrations compared to Fern Valley.

When compared with threshold guidelines, As, Ba, Co, Cr, Cu, Mn, Mo, Ni, Pb, Sb, Sn and Zn are within typical natural ranges (Table 7). However, V is higher than Eco-SSL levels (Ecological Soil Screening Level, US Environmental Protection Agency) (but lower than CCME) and Cd is slightly higher than PEC (European Food Safety Authority, Predicted Environmental Concentrations). This finding, again, reveals the issue of high Cd in soils. Although many elements are in their natural ranges, 80% of the locations are high in Cd (e.g. higher than PEC). Similar caveats apply to the interpretation of figures in relation to international guidelines on soils as to those on water quality; for example, soil in BTNR catchments is never used in food production.

The above results and discussions revealed high Cd, Sb and Se in stream water in Bukit Timah. Among these elements, Cd is also high in Fern Valley and Jungle Fall soils. Future studies need to address this topic to fully understand the sources and relevance of trace metals in Bukit Timah catchments.

5.5 *Association between soil properties and stream characteristics in catchments*

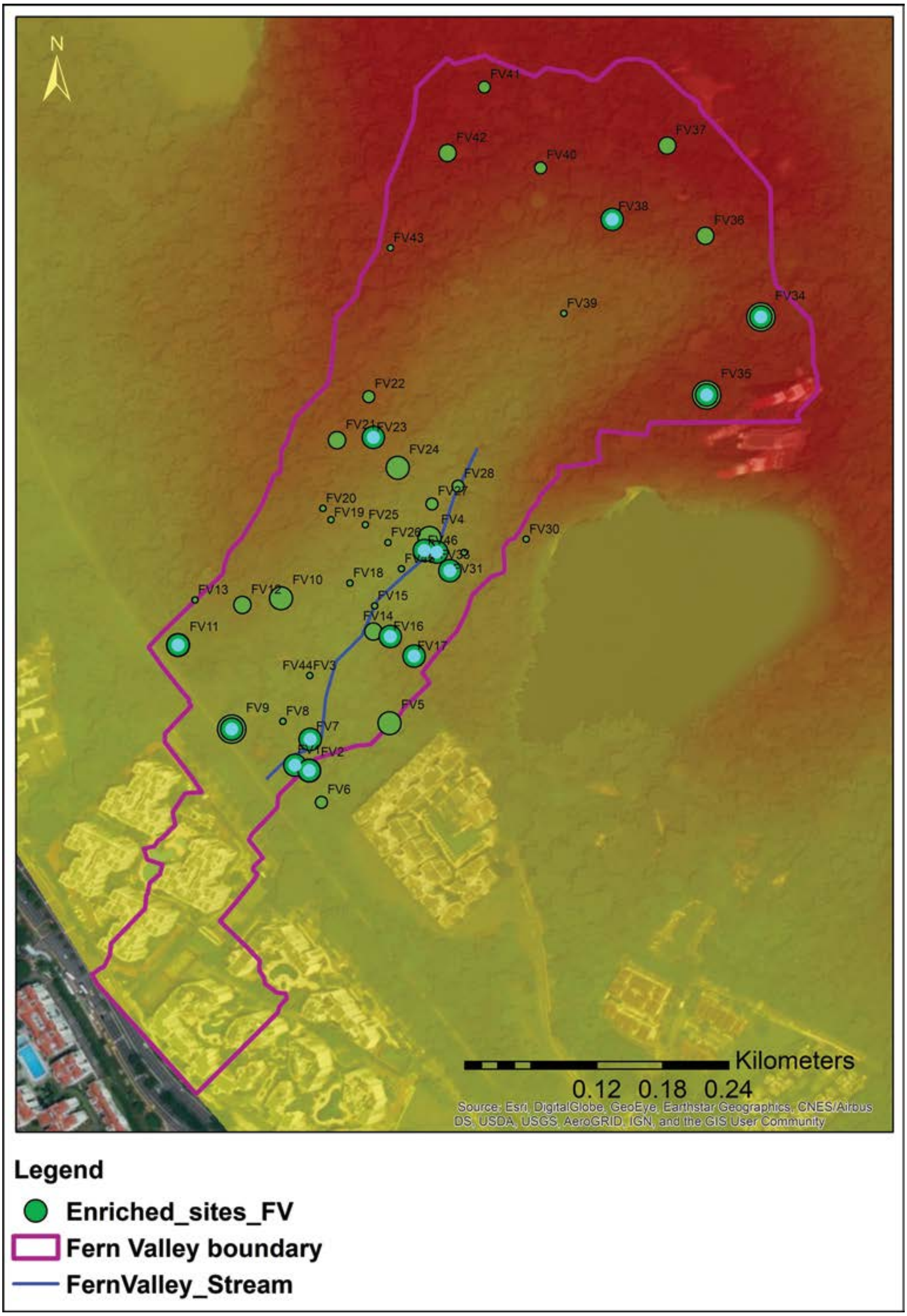
Our sampling strategy was not able to assess the direct association between soil and water. However, the linkage between soil and water could be qualitatively evaluated. The main direct linkage between catchment soil and stream water quality is through the hydrological regime (e.g. rainfall, runoff, groundwater movement). From the discussion above, there are hints that soil properties are associated with stream water parameters (e.g. rainfall intensity is positively correlated with Conductivity and TDS due to the soil dissolved components being leached to the stream through runoff). As a result, stream water pH can also be affected. In fact, low Fern Valley stream pH (median 5.2) and even lower Jungle Fall stream pH (median 4.21) are in accordance with low Fern Valley soil pH (median 4.39) and even lower Jungle Fall soil pH (median 4.11), respectively. Besides, the concentrations of Ba, Ca, Mg and Na (whose base cations determining soil alkalinity) are higher in Fern Valley than in Jungle Fall, and the concentration of Al (the element most influencing soil acidity) is higher in Jungle Fall soil compared to Fern Valley soil. Through weathering processes, these soil components are dissociated and carried to the streams, possibly leading to the observed differences in the pH of the streams in Fern Valley and Jungle Fall. In addition, the breakdown products of organic compounds in soil are carried to the streams, lowering the pH in Jungle Fall (median soil TOC in Jungle Fall is 2.14%, almost twice as much as those from Fern Valley, 1.26%).

Conclusions and recommendations

Evaluation of water quality in BTNR streams

Physicochemical parameters of water in streams of BTNR have now been established for future monitoring and comparison. Spatial data of the streams' physicochemical characteristics reveal their overall health, with few and mostly localised causes for concern.

The ten very small streams in BTNR originate within a very small area. They are therefore subject to similar but not identical geological, morphological, meteorological and biological influences. Disturbances on-site are limited in type and degree by the protected status of BTNR. Those disturbances described and quantified by Chatterjea (2019) include trail widening and soil compaction by visitors, potentially affecting surface wash, erosion, and groundwater penetration. All the streams are subject to similar influences arising off-site, including total rainfall and its seasonal variation, seasonal chemical signatures of the north-east and south-west monsoons, and chemical signatures from potential sources of airborne pollutants in the region such as traffic, power stations and industrial centres that could be several tens of kilometres from BTNR (Clews et al., 2018; Nguyen et al., 2018a, 2018b).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Fig. 49. Enriched sites (EF > 4) highlighted in bright blue for As, Mn and Mo in Fern Valley.

Table 8. Basic soil properties in Jungle Fall catchment, Bukit Timah Nature Reserve, Singapore. Sampling locations are shown in Fig. 5B.

Sample ID	**pH**	**Bulk Density (g/cm^3)**	**TOC (%)**	**Sand (%)**	**Silt (%)**	**Clay (%)**
BTS1	4.78	0.54	3.176	73.75	13.33	12.92
BTS2	5.02	0.52	2.475	75.17	12.61	12.22
BTS3	4.45	1.01	0.673	91.04	8.24	0.72
BTS4	4.77	0.48	6.808	71.76	22.24	6
BTS5	4.94	0.88	2.058	86.14	3.61	10.25
BTS6	4.70	0.31	4.557	87.33	3.5	9.17
BTS7	4.65	1.10	0.312	92.49	4.06	3.45
JF10	4.05	0.68	1.813	61.35	11.77	26.88
JF1NEW	4.05	0.94	1.716	72.44	22.83	4.72
JF2NEW	3.61	0.41	6.796	52.08	44.62	3.3
JF3	3.91	0.43	4.29	59.71	35.63	4.66
JF4	3.96	0.73	2.288	61.84	30.61	7.55
JF5NEW	4.15	0.75	1.582	67.83	7.24	24.93
JF6NEW	4.01	0.66	1.879	65.87	28.26	5.87
JF7	4.11	0.68	2.137	60.26	22.45	17.29
JF8	3.82	0.70	2.959	60.45	31.28	8.27
JF9NEW	4.10	0.44	2.389	64.73	34.44	0.83
JFex1	4.44	-	0.937	71.28	8.81	19.92
JFex2	4.07	-	1.799	55.72	12.71	31.57

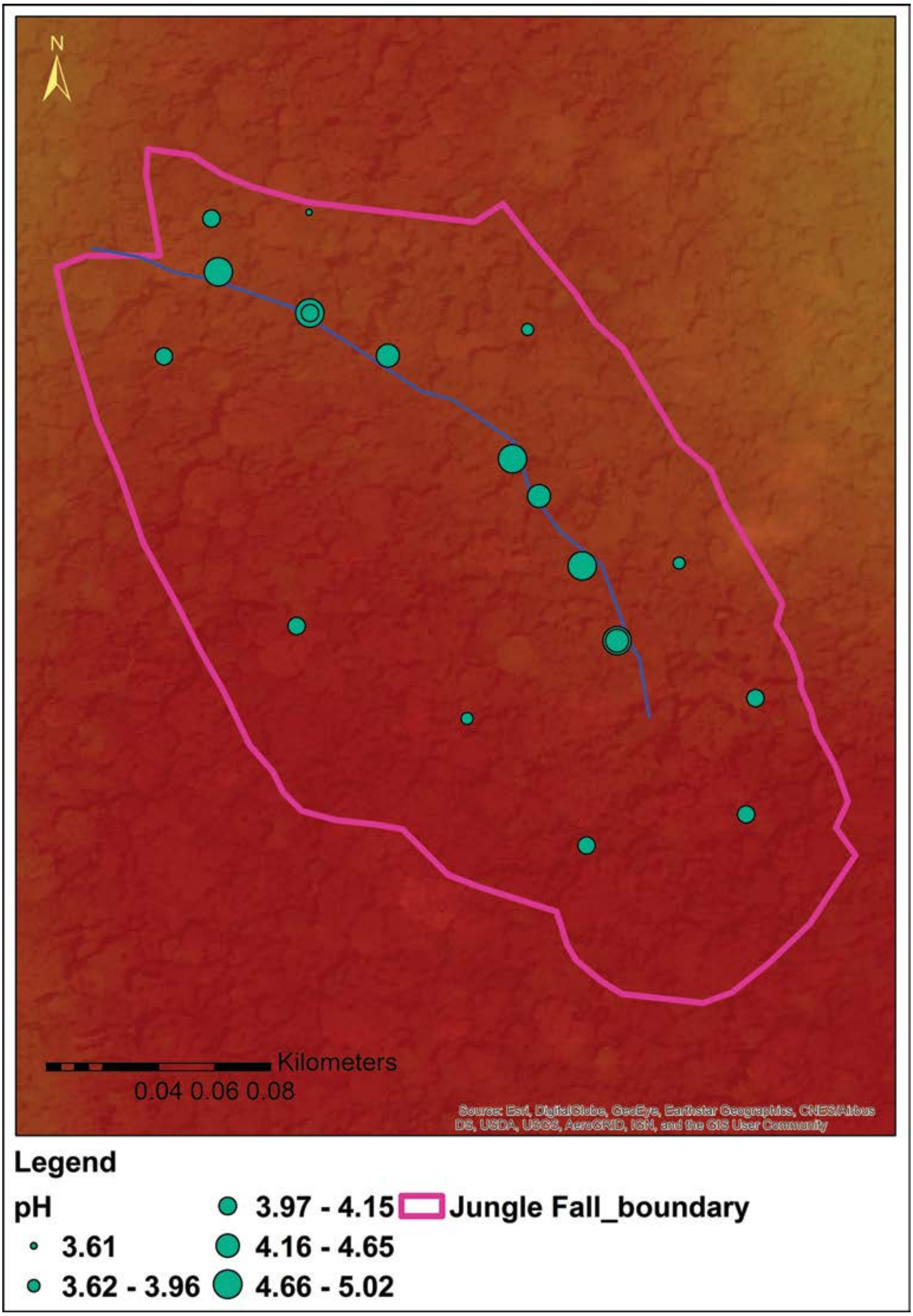


Fig. 50. Soil acidity in Jungle Fall catchment.

In spite of their overall similarity and their close proximity on different faces of a single hill, each of the streams shows individual characteristics. These are related to catchment size for each stream (Cai, 2019), the intensity of human impacts in different parts of BTNR (Chatterjea, 2019) that differentially affect the stream catchments, the current vegetation structure (primary, old secondary and maturing secondary forest) (Chan & Davison, 2019) affecting tree size, rainfall interception versus stemflow, leaf litter depth, root density and root penetration, as well as details of slope, bedrock, and soil chemistry. These factors play out through the expected interactions between soil, groundwater and rainfall. In turn, the physicochemical characteristics of the individual streams may be linked in part to the freshwater decapod crustaceans (Khoo et al., 2019), dragonflies and damselflies (Cai et al., 2019), and fishes (Li et al., 2019) that occur within each of them.

Our surveys suggest that stream temperature, TDS, salinity, the amount of TOC, TP, anions and cations vary within their expected natural ranges. Some parameters including DO and conductivity are slightly low, which may not be favourable for large aquatic animals. Some issues needing further investigation include low stream pH in Jungle Fall and Seraya catchments as well as the high concentration of Cd, Sb and Se in all streams.

Among all the surveyed streams, Asas stream displays significantly different values for all in-situ tested water parameters except turbidity, indicating that the stream water is unlikely to be sourced from natural groundwater, but is very likely to come directly from the neighbouring Singapore Quarry.

In general, both Fern Valley and Jungle Fall streams are in good condition, except for remarkably low stream pH in Jungle Fall. In spite of being small, both streams are unique and quite dynamic given the variations in parameters among surveyed sites along streams. These differences, however, may not be ecologically significant. Fern Valley's physical water parameters are consistently lower than those in Jungle Fall, except for water pH. In-stream variation of temperature, conductivity and TDS in two streams reveals opposing trends. This provides evidence that Fern Valley and Jungle Fall show different physicochemical behaviour. Our study also provides limited evidence of rainfall impact on stream parameters.

Water chemistry among the Bukit Timah streams does not differ significantly, except at the headwater of Lasia stream at the PUB (Public Utilities Board) Pipeline and the headwater of Asas stream. At Asas stream (sample AS7) high TOC, Na^+, NH_4^+, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, As, Mn and Sr were recorded whereas at the headwater of Lasia stream (LS9), high Ca^{2+}, SO_4^{2-} and Sr, low Ba were observed. High amounts of Na^+, Ca^{2+} and Sr agree with the aforementioned high stream pH at Asas. Also, the remarkably high Al concentration in Seraya and Jungle Fall is in accordance with low water pH in these streams. Fern Valley and Jungle Fall streams, in spite of their close proximity, are strikingly different. Although both are small, Fern Valley reveals a more sustainable capability in nurturing aquatic life given its near neutral stream acidity and considerably larger discharge compared to Jungle Fall. Both streams, however, contains high Cd, a toxic element.

Recommendation for follow-up

Stream acidification at Jungle Fall stream has been observed and documented for over a decade but the drivers of acidification are not completely understood. The consequence of such acidification has possibly caused the local extirpation of *Johora singaporensis* from its type locality in Jungle Fall stream. A comprehensive research programme to identify all the possible drivers of the acidification process would be needed before management measures could be properly identified, e.g. stream restoration (liming, modification of stream channel, removal of sedimentation), etc. Long-term monitoring (equipped with pH data-logger) needs to be put in place for streams where critically endangered species (e.g. *Johora singaporensis*) are found. The consequences of stream acidification need more study since it may affect other stream chemical properties and eventually aquatic life.

Our study revealed relatively high levels of Cd, Sb and Se in stream water in Bukit Timah. Among these elements, Cd is also high in Fern Valley and Jungle Fall soils. Future studies need to address this issue.

In fact, although they are small, these catchments are uniquely dynamic. Future investigations should aim to establish a long-term monitoring plan for physical and chemical properties of soil, rainfall and groundwater for a comprehensive understanding of the streams to guide a rehabilitation plan which could lead to the greater sustainability of aquatic biodiversity in streams of Bukit Timah hill

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