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Environmental Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tent20

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To cite this article: Ryuichi Watanabe, Hidenori Harada, Hidenari Yasui, Tuan Van Le & Shigeo Fujii (2021) Exfiltration and infiltration effect on sewage flow and quality: a case study of Hue, Vietnam, Environmental Technology, 42:11, 1747-1757, DOI: 10.1080/09593330.2019.1680739

To link to this article: https://doi.org/10.1080/09593330.2019.1680739

ENVIRONMENTAL TECHNOLOGY
2021, VOL. 42, NO. 11, 1747–1757
https://doi.org/10.1080/09593330.2019.1680739

Exfiltration and infiltration effect on sewage flow and quality: a case study of Hue, Vietnam

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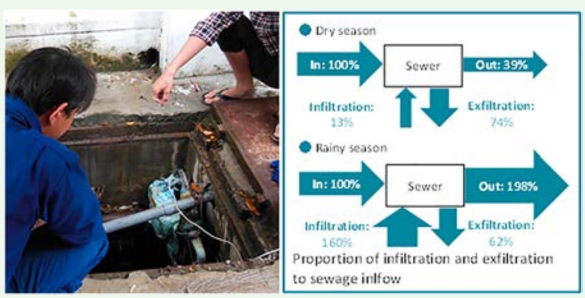
ABSTRACT

Sewage generated in Southeast Asia is typically characterized by small per-capita flow and low concentration. This study investigated the impacts of exfiltration (leaking-out) and infiltration (leaking-in) on sewage flow and quality in Hue, Vietnam. Sewage flow and quality were continuously monitored at the sewer outlet of a residential drainage area for 68 and 82 days during dry and rainy seasons, respectively. Infiltration was estimated based on the least sewage flow before morning. Lithium tracer tests were conducted to estimate the exfiltration ratio. The results indicated that sewage of the target sewer was weaker than the typical weak-strength sewage even on no-rain days of the dry season. Monitoring of electrical conductivity indicated that rainfall persistently decreased the sewage concentration for a maximum duration of 228 h. The estimated infiltration accounted for 11% and 62% of the total sewage inflow to the sewer during dry and rainy seasons, respectively. The tracer test indicated that exfiltration ratios during the dry and rainy seasons were 65.6% and 24.0%, respectively. As a result of developing the water balance, only 23% of the water supplied to the area reached the sewer outlet in the dry season, while 123% flowed in the rainy season. These results demonstrate that exfiltration decreased the sewage flow in the dry season, while infiltration significantly increased the sewage flow and decreased the sewage concentration in the rainy season. To the best of our knowledge, this is the first study to quantify the impacts of infiltration and exfiltration on sewage in Southeast Asia.



ARTICLE HISTORY
Received 2 April 2019
Accepted 9 October 2019

KEYWORDS
Exfiltration; infiltration; sewage flow; sewage quality; Southeast Asia

Introduction

Several cities in developing countries (except those in central areas) are not equipped with efficient wastewater treatment plants which are essential for preventing water pollution resulting from untreated wastewater [1]. Sewage characteristics such as flow rate and quality in developing countries are different from those in the developed countries due to differences in their water related infrastructures and anthropogenic activities. Further, limited research has been conducted on the characteristics of sewage in developing countries [2,3]. Therefore, a comprehensive understanding of sewage characteristics in developing countries is essential to design efficient treatment plants.

Sewage in the developing countries in Southeast Asia is generally characterized by relatively low concentrations. For instance, the BOD values of raw sewage have been reported as 50 mg L^{-1} in Ho Chi Minh City, 93 mg L^{-1} in Hue City, Vietnam, and 44 mg L^{-1} in Bangkok, Thailand [4–6]. These are lower than the typical values of middle- (190 mg L^{-1}) and low-strength

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Supplemental data for this article can be accessed https://doi.org/10.1080/09593330.2019.1680739

sewage (110 mg L^{-1}) indicated in a globally well-known wastewater engineering textbook [7]. In the recent years, several developed countries have initiated projects for the development of wastewater treatment plants in Southeast Asia. However, a few wastewater treatment plants have been reported to indicate overcapacity, i.e. the influent flow was significantly smaller with weak sewage strength than the designed capacity [5]. In general, this could be attributed to exfiltration (i.e. leaking-out) and infiltration (i.e. leaking-in) through the underground sewer network. However, these have not been sufficiently researched in the previous studies.

Although little is known about exfiltration and infiltration through sewer networks in developing countries (especially in Southeast Asia), water supply networks in developing countries are known to indicate significantly high exfiltration (i.e. water leakage). For instance, a cross-national analysis of the volume of non-revenue water (NRW; an indicator of water leakage) demonstrated that the estimated median NRW values for the developing and developed countries were 18.22 and 7.04 m^3 km^{-1} day^{-1}, respectively [8]. Further, studies on exfiltration from sewer networks in developed countries have reported values of 0–15% for Rümlang, Switzerland [9] and 0–41.2% for Berlin, Germany [10]. Considering the high NRW of water supply networks, significant exfiltration through sewer networks is expected for several developing countries in Southeast Asia which face challenges such as inefficient designs, old constructions, and poor maintenance of sewer networks. Moreover, significant infiltration is potentially expected in areas characterized by high groundwater tables.

Thus, exfiltration and infiltration mechanisms could potentially generate the small-flow and low-strength sewage typically observed in Southeast Asia. This study focused on understanding the impacts of exfiltration and infiltration on sewage characteristics in an urban residential area of Hue, Vietnam. The present study conducted continuous monitoring of sewage flow and quality as well as lithium tracer tests to estimate the water mass balance and the pollutant load of the sewer system in the study area.

Materials and methods

Study area

The present study was conducted in the Doan Thi Diem street drainage which is a residential area in Hue City, central Vietnam (Figure 1). The drainage occupied an area of 0.112 km^2 and exhibited a population density of 12,964 cap km^{-2} [11]. The water consumption in the study area was 153.7 L cap^{-1} day^{-1} [12]. Additionally,

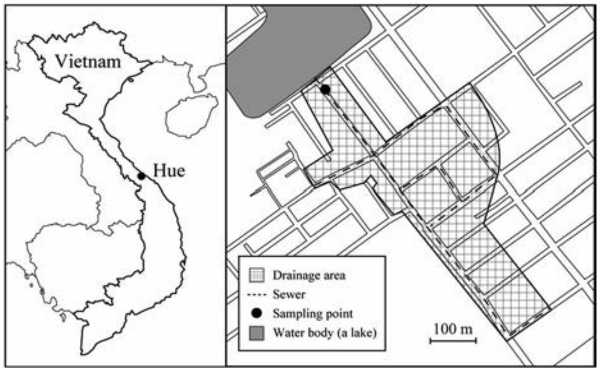

Figure 1. Location of the study site.

the annual precipitation from 2013 to 2016 ranged between 2,205.0 and 3,792.5 mm [13]. Combined sewers cover this area, and rainwater, therefore, flows into this system, penetrates into the ground, and/or evapotranspirates. Household greywater was usually discharged into the sewers, gardens, and/or road surfaces. Flush toilets were widely used and blackwater treated in the septic tanks was discharged into the sewers or infiltrated. As of 2017, the target drainage area was not equipped with a domestic wastewater treatment plant. In this study, the sewage sampling point was approximately 50 m upstream of the single sewer outlet which discharged into an open water body (Figure 1). This sampling point was assumed to be equivalent to the outlet of the sewer network.

Sewage flow rates, electrical conductivity (E.C.), and rainfall were continuously monitored and recorded at the sampling point. A V-notch weir with a water level logger (HOBO U20, Onset) and an area velocity flow meter (ISCO2150, TELEDYINE ISCO) were used for measuring sewage flow rates under high and low flow conditions, respectively. An E.C. logger (HOBO U24, Onset) was installed for recording the E.C. and water temperature. Sewage samples were collected at the sampling point by an autosampler (6712Avalanche, TELEDYINE ISCO) over a period of 30 days each for the dry (August 2017–September 2017) and rainy seasons (October 2017–December 2017) which comprised 23 and 13 no-rain days, respectively. Sewage samples (950 mL) were collected every 2 h to obtain a composite sample for each day. The composite samples were analyzed for SS, VSS, COD_{Cr}, BOD_5, TP, and TN following the standard methods [14].

Lithium tracer test

Tracer mass balancing is a suitable method for directly estimating the exfiltration from a sewer network [10]. In this study, lithium, which exhibits the advantage of general insensitivity to the environment [15], was selected as the tracer substance. Tracer tests were conducted on two no-rain days, i.e. 10 September 2017 (late dry season) and 16 January 2018 (late rainy season). Additionally, 307.00 g of LiCl was utilized for the former test while 1,500 g of LiCl and 1,000 g of $LiCl{\cdot}H_2O$ were utilized for the latter test. The tracers were injected through a sewer manhole located approximately 50 m downstream of the most upstream point of the sewer network. This injection point was assumed to be equivalent to the most upstream point of the sewer network. Sewage flow and Li concentration were continuously monitored at the downstream sampling point. Li concentrations were analyzed using a flame photometer (PFP7, JENWAY) with a 0.25 mg L^{-1} detection limit. Further, the Li loading recovered was compared to the Li loading injected to subsequently calculate the Li recovery ratio (R) for each test as indicated in Equation (1).

$$R = \frac{\sum V_i \times C_i}{L_0} \quad (1)$$

where R: Li recovery ratio (dimensionless), V_i: sewage volume discharged at the sampling point at time interval i (m^3), C_i: Li concentration at time interval i (g m^{-3}), and L_0: Li loading injected (g). Then, exfiltration ratio was calculated as 1–R. This study assumes that R represents the ratio of sewage, including infiltrated water that reaches the sampling point.

Infiltration of groundwater

According to the survey guidelines for infiltration to sewers [16], water flowing in the sewer in the absence of wastewater discharged from households could be regarded as the infiltrated groundwater and the least sewage flow before morning could be regarded as the estimated flow of the infiltrated groundwater. The study site was characterized by almost no wastewater discharge from midnight to early morning [17]. The length of the target sewer was approximately 250 m; therefore, the water consumed in the households would reach the sewer a few hours before morning. Subsequently, the flow of infiltrated groundwater was estimated from the least sewage flow before morning based on flow rate data from 21 and 7 days during the dry and rainy seasons, respectively. These days were selected from the period of our survey by excluding rain days and the two succeeding no-rain days after the end of a rainfall event during dry season, and rain days and one succeeding no-rain day after the end of a rainfall event during rainy season. Additionally, the minimum mean instantaneous flow rate before morning was considered equivalent to the infiltration flow.

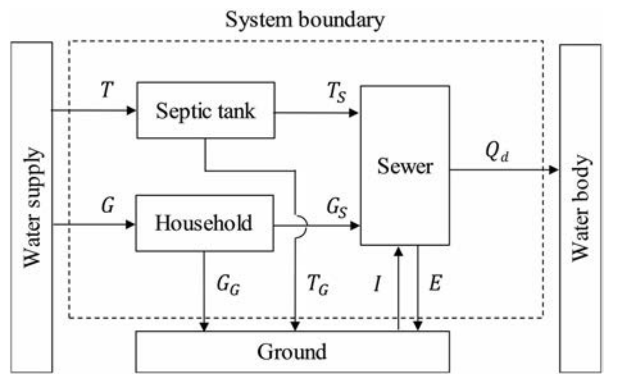

Figure 2. System boundary and components of the water balance model for the target sewer on no-rain days. T: flush toilet water, G: greywater, T_S and T_G: septic tank effluent discharged into the sewer and ground, respectively, G_S and G_G: greywater discharged into the sewer and ground, respectively, I: infiltration, E: exfiltration, and Q_d: sewage discharged from the single sewer outlet.

Estimation of water mass balance

This study estimated the water mass balance of the target sewer for no-rain days. Mass balance models reported in previous studies [18–20] were utilized to determine the system boundary and components (Figure 2).

This study assumed that the inflow to the sewer comprised septic tank effluent, greywater, and infiltrated groundwater, while the outflow comprised sewage discharged from the sewer outlet and exfiltration occurring through the sewer network. These have been expressed by Equations (2–4).

$$\sum_i Q_{\text{in},i} = \sum_j Q_{\text{out},j} \quad (2)$$

$$\sum_i Q_{\text{in},i} = T_S + G_S + I \quad (3)$$

$$\sum_j Q_{\text{out},j} = Q_d + E \quad (4)$$

where $Q_{\text{in},i}$: inflow i to the sewer (m^3 day^{-1}), $Q_{\text{out},j}$: outflow j from the sewer outlet (m^3 day^{-1}), T_S: septic tank effluent discharged into the sewer (m^3 day^{-1}), G_S: greywater discharged into the sewer (m^3 day^{-1}), I: infiltration (m^3 day^{-1}), Q_d: sewage discharged from the sewer outlet (m^3 day^{-1}), and E: exfiltrated sewage consisting of septic tank effluent, greywater, and infiltration (m^3 day^{-1}).

The calculation of Q_d excluded rain days and two succeeding no-rain days after the end of the rainfall event during dry season, and rain days and one succeeding no-rain day after the end of the rainfall event during rainy season. This elimination was done to minimize the effects of rainfall and estimate a stable dry-weather flow. Further, E was calculated as follows.

$$E = (T_S + G_S + I) \times (1 - R) \quad (5)$$

The septic tank effluent was discharged at two different locations (viz., the sewer and the ground) through onsite infiltration systems connected to the septic tanks. These flows were calculated using Equations (6) and (7), respectively.

$$T_S = W \times r_0 \times P \times 10^{-3} \times r_T \quad (6)$$

$$T_G = W \times r_0 \times P \times 10^{-3} - T_S \quad (7)$$

where W: daily water consumption (153.7 L cap^{-1} day^{-1}) [12], r_0: proportion of toilet water in the water consumption (0.20) [21], P: population of the drainage area (1,422 cap) [13], r_T: proportion of septic tank effluent discharged into the sewer (0.53) [6], and T_G: septic tank effluent infiltrated into the ground (m^3 day^{-1}).

Greywater was also discharged into the sewer and the ground (Equations (8) and (9)).

$$G_S = W \times (1 - r_0) \times P \times 10^{-3} \times (1 - r_G) \quad (8)$$

$$G_G = W \times (1 - r_0) \times P \times 10^{-3} - G_S \quad (9)$$

where r_G: proportion of greywater discharged to the ground/garden (–) and G_G: greywater discharged to the ground/garden (m^3 day^{-1}). However, it was difficult to estimate r_G since a significant proportion of the greywater was discharged to the ground/garden regardless of the plumbing system in the house. Therefore, in this study, r_G was estimated by the mass conservation law (Equation (2)).

Estimation of pollutant loadings

The design of a wastewater treatment plant not only depends on pollutant concentrations but also on pollutants loadings. In this study, the loadings of carbon, nitrogen, and phosphorus (estimated as COD_{Cr}, TN, and TP, respectively) were estimated at three sections, (viz., households, the sewer inlet, and the sewer outlet). It should be noted that only a proportion of the pollutants generated in the households reached the sewer inlet while the remaining were discharged to the ground/gardens. Further, only a proportion of the pollutants at the sewer inlet reached the sewer outlet while the remaining exfiltrated from the sewer network. Pollutant loadings at the households and the sewer inlet were estimated by Equations (10) and (11), respectively. Pollutant loadings at the sewer outlet were calculated using Equation (12).

$$L_{H,k} = L_{H-ste,k} + L_{H-gw,k} \quad (10)$$

$$L_{I,k} = L_{H-ste,k} \times r_T + L_{H-gw,k} \times (1 - r_G) \quad (11)$$

$$L_{O,k} = \frac{\sum_{l=1}^{n} (C_{k,l} \times Q_l)}{n} \times \frac{1}{P} \quad (12)$$

where $L_{H,k}$: loading of pollutant k (COD, N, or P) in household wastewater (g cap^{-1} day^{-1}), $L_{H\text{-}ste,k}$: loading of pollutant k in septic tank effluent (g cap^{-1} day^{-1}), $L_{H\text{-}gw,k}$: loading of pollutant k in greywater (g cap^{-1} day^{-1}), $L_{I,k}$: loading of pollutant k at the sewer inlet (g cap^{-1} day^{-1}), $L_{O,k}$: loading of pollutant k at the sewer outlet (g cap^{-1} day^{-1}), $C_{k,l}$: daily mean concentration of pollutant k at the sampling point on day l (mg L^{-1}), Q_l: sewage discharged from the sewer outlet on day l (m^3 day^{-1}), and n: number of monitoring days in dry season (23 days) and rainy season (13 days). It is noted that the average of Q_l during n days corresponds to Q_d.

Pollutant loadings in the septic tank effluent and the greywater were estimated by Equations (13–15).

$$L_{H-ste,COD} = U_{ste,COD} \times \frac{1}{P} \quad (13)$$

$$L_{H-ste,m} = U_{ex,m} \times (1 - k_{st,mk}) \times \frac{1}{P} \quad (14)$$

$$L_{H-gw,k} = U_{Gw,k} \times \frac{1}{P} \quad (15)$$

where $L_{H\text{-}ste,COD}$: COD loading in septic tank effluent (kg km^{-2} day^{-1}), $U_{ste,COD}$: unit COD loading in septic tank effluent (11.76 g cap^{-1} day^{-1}) [22], $L_{H\text{-}ste,m}$: loading of pollutant m (N, P) in septic tank effluent (kg km^{-2} day^{-1}), $U_{ex,m}$: unit loading of pollutant m in human excreta ($U_{ex,N}$: 8.1 g cap^{-1} day^{-1} and $U_{ex,P}$: 1.2 g cap^{-1} day^{-1}) [23], $k_{st,m}$: removal efficiency of pollutant m from septic tank ($k_{st,N}$: 0.09 and $k_{st,P}$: 0.18) [24], $L_{H\text{-}gw,k}$: loading of pollutant k in household greywater (kg km^{-2} day^{-1}), and $U_{Gw,k}$: unit loading of pollutant k in household greywater ($U_{Gw,COD}$: 37 g cap^{-1} day^{-1}, $U_{Gw,N}$: 1.0 g cap^{-1} day^{-1}, and $U_{Gw,P}$: 0.6 g cap^{-1} day^{-1}) [24]. Variables utilized in estimation of pollutant loading are summarized in Table S1 in supporting information.

Results and discussion

Sewage quality and seasonal variability

The sewage quality results for the outlet of the target drainage area are summarized in Table 1. The SS and

Table 1. Water quality of the composite samples collected at the sewer outlet.

Weather	Variable	Unit	Season	Mean	S.D.	Weather	Variable	Unit	Season	Mean	S.D.
No-rain days	E.C.	μS cm^{-1}	D	682.2	107.1	Rain days	E.C.	μS cm^{-1}	D	486.4	133.8
			R	427.8	80.6				R	301.0	76.3
	SS	mg L^{-1}	D	36.5	6.6		SS	mg L^{-1}	D	28.6	10.1
			R	18.6	5.4				R	12.4	5.3
	VSS	mg L^{-1}	D	29.7	7.0		VSS	mg L^{-1}	D	23.7	6.8
			R	15.2	4.5				R	9.4	4.0
	COD_{Cr}	mg L^{-1}	D	183.9	53.3		COD_{Cr}	mg L^{-1}	D	126.1	61.3
			R	51.0	33.3				R	17.4	10.7
	BOD	mg L^{-1}	D	89.0	29.7		BOD	mg L^{-1}	D	61.1	32.9
			R	20.0	13.5				R	7.6	4.1
	TP	mg L^{-1}	D	3.63	0.49		TP	mg L^{-1}	D	2.33	0.82
			R	2.06	0.53				R	1.39	0.56
	TN	mg L^{-1}	D	35.74	8.26		TN	mg L^{-1}	D	26.19	7.89
			R	11.00	7.37				R	8.27	6.50

Note: D and R indicate dry and rainy seasons, respectively. Dry and rainy seasons constituted 23 and 13 no-rain days, respectively. The total sample number was 30 for each season.

BOD concentrations in the sewage on the no-rain days of the dry and rainy seasons were 36.5 ± 6.6 (mean ± S.D.) and 89.0 ± 29.7 mg L^{-1} and 18.6 ± 5.4 and 20.0 ± 13.5 mg L^{-1}, respectively. Additionally, although septic tanks in Vietnam have been reported to indicate poor operating conditions [25], the SS and BOD concentrations in the sewage on the no-rain days of the dry season were lower than those reported by Tchobanoglous et al. [7] for a typical low-strength sewage (SS: 120 mg L^{-1} and BOD: 110 mg L^{-1}). Therefore, Hue City was characterized by low concentration sewage even on no-rain days of the dry season, and these results are consistent with those for the other developing countries in Southeast Asia [4,5].

Taking into account that a combined sewer system gathers both wastewater and rainwater, it is unsurprising that sewage in the rainy season is comparatively less concentrated than sewage during the dry season. However, a comparison of sewage quality on the no-rain days of the two seasons indicated that the rainy season sewage was still significantly less concentrated than the dry season sewage. This suggests that there could be other reasons for decreased sewage concentrations during the rainy season besides direct dilution by rainwater.

Impacts of rainfall on sewage quality

In this study, E.C. was continuously monitored to determine the changes in sewage quality after rainfall events and to subsequently appraise the impacts of infiltration on the target sewer. The study area received a total rainfall of 195.5 mm from 25–28 July 2017 (mid-dry season), and we assumed that the rainwater partly flowed into the target combined sewer network, whereas the remaining rainwater went into the ground. Consequently, the sewage was diluted as shown in Figure 3(a). The E.C. declined sharply once the rains started and subsequently maintained a low level. The dry weather resumed after the rainfall stopped and the E.C. gradually increased to approximately 800 μS cm^{-1}, which was equivalent to the E.C. value before this rainfall event. Therefore, the recovery of the E.C. to 800 μS cm^{-1} took approximately 250 h (over 10 days) since the end of the rainfall event. As indicated in Figure 3, the E.C. gradually increased after the end of each rainfall event;

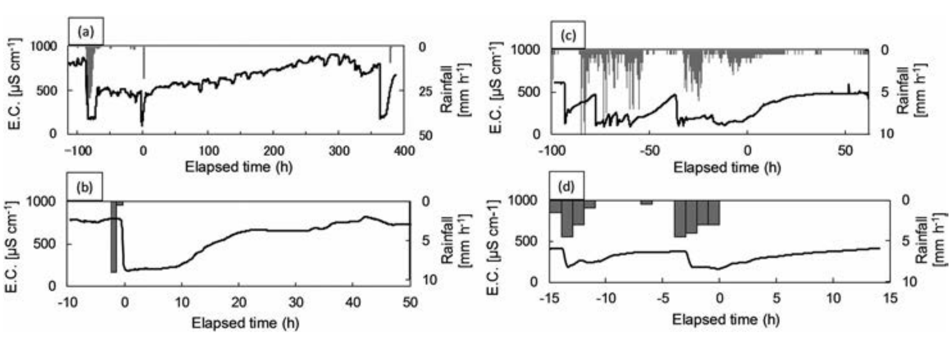

Figure 3. Transition of electrical conductivity (E.C.) after four rain events (a) 25–28 July 2017 (dry season), (b) 12–13 August 2017 (dry season), (c) 19–24 November 2017 (rainy season), and (d) 15–16 November 2017 (rainy season). Line and bar plots indicate E.C. and rainfall, respectively. X-axes show time elapsed after rainfall decreased to 0.5 mm h^{-1} or less.

however, the rainfall amounts and the time elapsed for the recovery of the E.C. to the pre-rainfall level varied across the individual cases.

Figure 4 indicates the relationship between rainfall amounts and elapsed times to recover the E.C. to 95% of the pre-rainfall E.C. level. It should be noted that Figure 4 excludes rain events in which another rain event occurred before the E.C. recovered to the 95% level. Furthermore, several rain events during the rainy season were characterized by intermittent light drizzle; therefore, the end of a rain event was defined by a rainfall intensity of 0.5 mm h^{-1} or less. As shown in Figure 4, rainfall amount and the time elapsed until 95% E.C. recovery indicated a strong correlation in the dry season, while no significant correlation was observed during the rainy season. Additionally, the heavier the rains during the dry season, the longer the elapsed time. The maximum elapsed time for 95% E.C. recovery was 228 h, thus indicating that sewage quality was affected by rainfall for such a long duration.

Elapsed times in the rainy season were significantly lower than those in the dry season. The minimum, median, and maximum elapsed times until 95% E.C. recovery were 15 (6 mm of total rainfall), 37 (9.5 mm), and 228 h (195.5 mm), respectively, for the dry season, while the corresponding values for the rainy season were 5 (82.5 mm), 15 (10 mm), and 41 h (12 mm), respectively. The shorter elapsed times during the rainy season could be attributed to the chronically low E.C. during the rainy season (even during the no-rain time), thus allowing faster recovery of the E.C. to the 95% level. These chronically low levels of E.C. implied continual long-term groundwater infiltration into the sewers, especially after rain events.

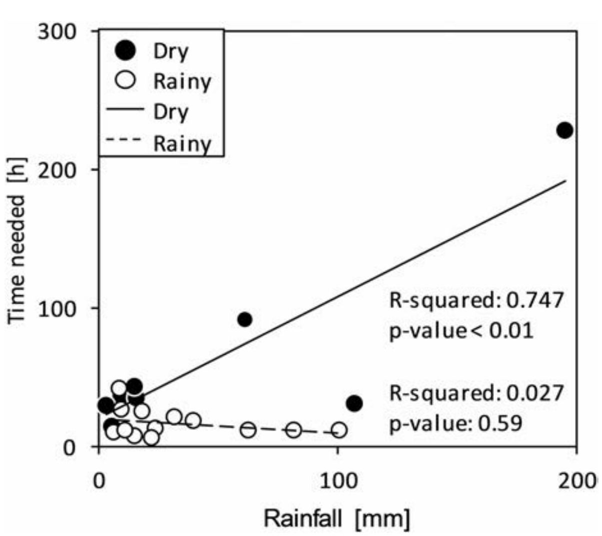

Figure 4. Relationship between rainfall and elapsed time for E.C. recovery to 95% of the pre-rainfall E.C. level. The results have been plotted for the dry and rainy seasons.

Groundwater infiltration

Groundwater infiltration flow was estimated from the base flow of sewage which was characterized by the absence of wastewater discharge from the households. Figure 5(a) presents the daily fluctuations in the sewage flow at the sewer outlet from 4 August to 12 September 2017 (dry season). To avoid the impact of rainfall, this estimate excluded rain days and the two succeeding days after the end of the rainfall event. The maximum elapsed time to recover the E.C. to 95% of the pre-rainfall E.C. level was 44 h, i.e. less than two days, during this period. The results indicated that sewage flow was characterized by two peaks (morning-noon and evening) and a trough (before morning). The minimum mean instantaneous flow rate was 0.81 m^3 h^{-1} at 5:15 am. This result is consistent with Tran et al. [17] who reported that the water consumption trend indicated a dip before morning whereas evident peak flows were indicated in the morning and evening (with a small peak around noon). As mentioned in the materials and methods section, infiltration into the sewers was represented by the base flow estimated in the absence of any wastewater discharge into the sewers. Therefore, the estimated infiltration flow into the sewers (*I*) was

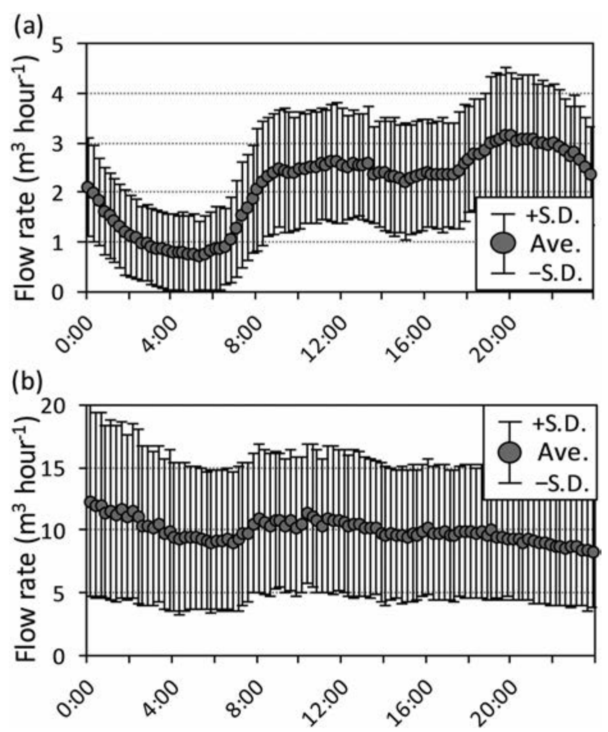

Figure 5. Fluctuations in sewage flow rates over a period of 24 h. (a) 4 August–12 September 2017 (dry season) ($n = 21$) and (b) 18 November 2017–16 January 2018 (rainy season) ($n = 7$). Data excluded rainy days and the two succeeding days after the end of the rainfall event for (a) and rainy days and one succeeding day after the end of the rainfall event for (b).

0.70 $m^3 h^{-1}$ (equivalent to 16.8 $m^3 day^{-1}$) during the dry season. The mean daily flow rate of sewage at the sewer outlet was 50.5 $m^3 day^{-1}$ during the same period; therefore, the estimated infiltration accounted for approximately 30% of the sewage monitored at the sewer outlet.

Figure 5(b) presents the daily fluctuations in the sewage flow rate from 18 November 2017 to 15 January 2018 (rainy season). These data do not include rain days and the day immediately succeeding the end of the rainfall event. In contrast to the dry season, no clear temporal trend of sewage flow was observed for the rainy season. These results could be attributed to the significant infiltration into the sewers. Additionally, the flow rate at the beginning of the day was not equal to that observed at the end of day and could be attributed to the discontinuous data (which excluded data for rain days and the day succeeding the end of the rainfall event). Assuming that water consumption and wastewater discharge trends were not significantly different between the dry and rainy seasons, groundwater infiltration during the rainy season (estimated from the minimum sewage flow before morning) was 9.1 $m^3 h^{-1}$ (equivalent to 218.4 $m^3 day^{-1}$) at 6:00 am. The mean daily flow rate of sewage at the sewer outlet was 269.7 $m^3 day^{-1}$ during the same period; therefore, the estimated infiltration accounted for approximately 80% of the sewage monitored at the sewer outlet. Thus, the results indicated that infiltration flow during the rainy season was 13 times higher than that in the dry season and that infiltration caused significantly high dilution of sewage in the rainy season.

Exfiltration

Figure 6 presents the lithium tracer test results for both dry and rainy seasons. The results indicated that Li concentrations at the sewer outlet peaked several hours after Li was injected into an upstream manhole of the sewer network and gradually decreased over time. The recovered Li mass was 12.27 and 273.3 g for the dry and rainy seasons, respectively. It should be noted that 50.26 and 359.5 g of Li was injected in the dry and rainy seasons, respectively. The estimated Li recovery ratios (*R*) for the dry and rainy seasons were 34.4% and 76.0%, respectively, and the exfiltration ratios were estimated as 65.6% and 24.0%, respectively. These results indicate that the elapsed time to reach the peak concentration of Li was longer during the dry season than the rainy season. Sewage flow rates at the sewer outlet were higher in the rainy season (>5 $m^3 h^{-1}$) than the dry season (~2 $m^3 h^{-1}$), even though tests were conducted on no-rain days for both seasons. Thus, the exfiltration ratio could be low during the rainy season due to high flow rate and high in the dry season due to slow flow rate.

To the best of our knowledge, sewer exfiltration ratios have not been experimentally investigated for developing countries. However, exfiltration ratios reported for developed countries are as follows: Rutsch et al. [10] estimated that exfiltration in a leaky sewer in Berlin ranged from 2.3% to 18.8%; Rieckemann et al. [9] reported that the exfiltration ratio in Rumlang, Switzerland ranged between zero and 15%; and Ellis et al. [26] estimated exfiltration rates of 5–10% in artificial leaky sewers. Compared to these results, the exfiltration ratios estimated for Hue City were significantly high, especially in the dry season, potentially from the poorly sealed connections of the sewers. Incidentally, the velocity of sewage flow at the sampling point was primarily less than 0.1 $m s^{-1}$ in the dry season and averaged at 0.3 $m s^{-1}$ in the rainy season. JSWA [27] reported that 0.6 $m s^{-1}$ was the velocity of sewage in public sewers in Japan required to prevent sedimentation and velocity decrease. The slow sewage velocity in the study area could also be attributed to significant sewage exfiltration which contributed to low flow rate sewage at the sewer outlet, especially in the dry season.

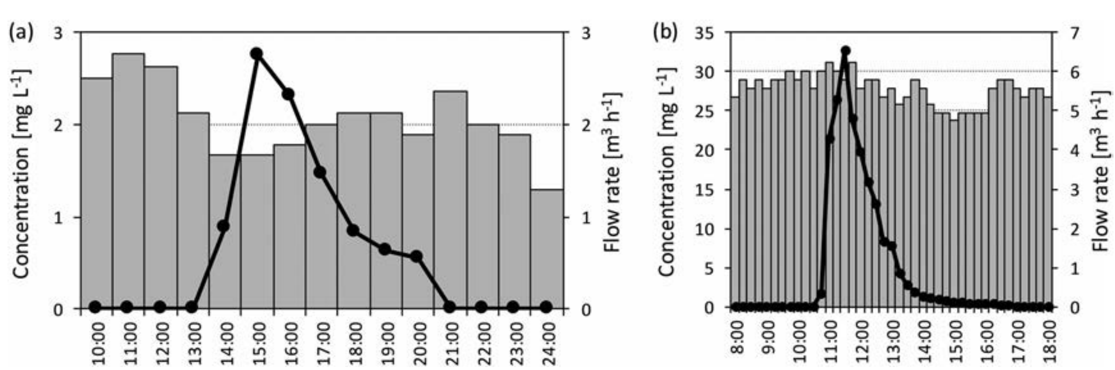

Figure 6. Li concentrations and sewage flows determined from the Li tracer tests. Panels (a) and (b) indicate the results for dry and rainy seasons, respectively. The line graphs and bar charts represent Li concentrations in the sewage and sewage flow rates, respectively.

Water, carbon, nitrogen, and phosphorus balances

In this study, water balance was estimated for no-rain days of both dry and rainy seasons. As shown in Figure 7, the average sewage flow discharged in the dry and rainy seasons was 50.5 and 269.7 m^3 day^{-1}, respectively. The proportion of greywater not discharged to the sewers (r_G) was calculated from the mass conservation law (Equation (2)) and the estimated values for the dry and rainy seasons were 0.390 and 0.352, respectively. Focusing on the output from the system, exfiltration was the largest outgoing flow, except for sewage discharged from the sewer outlet in both the dry and rainy seasons. Exfiltration can occur continually and significantly throughout the year, reducing the pollution load at the sewer outlet. Comparing the input of supplied water and the output of the sewage discharged to water body, only 23% of the input (i.e. supplied water) reached the sewer outlet in the dry season, while 123% of the input reached it in the rainy season. This difference was mainly caused by the difference of infiltration, which was 13 times more in the rainy season than in the dry season. The results indicate that infiltrated water significantly diluted sewage in the rainy season, decreasing the sewage concentration, as shown in Table 1. Additionally, infiltrated water occupied 11% and 62% of the total sewage inflow to the sewer, consisting of T_S, G_S, and I (Figure 2), during the dry and rainy seasons, respectively. JSWA [16] reported that the proportion of infiltration in the total sewer inflow for 26 drainage areas in Japan was 26% ± 18% (mean ± S.D.). Similarly, the value for Lyon was 38% ± 12% [28]. In contrast, the proportion for Hue was relatively low in the dry season and significantly high in the rainy season. This distinct seasonal difference could be attributed to the tropical monsoon climate. Therefore, water likely seeped underground during the high rainfall events of the rainy season and subsequently leaked into the sewers.

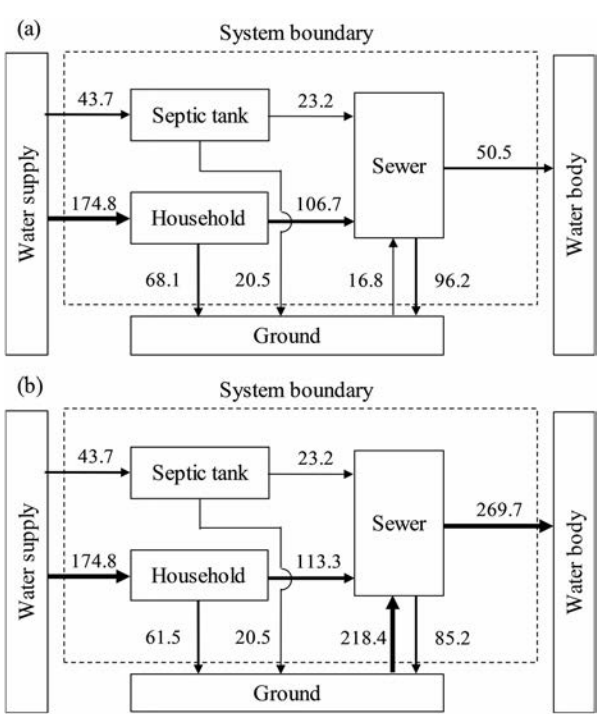

Figure 7. Water balance of the target sewer during the (a) dry season and (b) rainy season. Values next to the arrows indicate flow rates (m^3 day^{-1}). Flows were estimated as the averages of 23 and 13 no-rain days during the dry and rainy seasons, respectively.

The loading values of COD, N, and P at the household level were, regardless of the seasons, 48.76, 8.37, and 1.58 g cap^{-1} day^{-1}, respectively. The COD, N, and P loadings at the sewer outlet in the dry season were 8.99 ± 2.36 (mean ± S.D.), 1.76 ± 0.41, and 0.18 ± 0.04 g cap^{-1} day^{-1},respectively, while those in the rainy season were 15.08 ± 9.63, 3.11 ± 1.65, and 0.80 ± 0.56 g cap^{-1} day^{-1}, respectively (Figure 8). Additionally, the COD, N, and P loadings at the sewer inlet in the dry season were 59%, 54%, and 56% of the household values, respectively, while those in the rainy season were 62%, 54%, and 57% of the household values, respectively. These low proportions could be attributed to the limited connecting ratio (53%) between the septic tanks and the sewers and the limited discharging ratio (39% and 35% in the dry and rainy seasons, respectively) of greywater to the sewers. The seasonal differences could be attributed to the small difference in the greywater discharge ratios of the two seasons. Further, the COD, N, and P loadings at the sewer outlet during the dry season were 31%, 39%, and 20% of the sewer inlet values, respectively, while the values for the rainy season were 50%, 68%, and 88% of the sewer inlet loadings, respectively. The proportions of COD, N, and P loadings that reached the sewer outlet were calculated as 18%, 21%, and 11% and 31%, 37%, and 51% in the dry and rainy seasons, respectively. This indicates the overall trend of pollution loading reduction from the sewer inlet to the outlet, although the P reduction in the rainy season was unclear, owing to a large standard deviation. In addition, the reduction from the sewer inlet to the outlet was greater in the dry season than in the rainy season. This seasonal difference in pollution loading reduction was primarily associated with the significant seasonal differences in the exfiltration ratios (24.0% and 65.6% in the rainy and dry seasons, respectively).

Thus, large proportions of the COD, N, and P loadings were not collected by the sewer network in the study area. This could be attributed to significant non-

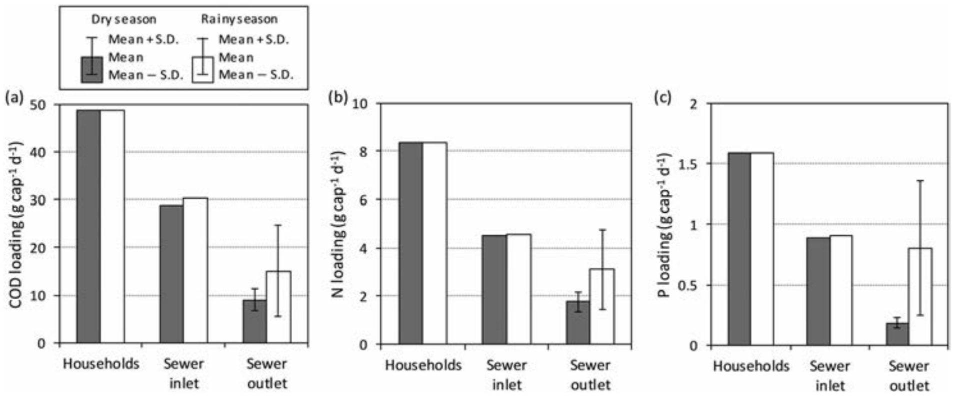

Figure 8. Loading values of (a) COD, (b) nitrogen, and (c) phosphorus at the households, sewer inlet, and sewer outlet.

discharge of blackwater and greywater into the sewers as well as high exfiltration ratios. Meanwhile, the low-concentration sewage could be explained by the above-mentioned two reasons as well as high infiltration ratios. Therefore, exfiltration and significant loss of pollutant loadings before discharge into the sewer significantly decreased the pollutant loadings in the sewage, while infiltration decreased the sewage concentration. Moreover, more than half of the sewage inflow exfiltrated from the sewers in the dry season. Additionally, the dry season sewage was less dilute due to significantly smaller infiltration. In contrast, a significantly smaller proportion of the sewage inflow exfiltrated in the rainy season and a significantly high infiltration diluted the sewage. Thus, sewage dilution caused by infiltration produced low-concentration sewage even on no-rain days of the rainy season (Table 1).

According to the Ministry of Construction, Vietnam [29], the sewer coverage ratios for the urban areas of Vietnam are expected to increase to 70–80% by 2025. In addition to this increase, the following changes potentially affecting sewage characteristics are expected: increased water consumption, improved sewer networks, improved wastewater pipe connections to sewers, and closed septic tanks that allow direct discharge of blackwater into sewers. These changes are being implemented in several developing countries in Southeast Asia and are likely to affect infiltration, exfiltration, and the proportion of wastewater discharged into the sewer, which have been shown to influence the sewage characteristics. Therefore, the results of this study are likely to aid future sewerage development plans and allow forecasting of sewage characteristics.

Conclusions

In this study, continuous monitoring of sewage flow and quality as well as lithium tracer tests were conducted in Hue, Vietnam to characterize small-flow and weak-strength sewage in Southeast Asia. Sewage of the target sewer was weaker than the typical weak-strength sewage even on the no-rain days of the dry season. As indicated by the continuously monitored E.C. data, rainfall continuously affected the sewage quality for a maximum duration of 228 and 41 h in the dry and rainy seasons, respectively. These results indicate the long-term impacts of infiltration. Further, the lithium tracer test results suggested significantly high exfiltration ratios (65.6% and 24.0% for the dry and rainy seasons, respectively). Additionally, infiltration accounted for 11% and 62% of the total sewage inflow to the sewer during the dry and rainy seasons, respectively, thus indicating significant dilution of sewage even on the no-rain days of the rainy season. Furthermore, the water balance results indicated that only 23% of the supplied water to the study area reached the sewer outlet in the dry season (attributed to high exfiltration ratios and partial discharge of septic tank effluent and greywater into the sewers), whereas 123% flowed at the outlet in the rainy season (due to significant infiltration). These results demonstrated that sewage exfiltration and partial discharge of septic tank effluent and greywater dominantly decreased the sewage flow and pollutant loadings in the dry season, while infiltration significantly increased the sewage flow and decreased the sewage concentration in the rainy season. Thus, this study focused on exfiltration and infiltration mechanisms to successfully characterize the sewage in Hue City. To the best of our knowledge, this is the first study to quantify the impacts of infiltration and exfiltration on sewage flow and quality in developing countries.

However, this study had several limitations. The water quality of the exfiltrate and the infiltrate was not determined. Therefore, while pollution loading values were determined for the households, sewer inlet, and the sewer outlet, a mass balance model of pollutant loadings was not developed. Further, this study was limited to the no-rain days. Sewage needs to be characterized for the rain days as well since the study region featured combined sewers. Further, this study was conducted in a small (largely residential) drainage area. A larger drainage area with mixed land use should be investigated in future studies. Nevertheless, this study advanced understanding of small-flow and weak-strength sewage typically observed in several developing countries in Southeast Asia. Sewage characteristics are expected to undergo dynamic changes in such countries due to rapid changes in the water-related infrastructures. As demonstrated in this study, future sewerage development plans should account for the impacts of infiltration and exfiltration on the sewage characteristics.

Acknowledgements

This study was supported by GAIA and a Sewerage Application Study from the Ministry of Land, Infrastructure, Transport and Tourism, and by JSPS KAKENHI, Grant Number JP16H02748. A survey group from Hue University of Science also supported to a field survey in Hue, Vietnam.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

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