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Evaluating the sensory and health impacts of exposure to sewer overflows on urban population

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ABSTRACT

Sewer overflow contains several hazardous contaminants causing adverse health effects and annoyance to the public. Despite this importance, few studies has hitherto been undertaken on examining the odor nuisance and risk of diseases due to contact with untreated overflow. However, quantitative investigation of odor emission from the sanitary sewage overflows has not been addressed. As such, this study aims to scrupulously investigate the deleterious impact of such phenomenon on public health in terms of the aforesaid matters. To this end, a multi-stage methodological approach was employed. Firstly, field data was collected from the vicinity of a wastewater treatment plant for three years, and then the concentrations of H_2S in the aqueous phase and gaseous phase were estimated based on the environmental parameters. Afterward, the Gaussian aerial dispersion model and Quantitative Microbial Risk Assessment (QMRA) were employed. In parallel, the impact of the exposure to the malodorous H_2S emitted from overflow cases was assessed. Furthermore, the results obtained from impact assessment were validated using the developed questionnaire survey. From the results obtained, the following major conclusions are drawn: (1) levels of $H_2S_{(g)}$ near the overflow were high enough to be perceived by individuals, (2) concentrations of $NH_{3(g)}$ in the ambient air were estimated lower than the perception threshold, (3) the sulfide concentration in the overflow was the most influential parameter with positive linear correlation with the concentration of $H_2S_{(g)}$, (4) the concentration of odor causes high annoyance, according to the questioning from the residents near the overflow events (5) exponential dose-response indicated 89–95% infection risk and (6) the good correlation between the estimated values of annoyance and the real annoyance level perceived by the residents proved accuracy of the methodology for estimation of H_2S concentration and annoyance level. The unique findings obtained from this study guide the environmental decision-makers to take pre-emptive actions, preventing risk of infection and complaints from the residents.

1. Introduction

Sewer overflows or discharge of the sewer from the conveying systems to the environment may occur due to the pipeline blockages, intrusion of storm-water into the sewer pipeline larger than their capacity, and infiltration into sewer system (Botturi et al., 2021; Emmons, 2017; Sumer et al., 2007). Sewer overflows are classified into two main categories namely: combined sewer overflows (CSO) and sanitary sewer overflows (SSOs). CSOs occur in the cities with the sewer pipeline infrastructure carrying sanitary sewer and stormwater together. One of the main reasons for CSOs is inadequate capacity of the combined sewer networks, especially due to increasing precipitation with climate change impacts. On the other hand, SSOs occur in the cities with separate collection system of sanitary sewer and stormwater due to the blockages, line breaks, mechanical or power failures, etc. (USEPA, 2004). Because of the higher concentrations of contaminants in SSOs, their occurrence is of great importance in terms of environmental risk assessment.

SSOs bring several contaminants such as fecal pathogens, organic pollutants, suspended solids, micro-pollutants, heavy metals, nutrients, and odorous compounds from the untreated wastewater into the urban areas and/or recreational areas such as beaches (Angerville et al., 2013; Launay et al., 2016; Madoux-Humery et al., 2016; Nickel and Fuchs, 2019; Phillips et al., 2012; Pongmala et al., 2015; Xu et al., 2018). Researchers employed several methods to monitor the CSOs and SSOs

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(Capodaglio et al., 2016a; Copetti et al., 2019; Viviano et al., 2017). Table 1 provides a comparison between CSOs and SSOs in terms of pollutant load and volume. Pathogens and organic compounds may be ingested or dermally contacted through the contact between the overflow and individuals' hands, which may cause gastrointestinal diseases (de Man et al., 2014). Impacts of the CSOs on the receiving waters such as lakes, rivers, reservoirs, and beaches have been extensively studied (al Aukidy and Verlicchi, 2017; Björklund et al., 2018; Madoux-Humery et al., 2016; Marchis et al., 2013; Passerat et al., 2011; Pollard et al., n.d.; Quijano et al., 2017; Riechel et al., 2016; Weyrauch et al., 2010). However, adverse effects of SSOs such as H_2S emission from them have been seldom reported. Due to the significance of overflows and their adverse health effects, several studies have been conducted to predict their occurrence and discharge of contaminants from them and provided management plans (Baek et al., 2015; Boënne et al., 2014; Goulding et al., 2012; Hofer et al., 2018; Honda et al., 2020; Kozak et al., 2020; Meyers et al., 2021; Montserrat et al., 2015; Morales et al., 2017; Schertzinger et al., 2019). On the other hand, management plans should include use of sustainable stormwater management approaches (Boguniewicz-Zabłocka and Capodaglio, 2020; Capodaglio et al., 2016b).

Besides several adverse effects on the receiving waters from the SSOs, they introduce large amounts of toxic compounds from the untreated sewer to the urban areas to which residents are exposed (Capelli et al., 2009; Lewkowska et al., 2016; Li et al., 2021; Prata et al., 2021; Ravina et al., 2020; Sivret et al., 2016). As Table 1 shows, SSOs and CSOs introduce approximately 1892×10^{14} and 69172×10^{14} MPN of fecal coliforms to the receiving water bodies, respectively (USEPA, 2004). Considering the average discharge volume and concentrations of pollutants in the CSOs and SSOs, the average amount of toxic compounds, nutrients and other pollutants to the receiving waters can be estimated.

1.1. Emission of malodorous compounds from SSOs

Among several toxic compounds, malodorous compounds such as hydrogen sulfide (H_2S), methyl mercaptan, dimethyl sulfide, dimethyl disulfide, ammonia (NH_3), trimethylamine, acetaldehyde, benzene, and ethyl-benzene are of great significance due to their formation at high levels in the wastewater, their toxicity at low levels, the annoyance of the residents even in the non-toxic levels, and exposure to them through ingestion, dermal contact, and inhalation (Agus et al., 2012; Park, 2020; Pochwat et al., 2019). Sivret et al. (2016) investigated several odorants emitted from sewers and prioritized them. H_2S in the sewer networks is formed under anaerobic conditions through the reduction of sulfate (SO_4^{2-}) in the sediments of the pipelines (Jiang et al., 2014; Lahav et al., 2006; Nielsen et al., 2008; Sharma et al., 2008). The general mechanism of H_2S formation in the sewer network is presented below (Baawain et al., 2019):

$$SO_4^{2-} + organic\,matter \xrightarrow{Anaerobic\,microorganisms\,(no\,dissolved\,oxygen)} H_2S + CO_2$$

Table 1
A comparison between SSOs and CSOs in terms of concentrations of pollutants and the volume of pollutants introduced to the environment due to SSOs and CSOs (USEPA, 2004).

	SSOs	CSOs
Fecal coliform (colonies/100 mL)	10^6–10^9	3–4 × 10^7
BOD_5 (mg/L as O2)	88–451	3.9–696
TSS ($mg.L^{-1}$)	118–487	1–4420
Cadmium ($\mu g.L^{-1}$)	0.1–101	0.16–30
Lead ($\mu g.L^{-1}$)	0.5–250	5–1013
Total Phosphorus ($mg.L^{-1}$)	1.3–15.7	1.1–20.8
Total Kjeldahl Nitrogen ($mg.L^{-1}$)	11.4–61	0–82.1
Average discharge volume (billion gallons)	10	850
Total BOD_5 load (Ib)	$< 10^7$	3.7×10^8
Total TSS load (Ib)	$< 10^7$	8.9×10^8
Total fecal coliform load (MPN × 10^{14})	1892	69172

Some empirical formulas were provided to estimate the concentrations of H_2S in the sewer pipelines, which was summarized by Hvitved-Jacobsen et al. (2000). Based on these formulas, higher temperature and higher organic content of wastewater intensify the formation of H_2S. H_2S is the major reason for pipeline corrosion and odor emission from the sewage to the atmosphere. The rate of H_2S emission or H_2S flux from sewage to air is dependent on wastewater pH, wastewater temperature, and the turbulence at the interface of air and wastewater (Yongsiri et al., 2004). On the other hand, in the case of a SSO, the emitted H_2S is dispersed in the atmosphere and the concentration of H_2S at a certain point is related to the H_2S flux from the sewage, wind speed, wind direction, air temperature, weather stability, and distance from the overflowing source (Rumsey and Aneja, 2014). H_2S is a toxic gas at ppm levels and with a very low perception threshold as shown in Table 2 (Hvitved-Jacobsen, 2002). Several reports have been released regarding the fatal or disease-causing accidents induced by exposure to H_2S (Nielsen et al., 2008).

Dispersion of odorous compounds such as H_2S may impair the quality of the surrounding environment, cause annoyance to the residents, be absorbed in the plants and properties rendering them useless, and cause hesitance in individuals to use them (Badach et al., 2018; Nicell, 2009; Sironi et al., 2010). These interferences of odor dispersion with the daily activities of residents necessitate the impact assessment of accidental exposure to the odorous compounds. Sewer odor from the manholes and their corresponding risk have been analyzed before (Pan et al., 2020; Pérez et al., 2013). However, despite several complaints about the odor annoyance (Hayes et al., 2017; Morgan et al., 2017), the odor nuisance due to the SSOs has rarely been investigated (Goulding et al., 2012). The relationship between the concentrations of H_2S in the atmosphere and several parameters such as wastewater characteristics and environmental parameters (e.g., wind speed and weather stability) has not been examined. More importantly, the current body of literature lacks the assessment of the impact of exposure to the odorous compounds emitted from SSOs; thus, there is a need to comprehensively assess the odor emission associated with SSOs.

1.2. Exposure to pathogens from the SSOs

Another adverse health effect of exposure to a SSO is entering pathogens, heavy metals, and micropollutants into human body through ingestion (Kozak et al., 2020; Sojobi and Zayed, 2022). Some researchers have attempted to find out the levels of heavy metals, micropollutants, and endotoxins in the sewer systems (de Man et al., 2014; Emmons, 2017; Houhou et al., 2009; Xu et al., 2018). The pathogens such as E. coli, Cryptosporydium, enterococci, staphylococci, Campylobacter, Giardia, norovirus, and enterovirus were found more important in this regard (Huang et al., 2017; Madoux-Humery et al., 2016; Scheurer et al., 2015; van Bijnen et al., 2018). Several papers have been published regarding risk assessment of exposure to E.coli through floods and recreational beaches and the gastrointestinal diseases due to that (Ashbolt

Table 2
Relationship between odor chemical concentration and odor intensity, adopted from Han et al. (2020).

Scale (Degree of Intensity)	Status	H_2S concentration (ppb)	NH_3 concentration (ppm)
0	None	<0. 5	<0.15
1	Threshold	0. 5	0.15
1.5		1.7	0.30
2	Moderate	5.6	0.59
2.5		19	0.85
3	Strong	63	2.35
3.5		210	4.68
4	Very strong	720	9.33
4.5		2390	18.62
5	Excessively strong	8100	37.1

et al., 2010; Eregno et al., 2016; Schets et al., 2011). Contact with the SSOs may have more serious impacts since untreated sewer contains higher concentrations of pathogens compared with floods or recreational beaches. This is due to the dilution of pathogens in floods and recreational beaches. Despite this, there has been no study assessing the risk of contact with sanitary overflow in terms of exposure to E.coli.

With the above in mind, the followings are the gaps to be tackled in this study, along with the employed objectives:

(1) The paucity of the impact assessment of exposure to the odorous compounds emitted from SSOs. To tackle this gap, this study uses the relative data collected from Hong Kong as a case study and simulates the H_2S flux from the overflows followed by H_2S dispersion modeling to find the annoyance level of the odor associated with the H_2S dispersion near the overflow. The estimated annoyance level was compared with perceived level from the people near the overflows.
(2) The lack of risk assessment of exposure to E.coli resulting from a SSO. To prudently address this shortcoming, this study aims to utilize the QMRA framework to find out the exposure amount to E.coli and the risk of infection from it.

Based on the data collected from manholes carrying untreated wastewater and located near a wastewater treatment plant in Hong Kong, the following contributions are noted:

(a) Identification of the major factors contributing to the H_2S and NH_3 flux to the atmosphere and its dispersion
(b) Unravelling the correlation between those factors and the $H_2S_{(g)}$ concentration at a certain point in the atmosphere
(c) Identification of the pathways of exposure to the pathogens of untreated wastewater and the risk of entering E.coli to human body
(d) Assessment of the effects of exposure to the odorous compounds emitted from accidental SSOs and comparison between the estimated annoyance level and the real annoyance level perceived by the people in the vicinity of a SSO.

The outcomes of this study provide insights into the separation distances from the SSOs as an odor source considering the meteorological and environmental parameters. These insights provide information for the urban development decision-makers to find the best locations for the manholes to prevent odor annoyance from accidental SSOs. On the other hand, estimating the risk of infection from different pathways of contact with the SSOs provides sufficient evidence for the city dwellers to take appropriate measures regarding their health in the case of SSOs.

2. Methodology

In this paper, a hybrid methodological approach is employed, including the experimental characterization of the samples from manholes, mass transfer and air Gaussian dispersion models, inquiry from the individuals, impact assessment, and QMRA. Fig. 1 shows the steps undertaken within the research methodology adopted in this study. In the following sections, the case study area and characterization methods of the samples are explained followed by the methods of simulation methods of odor flux and dispersion and QMRA of contact with the overflow.

2.1. Case study description and the analytical methods

Hong Kong's Stonecutters Island Sewage Treatment Works (STCISTW) is a chemically enhanced primary treatment plant and one of the largest ones in the world with a design flow of 2,450,000 $m^3.day^{-1}$, which is located in the southwest of the New Territories of Hong Kong. The study area and the overview of the Harbor Area Treatment scheme in Hong Kong is depicted in Fig. 2. Three manholes in the vicinity of STCISTW were selected for sampling untreated sewer. During the study period from Jan 2018 to Dec 2020, each month, samples were grabbed from the manholes and transferred to the laboratory in the headspace-free bottles kept at 4 ∘C. pH was measured onsite with Multimeter (WTW 3420). The other parameters, including biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total suspended solids (TSS), ammoniacal nitrogen (NH_3–N), and the total sulfide and E.coli of the samples were all measured according to the standard methods for the examination of water and wastewater (Baird et al., 2017), as mentioned in Table 3. The meteorological data regarding the wind speed and the air temperature were obtained from the Hong Kong observatory website. It should be noted that Hong Kong's sewer system is separate system and in case of overflow occurrence, it should be considered as SSO. On the other hand, samples were taken at certain SSO events near STCISTW and characterized in the laboratory followed by estimation of H_2S concentration. The characteristics of the SSO events and their occurrence time is tabulated in Table S1 in the supporting information. The impact assessment of the odor emission from the SSO events in real cases will be explained in the following sections.

2.2. Modelling H_2S flux from an overflow to the atmosphere

The rationale in modelling H_2S flux from an overflow is as follows. According to the two-film theory, H_2S flux from an overflow to the atmosphere has been modelled. Based on this theory, two films of gas and liquid are assumed to be formed in the interface of gas and liquid and the exchange of gas molecules between these two films are responsible for the gas flux from the liquid to the gas phase (Rumsey and Aneja, 2014).

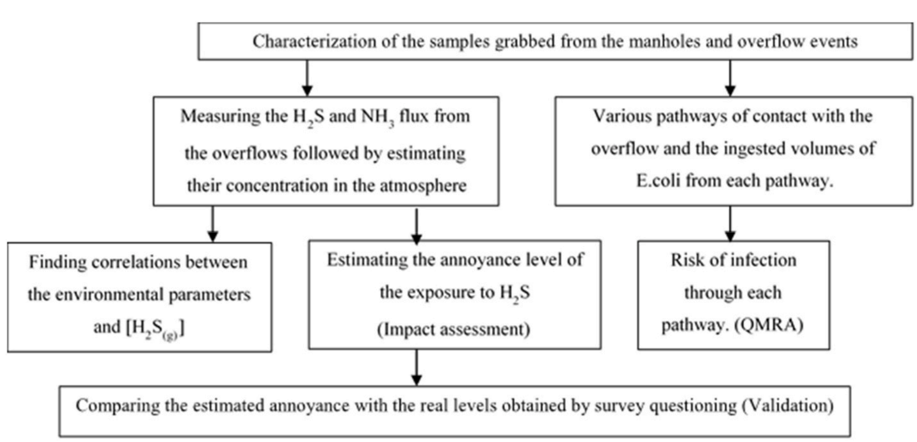

Fig. 1. The general scheme of this work.

Fig. 2. Overview of the Harbor Area Treatment scheme in Hong Kong (Reference: https://www.epd.gov.hk/epd/english/environmentinhk/water/hkwqrc/sewerage/hats.html). The samples were taken from the manhoels near "Stonecutters Island Sewage Treatment Works" depicted inside the red circle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Testing parameters and the corresponding parameters (Baird et al., 2017).

Parameters	Analytical methods	Unit
pH	4500-H + B.	–
TSS	2540 D.	$mg.L^{-1}$
NH_3–N	4500-NH_3 F.	$mg.L^{-1}$ as N
E. coli	9222 D.	$cfu.mL^{-1}$
BOD_5	5210 B.	$mg.L^{-1}$ as O_2
COD	5220 D.	$mg.L^{-1}$ as O_2
Total sulfide	4500-S^{2-} F.	$mg.L^{-1}$

The details of this theory can be found elsewhere (Blunden et al., 2008; Liss and Slater, 1974). The gas flux is the product of three terms as shown in Eq. (1):

$$J_{H_2S} = K_m[H_2S]_{ovf}H_L \tag{1}$$

where J_{H_2S} is the H_2S flux ($\mu g.m^{-2}.min^{-1}$) from the overflow to air, K_m is the mass transfer coefficient, $[H_2S]_{ovf}$ is the concentration of H_2S ($mg.L^{-1}$) in the bulk overflow, and H_L is Henry's constant (dimensionless) of H_2S. In the following, the way to obtain each of these parameters is explained.

K_m is found based on the study of Santos et al. (2006), where they developed an empirical expression considering the environmental parameters, including wind speed, air temperature, and liquid temperature, as expressed in Eq. (2):

$$K_m = -3.121\times10^{-6} - 4.277\times10^{-7}(T_{air}) + 7.3154\times10^{-7}(T_L) + 1.6659\times10^{-5}(U_*) \tag{2}$$

where T_{air}, T_L, and U_* are air temperature (°C), liquid temperature (°C), and friction velocity ($m.s^{-1}$), respectively. U_* is found according to Eq. (3):

$$U_* = 0.01U_{10}(6.1 + 0.63U_{10})^{0.5} \tag{3}$$

where U_{10} is the wind speed ($m.s^{-1}$) at 10 m height.

H_L is indicative of the H_2S equilibrium at the interface of the bulk liquid and air. The dimensionless value of H_L indicates the ratio of $\frac{H_2S\ concentration\ in\ the\ gas\ film\ \left(\frac{mg}{l}\right)}{H_2S\ concentration\ in\ the\ liquid\ film\ \left(\frac{mg}{l}\right)}$ and is equal to 0.389 at 298.15 K (or 25 ∘C). H_L is correlated to the bulk liquid's temperature by the Van't Hoff equation, as expressed in Eq. (4) where T is the temperature of the bulk liquid or overflow in this case (Stumm and Morgan, 1996)

$$\log(H_L) = \log\left(0.389\frac{298.15}{T}\right) - \left(\frac{\Delta H^\circ}{\ln(10R)}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right) \tag{4}$$

Concentration of H_2S in the overflow is related to the concentration of the total sulfide. Three forms of sulfide exist, in equilibrium with each other, in the aquatic environments as S^{2-}, HS^-, and $H_2S_{(aq)}$. It is noteworthy that only the non-ionized form of sulfide, $H_2S_{(aq)}$, can emit to the atmosphere (Blunden et al., 2008). The chemical equilibrium between these three species can be expressed as Eq. (5) and Eq. (6):

$$HS^-_{(aq)} \rightarrow S^{2-}_{(aq)} + H^+\ pK_{a1} = 7 \tag{5}$$

$$H_2S_{(aq)} \overset{K_d}{\rightarrow} HS^-_{(aq)} + H^+\ pK_{a2} = 14 \tag{6}$$

As it can be seen, the fraction of each of these species relates to the concentration of H^+ and consequently, pH. At the pH range of 6–8, typical of the wastewater pH, $H_2S_{(aq)}$, and HS^- constitute most of the total sulfide; therefore, the fraction of $H_2S_{(aq)}$ can be determined using Eq. (7):

$$f_{H_2S} = \frac{10^{-pH}}{10^{-pH} + K_d} \tag{7}$$

where K_d is the dissociation constant and correlated to the temperature of the bulk liquid as expressed in Eq. (8) (Stumm and Morgan, 1996):

$$\log(K_d) = -6.99 - \left(\frac{\Delta H^\circ}{\ln(10)R}\left(\frac{1}{T} - \frac{1}{298.15}\right)\right) \tag{8}$$

where ΔH° is the enthalpy change for the dissociation of H_2S and equal to 22.15 kJ mol^{-1}, R is the universal gas constant (0.008314 kJ $mol^{-1}.K^{-1}$), and T is the temperature of the overflow (K).

2.3. Dispersion models

Dispersion of the malodorous compounds in the SSOs leads to odor emission to the environment near the SSOs. Dispersion of volatile compounds such as H_2S and NH_3 can be simulated with the Gaussian model, which has been extensively used in the previous papers. Several attempts have been conducted to model the dispersion of compounds in the atmosphere and their variations in the space and time (Conti et al., 2020). Recognizing these variations enables the decision makers to apply appropriate measurements in order to avoid possible health impacts on the residents. Dispersion models can be used to estimate odor concentrations emitted from different sources such as farms, factories, petrochemical plants, and wastewater treatment units. Dispersion models generally follow three approaches of Gaussian, Lagrangian, and Eulerian ones; among them, Gaussian models have been employed more prevalently due to their easier application and requirement for less amount of data. They are however, more imprecise than other models and are poorly representative at low odor concentrations and non-elevated sources (see "A User's Guide for the CALPUFF Dispersion Model" available at http://www.src.com/calpuff/download/CALPUFF_UsersGuide.pdf). The main assumption of the Gaussian models is the steady-state conditions and continuous emission from the source (Danuso et al., 2015). Some commercial models based on the Gaussian plume model are AERMOD, LODM, STINK, and OdiGauss (Conti et al., 2020).

The general equation of the Gaussian dispersion model is expressed as Eq. (9).

$$C=\frac{Q}{2\pi\sigma_y\sigma_z u_h}\times\exp\left(-\frac{y^2}{2\sigma_y^2}\right)\times\left[\exp\left(-\frac{(z-h)^2}{2\sigma_z^2}+\exp\left(-\frac{(z+h)^2}{2\sigma_z^2}\right)\right]\quad (9)$$

where:

C: concentration of the volatile compound in surrounding space (mg. m^{-3});

Q: emission rate of a volatile compound from the emission source (μg.s^{-1});

y: distance from the source in the horizontal direction at the right angle to the downwind direction (m);

z: vertical distance from the source (m);

h: the height of the emission source, which is equal to 0 in this case, since the overflow is on the ground; and.

σ_y and σ_z: horizontal (y) and vertical (z) dispersion coefficients, respectively.

Dispersion coefficients σ_y and σ_z are calculated according to Danuso et al. (2015). According to the wind speed and the global hourly radiation, the stability class of HK's weather is either C or D. Therefore, the following formulas for the urban environment are used:

Stability Class	σ_y	σ_z
C	$0.22x(1+0.0004x)^{-1/2}$	$0.2x$
D	$0.16x(1+0.0004x)^{-1/2}$	$0.14x(1+0.0003x)^{-1/2}$

Since overflow is on the ground level, h = 0 and the equation is simplified as Eq. (10) by substituting Eq. (1) as Q or H_2S flux:

$$C=\frac{K_m[H_2S]_{ovf}H_L}{2\pi\sigma_y\sigma_z u_h}\times\exp\left(-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}\right)\quad (10)$$

It should be noted that in finding the concentration of H_2S at a certain point in the atmosphere, only 1 h of emission was considered in this work. It is due to the short-term effect of an accidental overflow. Therefore, temporal variations of the odorous compounds were not considered. Moreover, for the impact assessment, a maximum area of 100 m^2 was considered.

2.3.1. Sensitivity analysis

To find the most influential parameters on the H_2S concentration and the extent of their influence, a sensitivity analysis was done. To this end, all parameters but one was held constant and H_2S concentration at a certain point was found as a function of that parameter. For the sensitivity analysis, environmental parameters were set to the practical ranges as follow: 1 mg.L^{-1} for the total sulfide in the overflow, pH of 7, wind speed of 23 km h^{-1}, air temperature of 20 ∘C, overflow temperature of 25 ∘C, and hourly global radiation of 1800 kJ m^{-2}.hr^{-1}.

2.3.2. Impact assessment of the exposure to H_2S

Although exposure to the H_2S(g) emitted from an overflow at the ambient conditions does not lead to adverse health effects, it may represent a nuisance and adversely affect human activities (Sironi et al., 2010). Several methods have been proposed to evaluate the impact of the odor dispersion on the environment and individuals (Brancher et al., 2017, 2021; Han et al., 2020; Hayes et al., 2014, 2017; Nicell, 2009; Ranzato et al., 2012; Sironi et al., 2010; Stellacci et al., 2010). For example, Capodaglio et al. (2002) assessed the impacts of odor nuisance from expansion of a wastewater treatment plant by surveying and analysis of current and future designs of the wastewater treatment plants, identifying and quantifying the odor sources and considering odor reduction alternatives. In most of the studies conducted in this regard, a large area was considered and the odor impact was assessed through a long-time span. However, in this work, a small area in a short-time span was considered due to the temporary remaining of overflow on the ground and lower covering area of that compared with lagoons and farms as investigated by previous researchers.

Another way of evaluation of the odor impact is finding the odor threshold and obtaining the concentration of odor in the unit of OU.m^{-3}. The number of OU for a specific odor is the number of times that an odorous gaseous sample should be diluted with odor-free air to be perceivable by 50% of population exposed to it (Gostelow M et al., 2001). On the other hand, there is no specific correlation between the H_2S concentration and odor concentration, which is due to the subjectivity of the sense of odor. A few studies have provided correlations between the $[H_2S_{(g)}]$ and the concentration of odor based on experimental research. Blanes-vidal et al. (2009) proposed the following equation based on the studies of Noble et al. (2001) and Gostelow M et al. (2001):

$$OC=k(C_{H_2S}+\gamma)^{\beta}$$

Blanes-vidal et al. (2009) proposed k = 11143, γ = 5.35, and β = 0.73 based on their observations and provided the following correlation between OC and $[H_2S]$:

$$OC=11143(C_{H_2S}+5.35)^{0.73}$$

On the other hand, they proposed another correlation between $[H_2S]$ and odor as below; however, this correlation is for the pure H_2S:

$$OC=2000\times C_{H_2S}$$

Due to the subjectivity of odor perception, dose-response relations have been developed considering the probability of annoyance or odor detection (Nicell, 2003) as expressed in Eq. (11):

$$P=\frac{100}{1+\left(\frac{C_t}{C}\right)^{\frac{1-p}{p}}}\quad (11)$$

where:

P (in %): the probability of detection of an odor,

C: the concentration of the odorous compound (in ppb),

C_t: the threshold concentration of the specific odorous compound (in ppb), at which 50% of people can detect the odor, and

p (dimensionless): the 'persistence of response' of the specific odor.

For H_2S, Belgiorno et al. (2012) proposed p = 0.4 and C_t = 4.7 ppb according to their observations; therefore:

$$P=\frac{100}{1+\left(\frac{4.7}{[H_2S]}\right)^{\frac{1-0.4}{0.4}}}$$

However, odor concentration and comparison of odor threshold with the amount of emitted odor could not reflect the offensiveness and annoyance of the odor and cannot account for the bad feelings created for people (Nicell, 2003). The annoyance level is used to characterize the psychological adversity of exposure to a malodorous compounds. It is a function of the attitude and feelings of the people exposed to an odor source and related to complex human reactions to odor exposure causing negative appraisal (Van Harreveld, 2001). The advantages of this method are: (1) accounting for the direct and real effects of the odor emission from the SSOs (2) simplicity and (3) cost-effectiveness (Belgiorno et al., 2012). To quantify the annoyance level of the emitted odor from the SSOs, the relations between the odor annoyance and odor concentrations have been provided (Nicell and Henshaw, 2007; Nicell, 2003; Henshaw et al., 2006). To quantify the annoyance level, which is a number in the range of 1–10, with the unit of "AU", the models developed by Poostchi (1985) and Nicell (1986) was used. In summary, the panelists are asked to express their level of annoyance as 0−2 (Tolerable), 2−4 (unpleasant), 4−6 (very unpleasant), 6−8 (terrible) and 8−10 (unbearable). As it seems, the annoyance level is inherently subjective, however, it represents the real effect of the odor emission on people. On the other hand, Nicell (2003) developed a model to estimate the annoyance level of the odor based on the concentration of a specific compound as expressed by Eq. (12):.

$$A = \frac{10}{1 + \left(\frac{C_{5AU}}{C}\right)^{\frac{1-a}{a}}} \tag{12}$$

where a (measured in annoyance units, AU) stands for the degree of annoyance of the population and ranges from 0 to 1, C is the concentration of the odorous compound (in ppm), C_{5AU} denotes the odorant concentration where the population annoyance has a value of 5 AU, and a (dimensionless) is the 'persistence of annoyance' of the specific odor. The 'persistence of response' varies from 0 to 1 depending on the compound (Nicell, 2003). Parameters C_{5AU} and a were estimated to be 23 ppb and 0.68, respectively, based on the observations of people annoyed by the existence of H_2S in the atmosphere. Therefore, for $H_2S_{(g)}$ the below relationship can be developed:

$$A = \frac{10}{1 + \left(\frac{23}{[H_2S_{(g)}]}\right)^{0.47}}$$

To find the impact of the exposure to the odor emitted from a sanitary overflow, at 25 overflow events occurred through Jan 2018 to Dec 2020, 1 L of the overflow was collected and transferred to the laboratory to obtain its characteristics as shown in Table S1. The temperature, pH and covered area of the overflow were found on-site. The wind speed and air temperature were also found on-site. Based on the above mentioned parameters, the concentration of $H_2S_{(g)}$ at a certain point near the overflow was estimated followed by forecasting its annoyance level by Eq. (12). Since these impact assessment formulas are empirical, they were validated through surveying from the ordinary people passing by the overflows in the real cases as it will be explained below. It should be noted that the main focus of this work is assessing the annoyance level of the emitted odorous compounds specially H_2S from SSOs to the atmosphere. Therefore, the exact concentrations of H_2S in the atmosphere were not measured experimentally. However, the annoyance level of the emitted H_2S was estimated using the provided formula in the literature and compared with the real annoyance level perceived by the people exposed to H_2S in the vicinity of SSO events by surveying. The surveying method is explained in detail in the below sections.

2.3.3. Validation of the impact assessment results by surveying from the residents

In this work, the results of the impact assessment were validated through questioning survey from the people passing nearby a SSO event at each SSO event. Surveys based on the social participation have been used to assess the annoyance level of the odorous compounds on the people in the surroundings of the odor sources (Beghi et al., 2012; Nicolas et al., 2010). The reason to take the approach of the social participation to validate the results is to involve the ordinary people in the procedure of impact assessment and gain more realistic results regarding the perception of the residents (Conti et al., 2020; Hayes et al., 2014; Hayes et al., 2017; Sironi et al., 2010).

Table 4
The surveying questions from the volunteers.

Question	Answer
Are you interested in involving in the odor perception panel?	Yes
Are you in the age range of 18–60 years old	Yes
Have you ever smoked?	No
Have you ever suffered from respiratory problems	No
Have you ever experienced exposure to malodorous compounds in their last one year of life and complained about that?	Yes
Have you had any conflict of interest with DSD?	No

Firstly, 358 people were invited to an interview. A few questions were asked from them to find out their suitability for the project. The questions are tabulated in Table 4. Among 356 people, 129 of them were chosen., who answered the questions as tabulated in Table (Beghi et al., 2012). After selection of the volunteers, they were trained according to the ASTM E 544 standard (ASTM, 2004). On the other hand, the selected people, were explained about the general purpose of this work.

After selecting the people, the SSO at a certain place was predicted through monitoring the level of the sewer in the sewer manholes using a method, which will be published in the near future. The general procedure of SSO prediction is based on the increasing rate of sewer level in the manholes and if it exceeds 80% of the manhole height, the SSO was likely to occur and remain in the area for several hours. 25 SSOs were recorded and samples were taken to the laboratory to measure the raw wastewater characteristics as explained before. At each SSO event, volunteers were asked to attend the location of the SSO and provide their annoyance level in the range of 1–10 according to their training. The range of 1—10 was chosen to comply with the impact assessment method as described in section 2.3.2 and comprehensively discussed by Nicell (1994). The collected data was analyzed and the outliers were found by Orange 3.31.1 software and removed from the data. Then a normal distribution was ascribed to the remaining data and the mean and standard deviation of their answers were recorded. The distribution of the collected data was presented in Appendix A.The estimated annoyance level by the concentration of $H_2S_{(g)}$, which was found according to Eq. (12) was compared with the average of the reported values from the residents after removing the outlier data.

2.4. Quantitative microbial risk assessment from the exposure to pathogens

The framework of QMRA provides the probability of getting infected by a certain pathogen considering epidemiological studies, dose-response models, and hydrodynamic modelling. To do this, target pathogens, the exposure pathways, the amount of the pathogens entering body, and the response of the body to pathogens should be identified (Eregno et al., 2016). In this work, E.coli was chosen as the target pathogen due to its prevalence in the wastewater and the ease of measuring it. The average concentrations of E.coli, Giardia, Cryptosporidium, Norovirus, and Salmonella in the wastewater were estimated as 5.9×10^6, 759.5, 678.1, 5.1×10^5, and 3.16×10^2 respectively (Eregno et al., 2016). The amount of E.coli entering an individual's body is the product of the volume of the ingested contaminated water and the concentration of E.coli in that. Moya et al. (2011) suggested the maximum and minimum amounts of the ingested water from a flooding event, which is similar to the overflow, and shown in Table 4. Concentrations of E.coli in the raw wastewater was obtained by HK DSD each month from January 2018 to December 2020. The response of the human's body when exposed to a pathogen is represented by dose-response relationships, which describes the probability of infection. This response reflects the characteristics of the pathogen and the immune system of the host (Eregno et al., 2016).

To calculate the probability of infection due to the ingestion of E.coli-contaminated sanitary sewage, a beta-poisson dose-response model (DRM) is used (Abia et al., 2016). Ingestion of the overflow may be incidental or intentional. The probability of getting infected by swallowing a certain volume of contaminated water can be calculated by Eq. (13):

$$P_i = 1 - \left(1 + \frac{N}{\beta}\right)^{-\alpha} \quad (13)$$

where N is the number of E.coli ingested (or the dose), and β and α are the specific equation parameters of E.coli and equal 2.473 and 0.395, respectively (Haas et al., 2014; Strachan et al., 2005). The parameter N is the product of ingested volume and the concentration of E.coli in the overflow.

The total ingested volume of an overflow can be found according to Eq. (14) (de Man et al., 2014):

$$V_{T=}V_d + V_M + h \times a \times 2 \quad (14)$$

The parameters in Eq. (12) and their distributions are explained in Table 5. To obtain the risk of ingesting overflow, it is assumed that the maximum estimated volume of overflow is ingested by an individual; therefore:

$$V_{T=}5 + 52.2 + 2.34 \times 10^{-2} \times 2000 \times 10^{-4} = 57.2 \text{ mL}$$

Thus, at each exposure, 57.2 mL of overflow is ingested by an individual.

3. Results and discussion

3.1. The influence of environmental parameters on $[H_2S_{(g)}]_{(x,z)}$

According to Eq. (10), the effective parameters on $[H_2S_{(g)}]_{(x,z)}$ are concentration of total sulfide ($[S^{2-}]_T$), pH of the overflow, wind speed, overflow temperature, air temperature, $H_{L,(H_2S)}$, and the distance from the overflow. In the following parts, the effect of each of these parameters on $[H_2S_{(g)}]_{(x,z)}$ are discussed, and the sensitivity of $[H_2S_{(g)}]_{(x,z)}$ on each of them are obtained. To this end, the value of one parameter is varied, while the others are kept constant. To have realistic correlations, the environmental parameters are varied in the ranges close to the real observed cases. The constraint of the 5 °C higher value of the wastewater temperature than the air temperature is always held based on inquiry from the experts. The relationships between $[H_2S_{(g)}]_{(x,z)}$ and the environmental parameters' variations are investigated using linear or polynomial regression. The regression analysis was conducted using Microsoft-Excel Version 2016.

Table 5
Volume of the overflow ingested by an individual.

Factor	min	max	Other parameters	Distribution function	Reference
Ingested droplets (V_d)	0.5 mL	5 mL		uniform	Schijven and de Roda Husman (2006)
Ingested mouthful by children (V_M)	7.8 mL	52.2 mL	r = 4.72 λ = 5.3	Gamma	Schets et al. (2011)
skin-surface area of the hand that was mouthed (h)	1.97 × 10^{-2} (mm)	2.34 × 10^{-2} (mm)		uniform	EPA (2011)
skin-surface area of the hand that was mouthed (a)	100 mm^2	2000 mm^2		uniform	EPA (2011)
frequency of hand-mouth contact (f)			2 times per hour	Poisson	Freeman et al. (2001)

3.1.1. Effect of $[S^{2-}]_T$

Fig. 3 shows the concentrations of $[H_2S_{(g)}]_{(5,1.6)}$ in ppb unit from a 100 m^2 overflow when $[S^{2-}]_T$ varies in the range of 0–5 $mg.L^{-1}$. As it was expected, $[H_2S_{(g)}]_{(5,1.6)}$ linearly increased with increasing $[S^{2-}]_T$. This is due to the linear correlation between the $[H_2S_{(g)}]_{(x,z)}$ and H_2S flux from the overflow according to Eq. (10), which also has linear correlation with $[S^{2-}]_T$ ((Eq. (1)). The slope of this correlation depends on the other environmental parameters. At $[S^{2-}]_T$ as high as 0.54 mg/L in an overflow covering 100 m^2 of ground, $[H_2S_{(g)}]_{(5,1.6)}$ is 0.5 ppb, which is discernible for the residents. At higher than 5 $mg.L^{-1}$ of $[S^{2-}]_T$, the odor will be moderate and generates more annoyance.

3.1.2. pH of the overflow

pH variations affect the chemical equilibrium between the species in the aquatic environments followed by changes in the ionization and solubility of these species. Fig. 4 shows how the pH change in the range of 6–8 influences $[H_2S_{(g)}]_{(5,1.6)}$. As Fig. 4 shows, $[H_2S_{(g)}]_{(5,1.6)}$ drastically decreases with increasing pH from 6 to 8. The increase of pH causes a decrease in f_{H_2S} or the available H_2S to enter the atmosphere (Rumsey and Aneja, 2014). As Eq. (5) and Eq. (6) show, lower availability of $H_2S_{(aq)}$ at higher pH values is due to the ionization of $H_2S_{(aq)}$ to HS^- and S^{2-}, which are not volatile and cannot disperse in the atmosphere. Based on Eq. (5), at pH 7, 50% of $[S^{2-}]_T$ is in the molecular form or $H_2S_{(aq)}$, which can be volatilized. As pH increases, the ionized portion of H_2S increases and lowers the H_2S flux from the overflow. Although the concentration of H_2S and pH has logarithmic correlation with each other according to Eq. (7), in the pH range of 6–8, their correlation can be simulated by polynomial equation. It should be noted that the effect of pH on the activity of the microorganisms, involved in the generation of S^{2-}, was excluded in this study due to its higher complexity. The effect of pH variation on H_2S generation from SO_4^{2-} with the mediation of the organic compounds has been investigated in other studies (Rathnayake et al., 2021).

It should be noted that the in the sewer samples from the manholes and the SSOs, the pH was in the range of 6.8–7.1, however, to dig deeper in the influence of pH on the $H_2S_{(g)}$ emission, larger pH range of 6–8 was considered. On the other hand, the SSO samples were taken near the manholes before SSOs enter the receiving waters or collection systems.

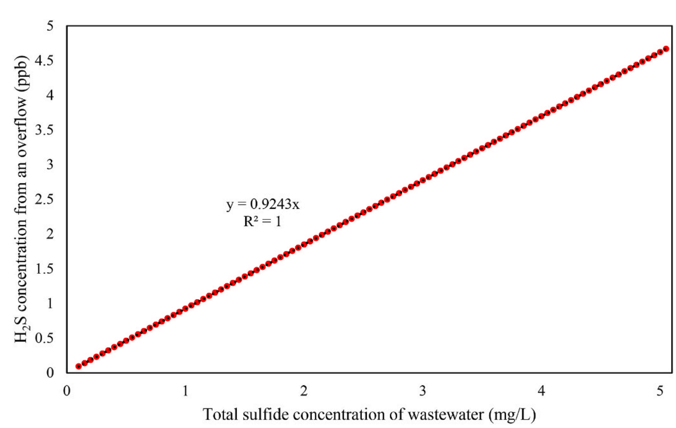

Fig. 3. Effect of $[S^{2-}]_T$ on $[H_2S_{(g)}]_{(5,\ 1.6)}$ from a 100 m^2 overflow. Conditions: pH of the wastewater = 7, wind speed = 20 km h^{-1}, weather stability class = D (neutral), air temperature = 20 ∘C, wastewater temperature = 25 ∘C, horizontal distance from the overflow in the downwind direction = 5 m, and vertical distance from the overflow = 1.6 m.

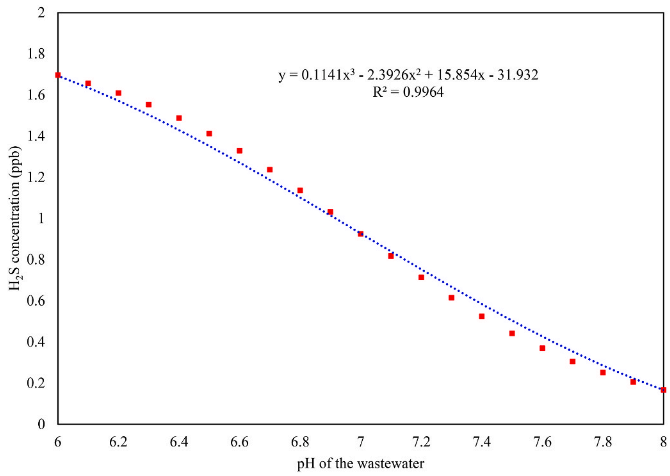

Fig. 4. Effect of the pH on $[H_2S_{(g)}]_{(5,\ 1.6)}$ from a 100 m^2 overflow. Conditions: $[S^{2-}]_T$ = 1 mg.L^{-1}, wind speed = 20 km h^{-1}, weather stability class = D (neutral), air temperature = 20 ∘C, wastewater temperature = 25 ∘C, horizontal distance from the overflow in the downwind direction = 5 m, and vertical distance from the overflow = 1.6 m.

Therefore, the pH of the SSOs were not buffered.

3.1.3. *Effect of air and wastewater temperature*

As mentioned earlier, the wastewater temperature was assumed to be 5 ∘C higher than the air temperature. Therefore, in identifying the effect of air temperature on $[H_2S_{(g)}]_{(5,\ 1.6)}$, all parameters were held constant; however, both air temperature and wastewater temperature were varied considering the above constraint. Fig. 5 shows how changing air temperature affects $[H_2S_{(g)}]_{(5,\ 1.6)}$. The air temperature sensitivity analysis showed that $[H_2S_{(g)}]_{(5,\ 1.6)}$ linearly increases with increasing the air temperature. However, in case of a 10 ∘C increase in the air temperature accompanied by a 10 ∘C increase in the wastewater temperature, $[H_2S_{(g)}]_{(5,\ 1.6)}$ increases by approximately 0.5 ppb.

The positive correlation between the air and wastewater temperature and the H_2S concentration is the result of increasing H_2S flux with increasing temperature. Increasing air and wastewater temperature affects several parameters such as the mass transfer coefficient (K_m), dissociation constant of H_2S (K_d), and $H_{L,(H_2S)}$. In case of a 10 ∘C increase in the air and wastewater temperatures, K_m increases by 3 × 10^{-7}. On the other hand, increasing wastewater temperature by 10 ∘C increases dissociation constant of H_2S by 3 × 10−1, leading to 5 × 10^{-7} unit decrease in the portion of $H_2S_{(aq)}$ from the total sulfide. H_L is also affected by temperature. It can be seen that K_m increases linearly with increasing the air and wastewater temperatures. The diffusivity of H_2S in wastewater increases with increasing wastewater temperature and results in decreasing its solubility and increasing mass transfer coefficient (Arogo et al., 1999; Rumsey and Aneja, 2014). On the other hand, the lower temperature of the air than that of the wastewater, which is reflected in the above-mentioned assumption, leads to instability in the interface of wastewater and air. Lower stability is followed by higher turbulence and higher mass transfer coefficient and H_2S flux from the surface (Rumsey and Aneja, 2014). It should be noted that the effect of temperature on the activity of the microorganisms involved in the generation of sulfide and its effect on the wind speed were not considered in this analysis. The collective effects of these phenomena resulted in a negligible increase in $[H_2S_{(g)}]_{(5,\ 1.6)}$ with increasing temperature. Moreover, at all temperatures higher than 10 ∘C, H_2S emitted from an overflow is perceivable. Blunden et al. (2008) also reported higher H_2S fluxes from the swine waste treatment storage system at summer compared with that in winter.

3.1.4. *Wind speed and weather stability*

Wind speed affects the $H_2S_{(g)}$ flux from the overflow by changing K_m. According to Eq. (2) and Eq. (3), increasing the wind speed from 10 km h^{-1} to 30 km h^{-1} increases K_m by 46%. This is due to increasing the instability on the top of the bulk liquid. Based on the Gaussian plume model, the concentration of a dispersed compound, in this case, H_2S, is inversely correlated with the wind speed. Considering both effects from the wind speed, it can be found that $[H_2S_{(g)}]_{(x,z)}$ decreases with increasing the wind speed, as shown in Fig. 6. It is noteworthy that, in the calculations, the neutral stability of the weather was assumed. If the weather was slightly unstable, $[H_2S_{(g)}]_{(x,z)}$ was changed due to the change in the dispersion coefficients of σ_y and σ_z. Fig. 6 shows that at all wind speeds, which may occur most of the days during a year, H_2S emitted from an overflow can be perceived by the people passing by it.

The stability classes of the weather were classified as very unstable (A), moderately unstable (B), slightly unstable (C), neutral (D), slightly stable (E), and moderately stable (F). The stability class of weather depends on the meteorological conditions such as wind speed, the hourly global radiation, time of a day, air temperature, and wind direction (Danuso et al., 2015). Fig. 7 shows that $[H_2S_{(g)}]_{(5,\ 1.6)}$ at slightly unstable weather is slightly higher than that at the unstable weather. However, with increasing the stability of weather, $[H_2S_{(g)}]_{(5,\ 1.6)}$ decreased, and at stable weather, almost no H_2S could be perceived.

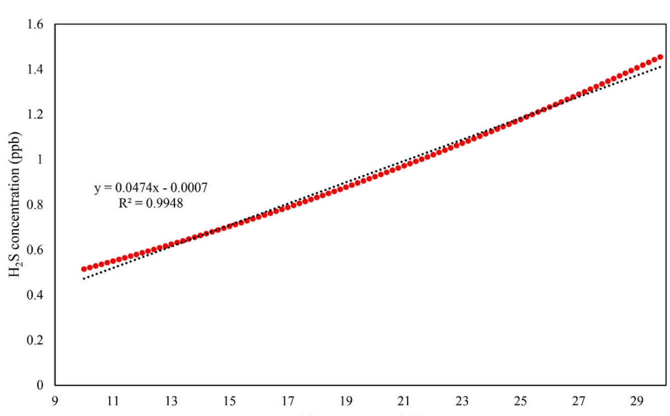

Fig. 5. Effect of the air temperature on the concentration of $[H_2S_{(g)}]_{(5,\ 1.6)}$ from a 100 m^2 overflow. Conditions: $[S^{2-}]_T$ = 1 mg.L^{-1}, pH = 7, wind speed = 20 km h^{-1}, weather stability class = D (neutral), horizontal distance from the overflow in the downwind direction = 5 m, and vertical distance from the overflow = 1.6 m. It is assumed that the wastewater temperature is 5 ∘C higher than the air temperature.

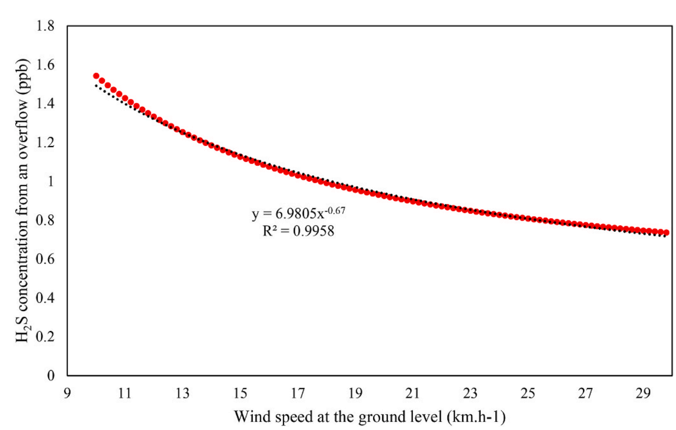

Fig. 6. Effect of the wind speed on $[H_2S_{(g)}]_{(5,\ 1.6)}$ from a 100 m^2 overflow. Conditions: $[S^{2-}]_T$ = 1 mg.L^{-1}, pH = 7, air temperature = 20 ∘C, wastewater temperature = 25 ∘C, weather stability class = D (neutral), horizontal distance from the overflow in the downwind direction = 5 m, and vertical distance from the overflow = 1.6 m. It is assumed that the wastewater temperature is 5 ∘C higher than the air temperature.

3.1.5. Horizontal distance from the overflow in the downwind direction

Fig. 8 shows the $[H_2S_{(g)}]_{(x,z)}$ at different horizontal distances at the downwind direction and 1.6 m vertical distance from the overflow. As the figure displays, $[H_2S_{(g)}]_{(x,z)}$ decreases in proportion with a power function of horizontal distance in the downwind direction, and at the distances higher than 20 m, $[H_2S_{(g)}]_{(x,z)}$ reaches below perception limit of H_2S, which is 0.5 ppb.

3.1.6. Vertical distance from the overflow

Fig. 9 shows the decreasing trend of H_2S concentration with increasing the vertical distance from the overflow. This figure is for the points at 5 m horizontal distance from the overflow. At this horizontal distance in the downwind direction, the H_2S concentration at the elevations higher than 1.8 m is below the perception limit. However, at the closer horizontal distance to the overflow, the H_2S odor is more perceivable. Therefore, most of the people at the horizontal distances lower than 5 m from the overflow, may perceive the H_2S odor.

3.1.7. Volume of the overflow

It was assumed that the thickness of overflow covering the ground is 1 mm; therefore, 1 m^3 overflow covers 100 m^2 of the ground. On the other hand, the flatness of the ground and 1 h of remaining overflow on the ground is assumed. The assumption of 1 h remaining overflow is due to the fact that the Gaussian model responds to 1 h. According to the calculations, 1 m^2 of overflow leads to $[H_2S_{(g)}]_{(5,1.6)}$ of 0.009 ppb. Thus, the minimum overflow to generate the perceivable odor of H_2S at 1.6 m height and 5 m away from the overflow in the downwind direction is 54 m^2 or approximately 0.54 m^3.

3.1.8. Spatial distribution of odor

Fig. 10 shows the diffusion of $H_2S(g)$ in the wind direction and vertical direction from a 100 m^2 overflow. As it shows, at the heights beyond 1.5 m, the concentration of $H_2S(g)$ reaches below 0.5 ppb, the discernible value of $H_2S(g)$. Moreover, beyond 12 m, $H_2S(g)$ was nearly unperceivable and the risk of annoyance can be ignored. It should be noted that due to the low concentration of $H_2S_{(g)}$ at distances higher than 10 m, the georeferenced figures are not provided, however, at the cases of high concentrations of odorous compounds from other sources such as the power plants, the georeferenced figures are more helpful.

3.1.9. Ammonia odor from an overflow

Another malodorous compound, which may be emitted from the raw wastewater is NH_3. Ammonia is found in the wastewater in two forms of NH_3 and NH_4^+, which are in equilibrium with each other as expressed in Eq. (15):

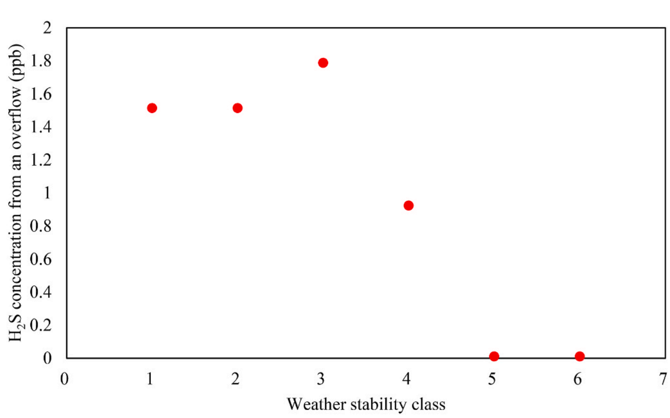

Fig. 7. Effect of the weather stability on the concentration of $[H_2S_{(g)}]_{(5,\ 1.6)}$ from a 100 m^2 overflow. Conditions: $[S^{2-}]_T = 1$ mg.L^{-1}, pH = 7, wind speed = 20 km h^{-1}, air temperature = 20 ∘C, wastewater temperature = 25 ∘C, weather stability class = D (neutral), horizontal distance from the overflow in the downwind direction = 5 m, and vertical distance from the overflow = 1.6 m.

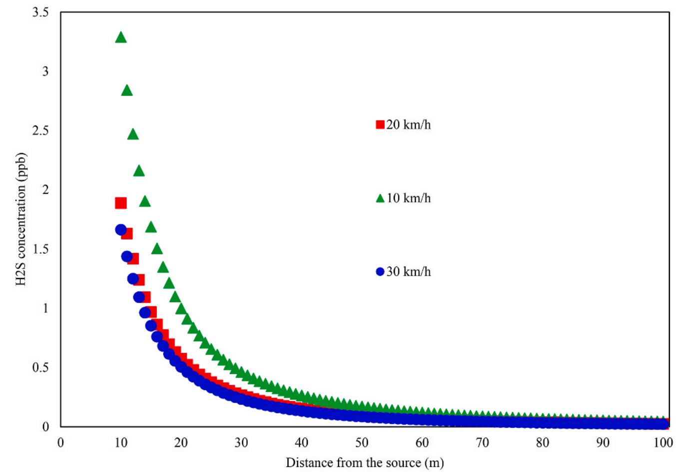

Fig. 8. Concentration of $[H_2S_{(g)}]_{(x,z)}$ at different horizontal distances and different wind speeds from 100 m^2 overflow at the downwind direction. Conditions: $[S^{2-}]_T = 1$ mg.L^{-1}, pH = 7, wind speed = 20 km h^{-1}, air temperature = 20 ∘C, wastewater temperature = 25 ∘C, weather stability class = D (neutral), and vertical distance from the overflow = 1.6 m.

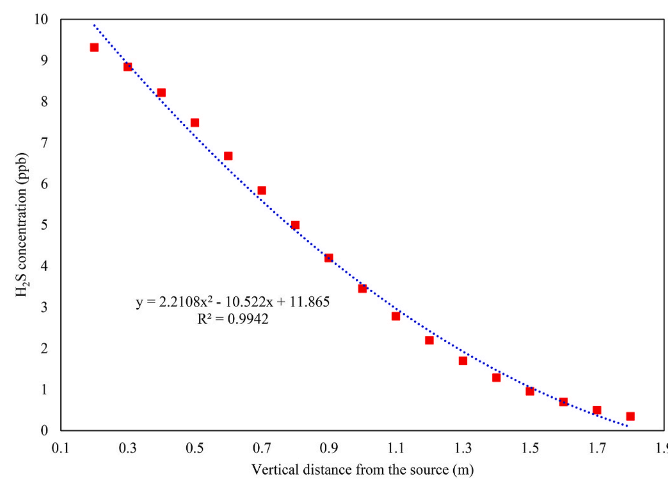

Fig. 9. $[H_2S_{(g)}]_{(x,z)}$ at different vertical distances from the overflow at 5 m horizontal distance from a 100 m^2 overflow in the downwind direction. Conditions: $[S^{2-}]_T = 1$ mg.L^{-1}, pH = 7, wind speed = 20 km h^{-1}, air temperature = 20 ∘C, wastewater temperature = 25 ∘C, weather stability class = D (neutral), and horizontal distance from the overflow = 5 m.

$$NH_4^+(aq) \overset{K_d}{\rightarrow} NH_{3\ (aq)} + H^+\ pK_{a2} = 9.5 \quad (15)$$

The framework of finding $[NH_{3\ (g)}]_{(x,z)}$ in the atmosphere is exactly the same as that of $[H_2S_{(g)}]_{(x,z)}$ and the only differences are the dissociation constant of NH_3 and its Henry's law constant. Concentrations of NH_3 in the raw municipal wastewater is in the range of 20–40 mg.L^{-1}. Since pK_a of NH_4^+ is 9.5, at pH = 7, $\frac{[NH_3]}{[NH_4^+]} = 10^{-2.5} = 0.003$ and in presence of 40 mg.L^{-1} as N of NH_3, 0.126 mg.L^{-1} of it is in form of $NH_{3\ (aq)}$, which is volatile. On the other hand, the Henry's law constant of NH_3 in dimensionless form is 0.00073. Considering these, at pH = 7, wind speed of 20 km h^{-1}, wastewater temperature of 25 ∘C, and air temperature of 20 ∘C, the ammonia flux from an overflow is 8.7×10^{-4} μg m^{-2}.s^{-1}, which is 5×10^{-4} times bigger than that of H_2S at similar conditions with $[S_2^{2-}]_T = 1$ mg.L^{-1}. This implies that the concentration of $NH_{3\ (g)}$ emitted from 100 m^2 of overflow, 5 m in the downwind direction, and 1.6 m above the overflow is 4.3×10^{-4} ppb, which is much less than its threshold limit, 150 ppb. Due to the ionization of NH_3 at neutral pHs to NH_4^+, its low Henry's law constant and its high threshold odor, $NH_{3\ (g)}$ emitted from an overflow is not perceivable for the residents.

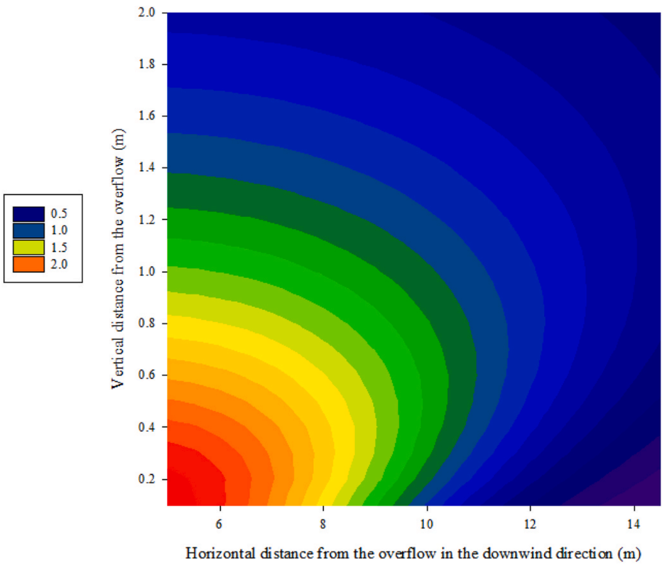

Fig. 10. The spatial distribution of $H_2S_{(g)}$ from a 100 m^2 overflow in the atmosphere in the downwind direction (x-axis). Conditions: $[S^{2-}]_T = 1$ mg.L^{-1}, pH = 7, wind speed = 20 km h^{-1}, air temperature = 20 ∘C, wastewater temperature = 25 ∘C, and weather stability class = D (neutral).

3.1.10. *Concentration of $H_2S_{(g)}$ near an overflow from a manhole*

In this study, to evaluate the validity of the modelling results, an approach easier than direct measurement of $[H_2S_{(g)}]_{(x,z)}$ was adopted. It should be affirmed that the major objective of the impact assessment of odor dispersion modelling is to assess the annoyance of emitted H_2S. This approach was held due to the following reasons: (1) the annoyance, not the concentration of H_2S, being the focus of this research, (2) difficulty and large errors of periodically determining emission rates (Tansel and Inanloo, 2019) and (3) large variability of meteorological conditions making the accurate measurements questionable. To this end, instead of measuring concentration of $H_2S_{(g)}$ in the atmosphere, the perception of $H_2S_{(g)}$ in the vicinity of a manhole containing untreated wastewater before entering a wastewater treatment plant was assessed. From Jan 2018 to Dec 2020, each month, at a certain day, a wastewater sample was taken from a manhole near the SCISTW located in the southwest of the New Territories of Hong Kong was taken and transferred to the laboratory for measuring major parameters of the wastewater such as pH, BOD_5, sBOD, COD, TSS, VSS, NH_3–N, TKN, NO_x-N, TP, OP, SO_4^{2-}, total S^{2-}, soluble S^{2-}, ORP, Cl^-, conductivity, alkalinity, OG, and E.coli. All measurements were conducted according to (Baird et al., 2017).

Fig. 11 shows the concentration of $H_2S_{(g)}$ at 5 m above an overflow covering 100 m^2. It was assumed that the temperature of the wastewater was close to the maximum mean temperature of that month. This assumption was made based on the inquiry from the experts and investigating the data extracted from the studies of (Cipolla and Maglionico (2014) and; Golzar et al. (2020). It is noteworthy that there is no correlation between the air temperature and the wastewater temperature, and the wastewater temperature depends on several parameters such as the temperature of the upstream inflow and the soil temperature (Dürrenmatt and Wanner, 2014; Hadengue et al., 2021). However, to estimate the wastewater temperature, the above-mentioned assumption seems reliable. The average monthly air temperature is found from the Hong Kong observatory. On the other hand, the concentration of H_2S in the aqueous phase was calculated according to the overflow's pH and the dissociation constant of H_2S, which is correlated to wastewater's temperature (Eq. (7) and Eq. (8)). Finally, $H_{L\ (H_2S)}$ was calculated according to Eq. (4), considering the air temperature.

As Fig. 11 shows, in 15 months among the 36 months of observation, $[H_2S_{(g)}]_{(5,\ 1.6)}$ was below 0.5 ppb, which was the threshold of its perception. The highest $[H_2S_{(g)}]_{(5,\ 1.6)}$ was 2.8 ppb that occurred in June 2020. Interestingly, 10 of the cases were higher than 1 ppb, among which, 7 cases occurred in the summertime. The higher concentration of $H_2S_{(g)}$ during summertime may be due to the higher concentration of $H_2S_{(aq)}$ in summer, which can be attributed to the higher activity of sulfate-reducing bacteria (SRB) at higher temperatures. To find any possible correlation between the environmental parameters and $[H_2S_{(g)}]$, the diagrams of $[H_2S_{(g)}]$ and each parameter was obtained. Fig. 12 shows a positive correlation between $[S^{2-}]_T$ in the wastewater and $[H_2S_{(g)}]$. It is noteworthy that two of the data was omitted due to being outliers, which had $[S^{2-}]_T$ of 2.3 and 3.7 mg.L^{-1} in January 2018 and February 2018, respectively. This may be due to the error of measurements. The positive linear correlation between $[H_2S_{(g)}]$ and $[S^{2-}]_T$ in the wastewater can be explained by Eq. (1), in which $[H_2S_{(g)}]$ and $[H_2S_{(aq)}]$ are linearly correlated. Since pH of the wastewater is 6.9–7, $[H_2S_{(aq)}]$ is approximately 0.5 times bigger than $[S^{2-}]_T$.

On the other hand, as Fig. 13 shows, there is no correlation between the wind speed and $[H_2S_{(g)}]_{(5,\ 1.6)}$. Moreover, the air temperature and $[H_2S_{(g)}]_{(5,\ 1.6)}$ have no correlation with each other.

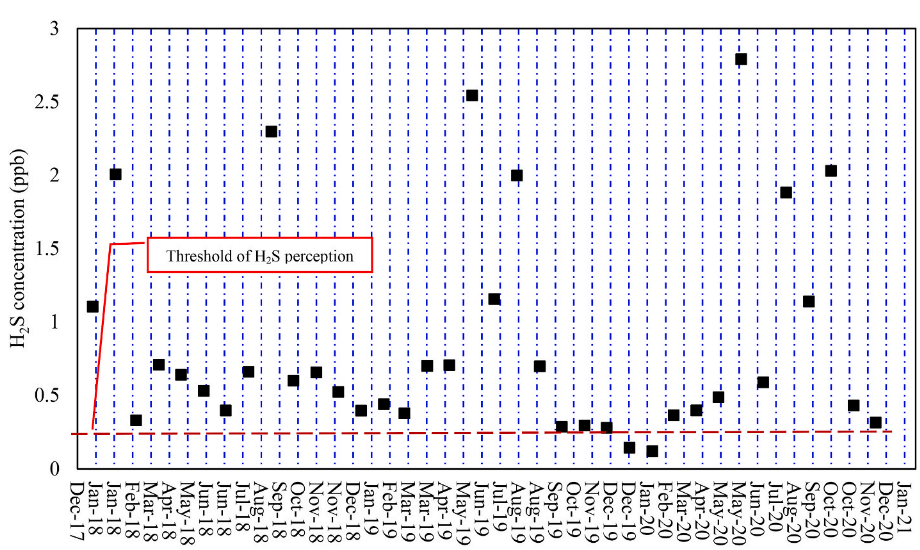

Fig. 11. Concentrations of H_2S at a point 1.6 m above an overflow covering a 100 m^2 and 5 m away from that in the downwind direction. Conditions of the wastewater and weather is specified in the supporting information.

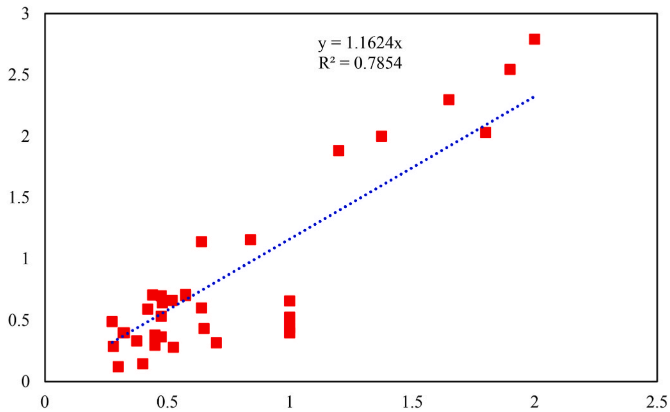

Fig. 12. [$H_2S_{(g)}$]$_{(5,\ 1.6)}$ at different $[S^{2-}]_T$.

3.2. Impact assessment of odor emission from an overflow

In the previous sections, the estimated values of $[H_2S_{(g)}]$ in the atmosphere in case of hypothesized SSOs were calculated. In this section, the concentrations of $H_2S_{(g)}$ near the real cases of SSOs are estimated based on the characteristics of the overflown sewer and the annoyance level of emitted H_2S in the vicinity of SSOs were calculated using Eq. (12). To validate the estimated amounts of annoyance level, a questioning survey from the people was conducted at each case as explained in section 2.3.3. Since the concentrations of total sulfide in the sewer samples were high enough, that the emitted odor was perceivable to the trained people at all cases, Eq. (11), which estimated the probability of the odor perception, was not used and Eq. (12) was used to estimate the annoyance level and the resulted values were compared with the average values reported by the trained people who were at the place of the SSO events.

As explained before, the annoyance level of $[H_2S_{(g)}]$ was estimated and validated instead of measuring $[H_2S_{(g)}]$ due to two reasons: (1) the higher sensitivity of human nose in perceiving odor of $H_2S_{(g)}$ compared with the gas detection instruments and (2) importance of people's opinion regarding odor perception than merely measuring concentrations of odorous compounds such as $H_2S_{(g)}$. It should be noted that for the cases of emission of other gaseous contaminants, which are not easily perceivable for human being, accurate measurement of their concentrations is of great importance, however, for the case of $H_2S_{(g)}$ emission, its perception by people and the annoyance level by it, is more important.

Table 5 shows the estimated values of $[H_2S_{(g)}]$ near the overflow events and the estimated annoyance level due to the exposure to it. The first column of Table 5 constitutes the estimated values of $[H_2S_{(g)}]$ in the atmosphere near the SSOs. These values were obtained using the values of the sewer parameters as comprehensively explained before. As it shows, concentration of $H_2S_{(g)}$ in the atmosphere near the overflows were all higher than 0.5 ppb, which is the threshold limit of the H_2S perception. At 18 cases out of 25, $[H_2S_{(g)}]$ was lower than 5.6 ppb, the moderate level and at the rest of the cases, which included 24% of them, $[H_2S_{(g)}]$ exceeded the moderate levels.

The second column of Table 5 is the estimated values of the annoyance degree for the trained people in the field, measured by Eq. (12). As an example, if the concentration of $H_2S_{(g)}$ is 1.81 μg.L^{-1}, the annoyance level is estimated using Eq. (12) as below:

$$A = \frac{10}{1+\left(\frac{C_{5AU}}{C}\right)^{\frac{1-a}{a}}} = \frac{10}{1+\left(\frac{23}{[H_2S_{(g)}]}\right)^{0.47}} = \frac{10}{1+\left(\frac{23}{1.81}\right)^{0.47}} = 2.32$$

In this equation, "a" is a dimensionless number in the range of 0–1 and represents the annoyance level or "persistence of annoyance" of a certain compound for people. The maximum value was 22.26 ppb with the annoyance level of 4.96.

On the other hand, C_{5AU} represents the concentration of a certain odorous compound, in this case, $H_2S_{(g)}$, which has the annoyance level of 5 AU for the average people. Nicell (2009) suggested values of "a" and "C_{5AU}" as 0.68 and 23 ppb, respectively, for $H_2S_{(g)}$. These results suggested that the occurrence of an accidental overflow at a populated residential area may cause annoyance to several people commuting there, leading to their complaints and dissatisfaction.

3.3. Validation of the impact assessment results

To validate the estimated impact assessment results, firstly, the data collected from the volunteers were analyzed. The outliers of the data at each SSO was removed using Orange software and the remaining data were presented in Appendix A. On the other hand, the mean and standard deviation of the data at each SSO event was calculated as presented in Table 6. On the other hand, the concentration of $H_2S_{(g)}$ in the vicinity of each SSO event was calculated using the data provided by DSD and the equations provided in sections 2.2 and 2.3. After finding the concentration of $H_2S_{(g)}$ at a certain location, the annoyance level of exposure to that amount of $H_2S_{(g)}$ was estimated using Eq. (12) as explained by an example in section 3.2. The estimated values of the annoyance level (as shown in Table 5) were compared with the data obtained from a survey questioning from the people nearby the overflow(as shown in Table 6).

Fig. 14 depicted the estimated annoyance level versus the real nuissance level with the slope of 1.03 and R^2 of 0.88 implying a good agreement between them. As it shows, the estimated levels are generally lower than the real levels. This maybe due to the underestimation of the H_2S concentration at the surveying point, which is due to decresing area of the overflow as it was drained into the stomwater collection network. This indicates that the integration of the dispersion model and the impact assessment method gives an acceptable estimation of annoyance level of the odor emitted from an overflow. Moreover, the prediction of the overflow events accompanied by online H_2S, temperature and pH detection values, can provide a warning system to announce the people avoid passing nearby the overflow occurrence places.

3.4. Exposure to the other contaminants of an overflow

Exposure to the other contaminants of an overflow can be through ingesting droplets splashed from the overflow, ingested mouthful by children, and contact of contaminated hand to mouth. Since there was no standard for finding the volume of overflow ingested by the residents, the same standard for floods as suggested by Moya et al. (2011) is used.

Calculations show that ingesting even 1 mL of overflow leads to gastro-intestinal diseases with 98% probability. This has been also confirmed by other researchers (Abia et al., 2016). Therefore, any contact with the overflow or untreated sewage through direct ingestion or inhalation of droplets or contact of the contaminated hands with mouth pose health risks to the individuals and should be strictly avoided. This is due to the high concentrations of E.coli in the untreated wastewater. As mentioned in Table 4, there are three ways of exposure to the contaminated water in the form of flood in the urban areas: (a) ingesting droplets (0.5–5 mL), (b) ingesting mouthful by children (7.8–52.2 mL), and (c) hand-to-mouth contact.

Swallowing 0.5 mL of diluted untreated wastewater droplets by 10, 10^2, 10^3, and 10^4 times leads to gastro-intestinal diseases by 96%, 90%, 75%, and 44%, respectively. High risk of getting diseases by ingesting even 10^4 times diluted untreated raw wastewater indicates that exposure to the combined overflow, which is the combination of sanitary sewer and storm-water, poses high risk of illnesses. Taking higher amounts of contaminated water increases the risk of diseases. The risk is higher for children, since they may swallow mouthful of contaminated water. The minimum volume of mouthful digestion is 7.8 mL containing averagely 1.7×10^7 CFU/100 mL E.coli or 1.2×10^6 of E.coli, which leads to diseases with higher than 99% probability. Hand-to-mouth

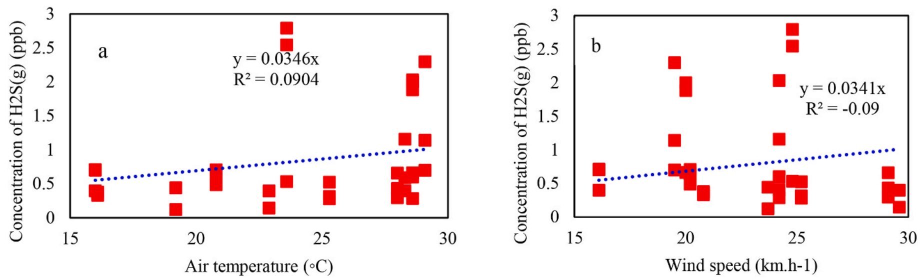

Fig. 13. The correlation between the (a) air temperature and (b) wind speed with $[H_2S_{(g)}]_{(5,\ 1.6)}$ near a manhole containing raw wastewater.

Table 6
The estimated concentrations of H_2S and annoyance level from overflows and the comparison with the people's annoyance level.

Date of the SSO	Estimated H_2S concentration in the atmosphere near an overflow ($\mu g.L^{-1}$)	Estimated degree of annoyance	Average degree of annoyance, reported by the people	standard deviation of the reported annoyance levels	The number of surveyed people	Number of the outliers among the reported data during survey
18/4/2018	1.81	2.32	2.28	0.67	105	5
9/5/2018	0.87	1.77	2.31	0.69	104	4
16/5/2018	0.78	1.69	1.94	0.55	104	4
13/6/2018	2.73	2.69	2.72	1.21	105	5
22/6/2018	5.05	3.29	3.15	1.09	103	3
6/7/2018	9.14	3.93	3.6	1.41	104	4
24/7/2018	13.34	4.36	4.65	2.11	105	5
9/8/2018	2.31	2.54	1.84	0.61	105	5
13/5/2019	1.73	2.29	2.68	0.98	104	4
20/5/2019	0.89	1.78	1.88	0.54	107	7
25/5/2019	11.81	4.22	4.43	1.89	104	4
9/6/2019	0.79	1.71	2.03	0.50	103	3
19/6/2019	15.84	4.56	4.07	1.62	104	4
9/7/2019	2.25	2.51	3.08	1.27	104	4
28/7/2019	5.32	3.34	3.27	1.21	103	3
3/8/2019	0.26	1.09	1.72	0.60	105	5
11/2/2020	0.91	1.79	2.27	0.85	106	6
10/4/2020	3.51	2.93	2.96	0.99	105	5
6/5/2020	2.05	2.43	2.72	0.90	105	5
15/5/2020	10.90	4.13	3.96	1.25	104	4
2/6/2020	22.26	4.96	4.24	1.74	105	5
13/6/2020	8.07	3.79	4.46	1.62	103	3
20/7/2020	2.42	2.58	2.84	0.95	106	6
16/8/2020	7.83	3.76	3.93	1.83	105	5
12/9/2020	11.31	4.17	4.59	1.80	105	5

contact has the lowest risk compared with mouthful digestion and digesting droplets. The skin-surface area of the hand that is mouthed is in the range of 100–2000 mm^2 and the thickness of the water layer in the contaminated hand varies in the range of 1.97×10^{-2}–2.340×10^{-2} mm. If the frequency of hand-to-mouth contact is 2 times per hr, the maximum and minimum volume of the contaminated water ingested through hand-to-mouth contact are 0.00197 and 0.0468 mL, respectively. Therefore, the probability of E-coli-related diseases by hand-to-mouth contact with the untreated wastewater is 86%–96%, which is lower than the other two pathways; however, it is still risky. It should be noted the risk of other diseases generated by other pathogens such as Campylobacter, Salmonella, Cryptosporidium, Giardia, and Norovirus was not included. Considering health risks of exposure to other pathogens increases the risk of illnesses.

Moreover, ingestion of untreated raw wastewater enters several contaminants such as suspended solids (e.g., TSS, BOD_5, and COD), heavy metals, micropollutants (e.g., antibiotics and medicines), and ions (e.g., NO_3^- and PO_4^{3-}). Table 7 presents the mass values of the contaminants entering body of a resident in case of swallowing or inhaling 1 mL of an overflow. TSS, BOD_5, and COD are bulk parameters representing several organic and inorganic compounds with unknown hazardous effects on human beings. Therefore, there is no dose-response for the exposure to TSS, BOD_5, and COD.

These results imply that strict measures should be taken in the times of overflow occurrence, for instance, providing sufficient drainage facilities near manholes to immediately guide the overflows to the drainage systems. The high cost of building drainage systems necessitates predicting overflows and announcing residents before any overflow occurrences.

4. Implications

Odor dispersion and E.coli infection risk from overflows were comprehensively assessed in this study.

(1) Odor from overflows can be perceived by the individuals nearby; however, it does not have adverse health effects. To avoid annoyance resulted from the odor, it is recommended that citizens keep at least 10 m away from overflows.
(2) The QMRA results of this study indicated a high risk of gastrointestinal diseases due to the inhalation of droplets of overflows or digestion of them through contaminated hand-to-mouth contact. The risk is even higher for the children due to the higher probability of their exposure to overflows. The results of this research will be beneficial when selecting the locations of manholes to minimize the effects of the possible overflows on the surrounding residents. On the other hand, the methodology of this research could be extended to consider more variables regarding the infection risk assessment.

5. Conclusions and recommendations

In this study, the odor assessment together with microbial risk assessment of sewer overflow was performed for the first time. Based on

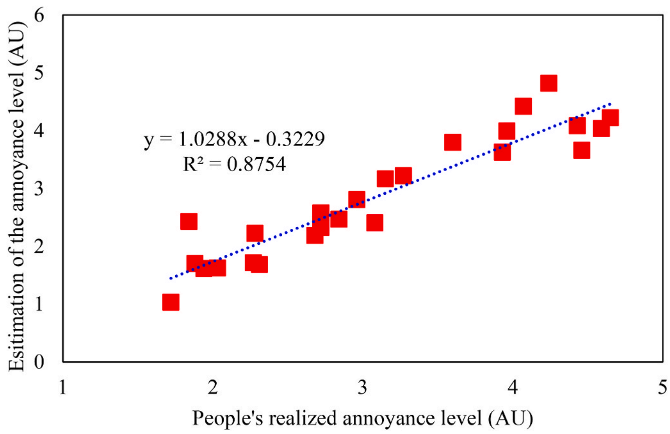

Fig. 14. The comparison of the estimated annoyance level and the people's perceived annoyance.

Table 7
Mass value of the contaminants entering body of an individual through digesting 1 mL of untreated raw wastewater.

Contaminant	Average concentration in the raw wastewater (mg. L^{-1})	Mass value of the contaminant entering body by ingesting 1 mL of raw wastewater (μg)
BOD_5	189	189
COD	434	434
TSS	237	237
NO_3^-	0.1	0.1
PO_4^{3-}	4.2	4.2
NH_3	22.3	22.3

the data collected from the manholes before the largest wastewater treatment plant of Hong Kong and the overflow events and survey questioning from the commuters the following major conclusions were drawn:

(1) Using a mass transfer model and Gaussian dispersion model, the correlations between the environmental parameters and $[H_2S_{(g)}]$ was obtained; it is revealed that $[H_2S_{(g)}]$ had linear correltion with the total sulfide concentration in the wastewater, however, the correlation between $[H_2S_{(g)}]$ and pH, wind speed, air and wastewater temperature was nonlinear.
(2) The total sulfide concentration in the wastewater was found to have the major influence on the perceived odor; it is seen that $[H_2S_{(g)}]$ increased by 85% with 2 times increase of the total sulfide concentration in the wastewater.
(3) Using an impact assessment method, the annoyance level of the perceived H_2S to the people near the overflow was obtained; it was found out that the estimated values of the annoyance levels to due the emitted H_2S complied with the real perceived values by the people indicating applicability of the integrated dispersion modelling and impact assessment.
(4) Considering different pathways of the contact with overflow, the infection risk of digesting or inhaling overflow was estimated; it is seen that inhaling or digesting a few droplets of overflow cause higher than 90% risk of gastrointestinal diseases.
(5) Inhaling H_2S in the vicinity of an overflow was found to make annoyance, however with no adverse health effects.
(6) Contaminated hand-to-mouth contact and inhaling overflow droplets were recognized as leading to higher than 85% and 95% risk of infection, respectively.

It should be noted that the collected data in this research did not include the amounts of the pathogens other than E.coli, despite the fact that the other pathogens may pose more serious health effects on the residents. On the other hand, the annoyance level due to exposure to the malodorous compounds emitted from the overflows was obtained in short distances and within 1 h. More research should be conducted to investigate the impact of the exposure to the overflows for longer times and at higher distances. Considering the drastic effects of the contact with untreated sewer, it is utterly important to focus on predicting the sanitary overflow occurrence in advance in order to warn individuals to avoid exposure to them. The residuals such as TSS rendered from the untreated sewer on the streets have the potential to be transferred to the environment where human beings may be exposed to. Their seriously adverse health effects merit further investigation.

CRediT authorship contribution statement

Ehsan Aghdam: Conceptualization, Data curation, Methodology, Software, Formal analysis, Investigation, Visualization, Validation, Writing – original draft, Writing – review & editing. **Saeed Reza Mohandes:** Conceptualization, Project administration, Supervision, Writing – original draft, Writing – review & editing. **Tarek Zayed:** Writing – original draft, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix. BSupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.137498.

Appendix A

The distribution of the reported values of annoyance level perceived by the volunteers at 25 SSO events in provided below.

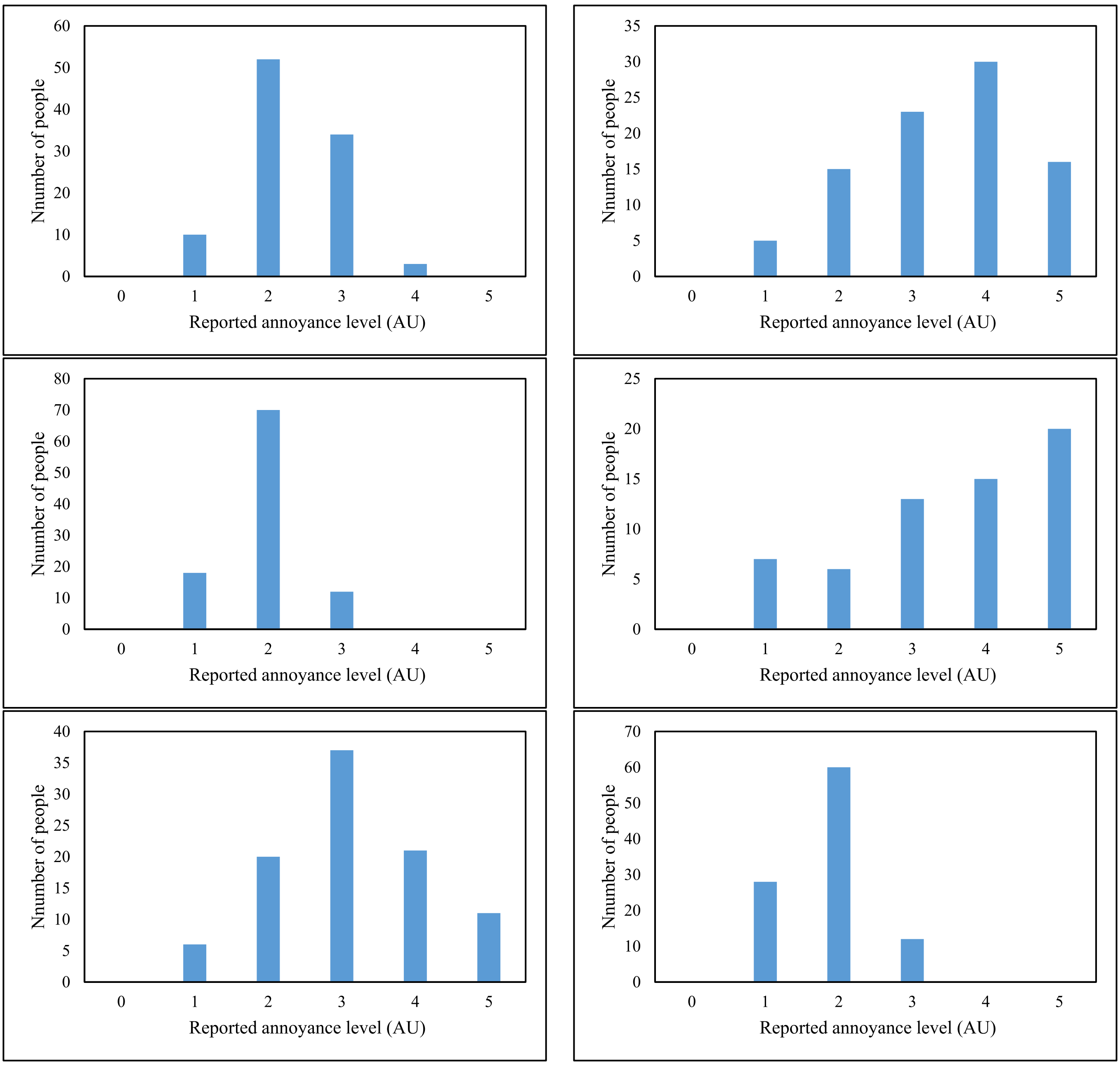

Fig. A1. Reported annoyance level for each of the overflow occurred.

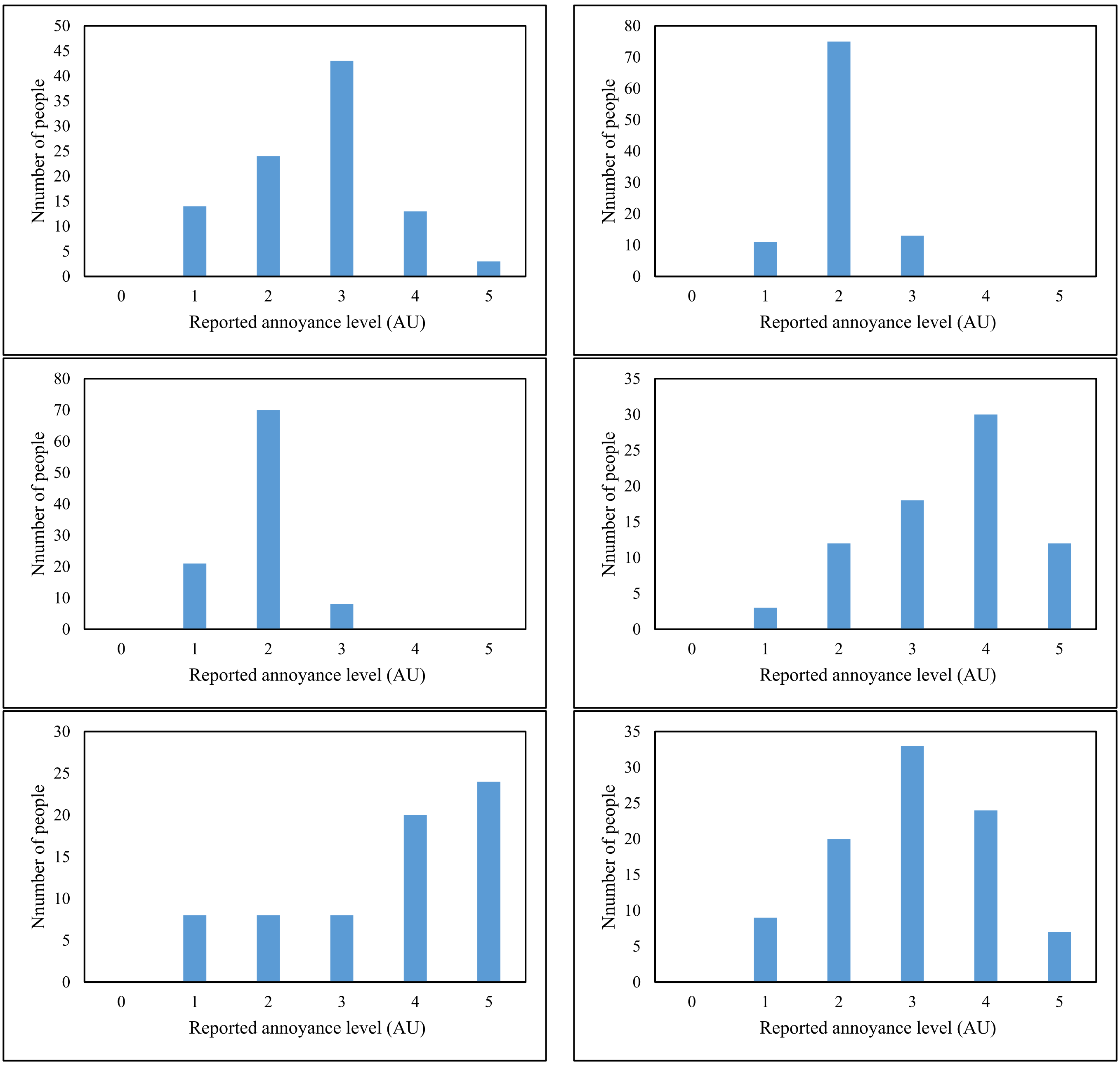

Fig. A1. (*continued*).

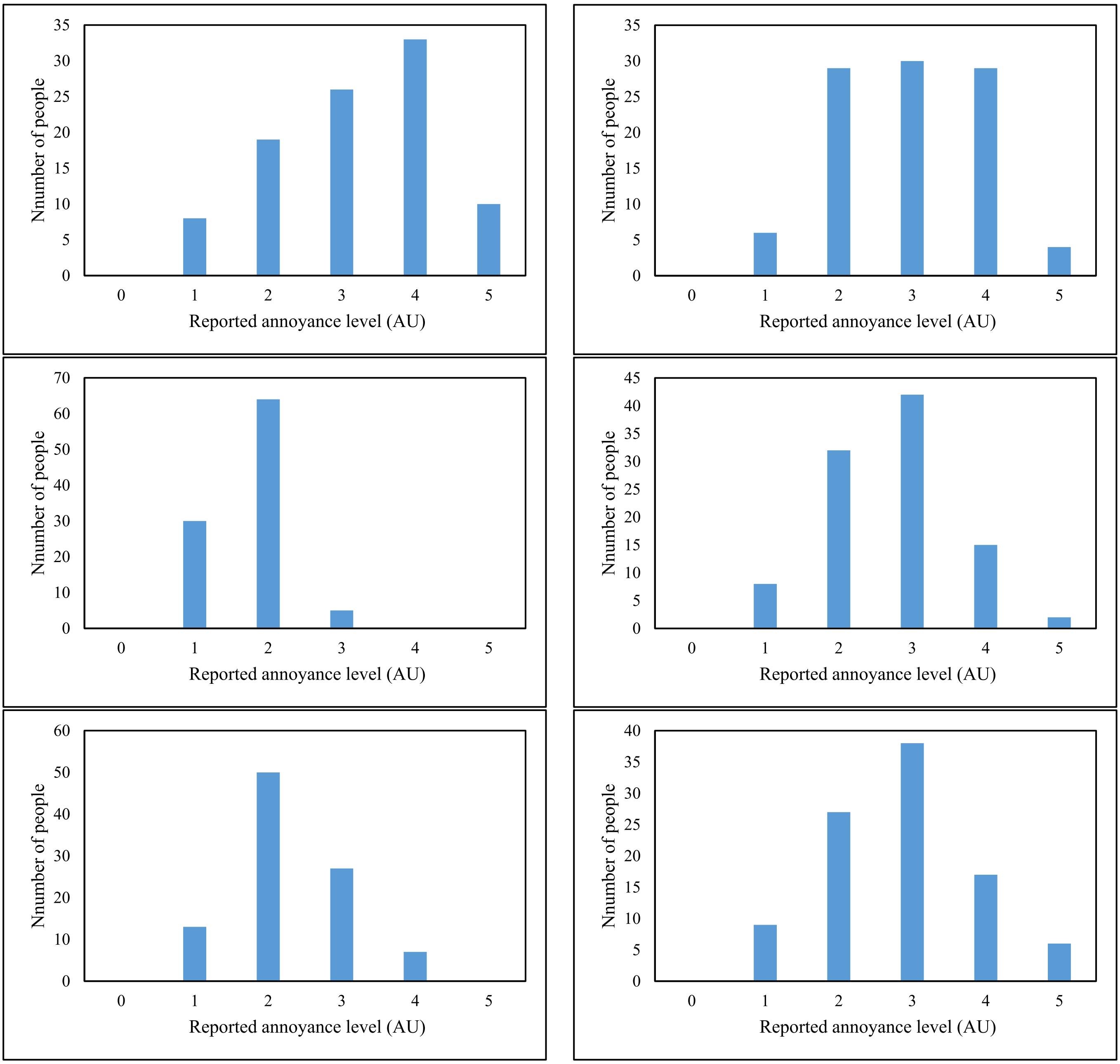

Fig. A1. (*continued*).

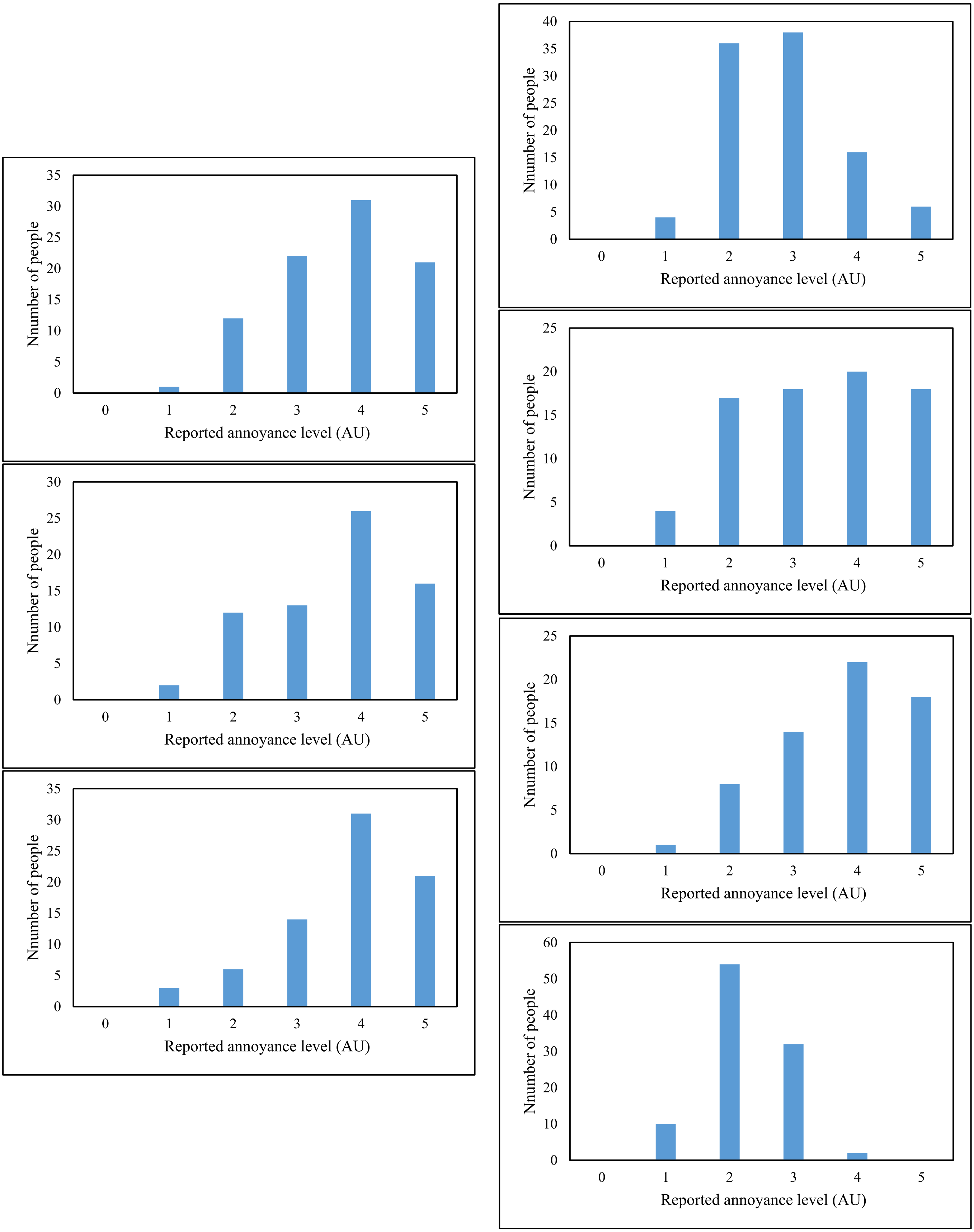

Fig. A1. (*continued*).

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