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LETTER

# Sea-level rise drives wastewater leakage to coastal waters and storm drains

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## Scientific Significance Statement

Recent modeling studies show groundwater inundation (GWI) of coastal wastewater infrastructure (e.g., sewer lines, cesspools) with sea-level rise. Still, this process has not been empirically demonstrated prior to this study. Here, we use geochemical tracers to demonstrate that tidally driven GWI of wastewater infrastructure is occurring today leading to wastewater discharge to the coast and storm drains in urban Honolulu, Hawai'i. The results of this study indicate that higher ocean water levels are leading to negative impacts to coastal water quality, biogeochemical cycling, and ecological health.

## Abstract

Sea-level rise (SLR) is expected to compromise coastal wastewater infrastructure (WIS) via groundwater inundation (GWI). We conducted a field-based study in urban Honolulu, Hawai'i using spring tides as a proxy for future sea levels to quantify the hydrologic connection of WIS. This study focused on two possible pathways: (1) direct GWI of WIS and subsequent discharge into the coastal ocean and (2) indirect inundation of WIS evidenced in storm drains. We used geochemical tracers and emerging organic contaminants (EOCs) to monitor groundwater discharge and its wastewater content. Groundwater discharge and EOCs fluctuated with tides for coastal and canal groundwater and surface water samples, and storm drains, indicating tidally driven GWI and wastewater discharge. This study presents some of the first field-based evidence for GWI of coastal WIS and demonstrates that SLR is creating additional risks to environmental and human health.

## Introduction

Global mean eustatic sea level is expected to rise 0.3–1 m by 2100, with less conservative estimates ranging up to 2 m or greater (Wong et al., 2014; Sweet et al. 2017). Perigean spring (or king) tides provide an early glimpse of negative sea-level rise (SLR) impacts, such as flooding, beach erosion, and water quality degradation (Thompson et al. 2019; Sweet et al. 2020). While most studies addressing SLR impacts have focused on

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Additional Supporting Information may be found in the online version of this article.

surface flooding and seawater intrusion, a few recent studies have highlighted the effects of groundwater inundation (GWI) (e.g., Habel et al. 2017; Elmir 2018; Befus et al. 2020). For example, as the water table rises with SLR (Rotzoll and Fletcher 2012), it potentially leads to tidal or even permanent GWI of wastewater infrastructure (WIS), such as sewage pipes or onsite sewage disposal systems (e.g., septic tanks, cesspools; Habel et al. 2017), decreasing their treatment efficacy. WIS are already in critical decline in many areas—for instance, an estimated 23% of sewer lines in the United States currently have defects (USEPA 2002). A frequently used alternative to municipal wastewater treatment, onsite sewage disposal systems are also a common groundwater contaminant source in many areas globally, including Hawai'i (Whittier and El-Kadi 2009). It is expected that the frequency and magnitude of wastewater-related water quality problems will increase with SLR as infrastructure becomes progressively more inundated.

Groundwater fluctuates with sea level in coastal areas, where the water table is at or above mean sea level (Rotzoll and Fletcher 2012). This hydrologic connection serves a double role, causing water table uplift resulting in inundation of and leakage from WIS while also facilitating discharge of released wastewater contaminants as water drains back into the ocean. Submarine groundwater discharge (SGD) refers to groundwater that discharges to the coastal ocean and can be a major source of excess nutrients, metals, and emerging organic contaminants (EOCs; e.g., pharmaceuticals, pesticides) to coastal water bodies (e.g., Moore 2010; Luijendijk et al. 2020; McKenzie et al. 2020*a*; Szymczycha et al. 2020). Total SGD is comprised of both saline and fresh terrestrial/meteoric groundwater. Fresh SGD is primarily driven by the hydraulic gradient and is typically highest at low tide. Tidal pumping, a significant component of saline SGD, adds water to the aquifer during high tide and then partially drains to the ocean during low tide (Kim and Hwang 2002; Michael et al. 2005; Santos et al. 2009).

Geochemical tracers are used to detect groundwater discharge and provide evidence of wastewater discharge to the environment. Naturally occurring radionuclides, such as radon, are comparatively enriched in groundwater and commonly applied as groundwater tracers. Wastewater inputs to water bodies can be evidenced by tracers such as EOCs and nutrients. EOCs are good wastewater tracers because of their unique anthropogenic source and refractory nature; however, one challenge of using EOCs is that their source (human consumption) is variable and degradation rates or behavior in the environment differ between compounds (Lapworth et al. 2012). Nutrients, while not unique to wastewater, are frequently enriched in wastewater and often accompany wastewater discharge studies.

While models can capture WIS inundation under future SLR (Rotzoll and Fletcher 2012), this is the first field-based geochemical study documenting SLR-driven GWI impact on coastal WIS. The overarching hypotheses for this study are (1) there is a hydrological connection from WIS to storm drains and the coastal ocean during extreme tides, and (2) GWI of WIS and subsequent wastewater discharge to storm drains and the coastal ocean can be evidenced by a combination of SGD (radon) and wastewater tracers (EOCs and nutrients). Two pathways for SLR to impact water quality via GWI were evaluated at two model sites in Honolulu, Hawai'i: (1) direct inundation of coastal WIS affected by tidal pumping and resulting discharge as SGD and (2) seawater entering storm drains during high tide (otherwise known as storm drain backflow; Fig. 1). Both processes are significant as they release wastewater to the environment leading to increased ecological and human health risks.

## Methods

### Study site

This study was conducted in two low-lying urban districts of Honolulu, Hawai'i (Māpunapuna and Waikīkī) (Fig. 2; Table S1; Appendix S1). Waikīkī, a popular tourist destination, was marshland prior to construction of the Ala Wai Canal and addition of anthropogenic fill (Wiegel 2008). The Ala Wai Canal is tidally influenced, receives stream input from Mānoa-Pālolo and Makiki Streams, and is chronically polluted, in part because of poor circulation and retention of stream pollution (USEPA, https://mywaterway.epa.gov/waterbody-report/21HI/HIW00034/2018, last accessed 15 July 2020). Water residence times within the canal are poorly constrained but range from a few hours to >8 d, depending on wind speed, tidal fluctuations, rainfall, and canal location (Gonzalez 1971). Māpunapuna is an industrial district located within 0.5 km from the coast, bordered by the Daniel K. Inouye International Airport and Kahauiki Stream. The area is subject to frequent nuisance flooding during high tides or heavy rainfall due to storm drain backflow of ocean water from Ke'ehi Lagoon (Habel et al. 2020).

Continuing SLR is anticipated to result in both rising coastal waters and GWI in Waikīkī and Māpunapuna due to narrow unsaturated zones above the water table (Habel et al. 2017, 2020). The Honolulu tide gage record (NOAA; station ID: 1612340) has a semi-diurnal range of 0.58 m with a $1.51 \pm 0.21$ mm/year (30-year average) rate of local SLR. Models show that nuisance flooding can occur when tides exceed 0.20–0.35 m above the mean higher high water datum (Sweet et al. 2014; Thompson et al. 2019; Habel et al. 2020).

In addition to the narrow unsaturated zone within the water table aquifer, proximity to the coast, and low elevation, Waikīkī and Māpunapuna are prime candidates for groundwater wastewater contamination. There are 96 cesspools in Waikīkī and Māpunapuna, offering no wastewater treatment (Whittier and El-Kadi 2009). Cesspools require at least 4.4 m of vertical unsaturated space from the ground surface (with at least 0.9 m from the base of the cesspool structure to the

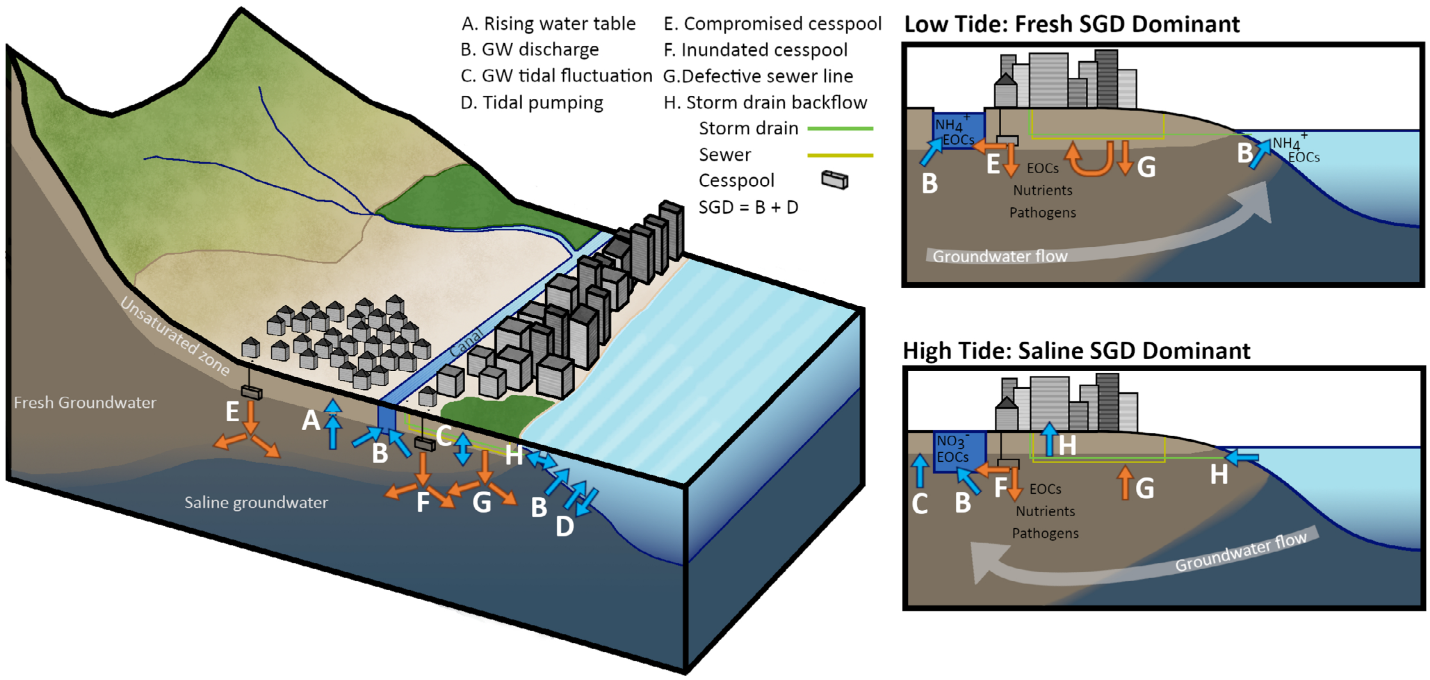


**Fig 1.** Connection between groundwater, surface water, storm drains, and WIS. Wastewater flow is indicated by orange arrows and groundwater flow by blue arrows. At low tide, SGD is primarily driven by the hydraulic gradient compared to high tide, where SGD is dominated by saline SGD. Under current conditions, rising groundwater levels fluctuate with the tide as shown in C, but under future sea levels, the water table is expected to rise permanently, as shown in (A). This study aims to investigate how groundwater and wastewater flow are linked to one another at higher water levels during spring tides.

water table) to function properly (Department of Health 2004); however, models show that 86% of onsite sewage disposal systems between the Downtown and Waikīkī neighborhoods are at least partially inundated by groundwater during mean spring tide conditions today (Habel et al. 2017). Significant portions of storm drains and sewer lines are also predicted to flood under future SLR scenarios (Spirandelli et al. 2018).

## Sampling strategy and analysis

Water samples were collected from seven locations (four coastal and three storm drain sites) between July and October 2018 during king and spring tides (McKenzie et al. 2020*b*, 2020*c*; Fig. 2; Table S1). Radon is a well-established, naturally occurring groundwater tracer (e.g., Burnett and Dulaiova 2003), and was used as the primary groundwater tracer in this study. Continuous radon time series of surface/storm drain water and discreet sampling (coastal groundwater) were conducted for each site. At low, mid, and high tide, water was also sampled and filtered onsite through a 0.45 μM filter for EOCs and nutrients and kept at 4°C until analysis. For coastal sites, both surface water and groundwater were sampled through push-point samplers (MHE products). Low and high tide water table heights for dates sampled were modeled using MODFLOW as described in Habel et al. (2020), where steady-state conditions of head were simulated considering sea level elevations and tidal stages observed at the time of sampling. The model was calibrated using 247 discrete water-level observations obtained from the Hawai'i Department of Health Leaky Underground Storage Tank records and 73 sets of continuous water-level measurements compiled from local hydrogeologic studies. Total SGD fluxes were calculated using both a transient mass balance model (Dulaiova et al. 2010) and residence-time based approach (Burnett and Dulaiova 2003; Appendix S2; Fig. S1).

Three EOC compounds previously used for wastewater tracing (e.g., Knee et al. 2010; Lapworth et al. 2012) were analyzed (carbamazepine, caffeine, and fluoroquinolones). These compounds differ in terms of environmental persistence and mobility (Table S2). Samples were collected ($n$ = 49) into pre-combusted amber glass bottles with Teflon-lined caps. EOCs were analyzed at the University of Hawai'i at Mānoa using an enzyme-linked immunosorbent assay compound-specific kits (Abraxis LLC). Compound-specific instructions were followed for sample preparation and then analyzed at a 450 nm wavelength on a spectrophotometric microplate reader (Abraxis ON 475010, microplate format, 96 well, Model 4303). Detection limits were 24, 150, and 10 ng/L for carbamazepine, caffeine, and fluoroquinolones, respectively. To assess environmental risk, risk quotients (RQ) were also calculated following European Union guidelines for environmental risk assessment (European Commission 2003, Appendix S3).

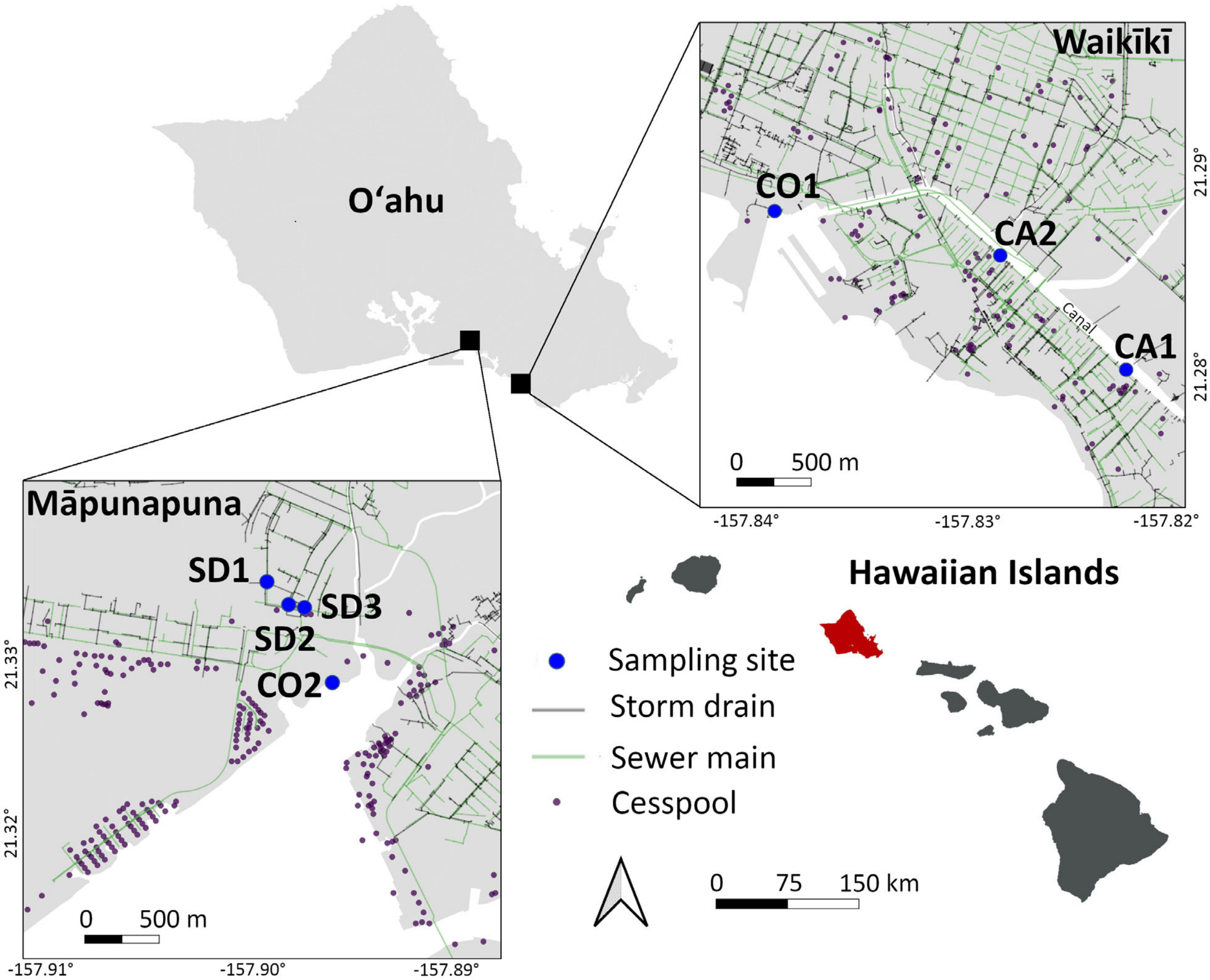


**Fig 2.** Locations of study sites on the island of O'ahu. Waikīkī and Māpunapuna are districts within Honolulu. Sampling sites are indicated with larger blue dots, cesspools with smaller purple dots, and storm drains and sewer mains are shown with black and green lines, respectively.

Dissolved nutrients were collected into acid-cleaned high-density polyethylene (HDPE) bottles. Samples were analyzed for total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), $NO_3^- + NO_2^-$, $PO_4^{3}$, and $NH_4^+$ with a SEAL AutoAnalyzer 3 HR in the S-Lab at the University of Hawai'i at Mānoa. Dissolved inorganic nitrogen (DIN) concentrations were calculated as the sum of $NO_3^- + NO_2^-$ and $NH_4^+$. Dissolved organic nitrogen (DON) concentrations reflect the difference between TDN and DIN.

EOC and nutrient scores were calculated using Eqs. (1) and (2) (after Abaya et al. 2018), where $CBZ_{norm}$, $CFN_{norm}$, $FQL_{norm}$, $TDN_{norm}$, and $TDP_{norm}$ refer to the normalized concentrations of carbamazepine, caffeine, fluoroquinolones, TDN, and TDP. EOC and nutrient scores were calculated to allow for comparison between sampling sites and tidal stages. Storm drain and coastal sites were normalized separately from one another because they represent different environments.

$$EOC_{score} = CBZ_{norm} + CFN_{norm} + FQL_{norm}, \quad (1)$$

$$Nut_{score} = TDN_{norm} + TDP_{norm}. \quad (2)$$

Relationships, correlations, and conclusions were confirmed using several statistical methods, including principal components analysis and Mood's median test. Statistical relationships were calculated using Python 3.8 and maps were generated with ESRI ArcMap 10.1, QGIS 3.10, and GNU Image Manipulation Program 2.10.

## Results

### Groundwater discharge

Overall, radon concentrations and SGD were higher during king tides compared to spring tides for the Waikīkī sites (Fig. 3; Table S3; Appendix S4). The tidal pattern of radon confirms horizontal tidal groundwater flow (Fig. 1) resulting in increased groundwater discharge on the canal side of Waikīkī during high tide.

For Māpunapuna, SD1 and SD2 showed significant increases in both radon and salinity at high tide, preceding flooding of the street via storm drains by several minutes (Fig. 3). Radon concentrations increase to nearly 800 and 250 Bq/m$^3$ for SD1 and SD2, respectively. The other storm drain site, SD3, which is not directly connected to SD1 and SD2, had decreasing radon concentrations from low to high tide coincident with increasing salinity.

## Nutrients and EOCs

Nutrient concentrations were greatest at CA1 and EOCs at CA2 and CO1 in Waikīkī (Fig. 4; Table S4). Nutrients at CA1 were dominated by nitrate in surface water (range = 36–100 μM) and ammonium in groundwater (range = 51 to 81 μM). From low to high tide, TDN increased at CA1 in surface water and decreased in groundwater. The other Waikīkī sites, CA2 and CO1 had comparable nitrogen compositions in both surface water and groundwater, with TDN decreasing from low to high tide for both water types. Nutrient

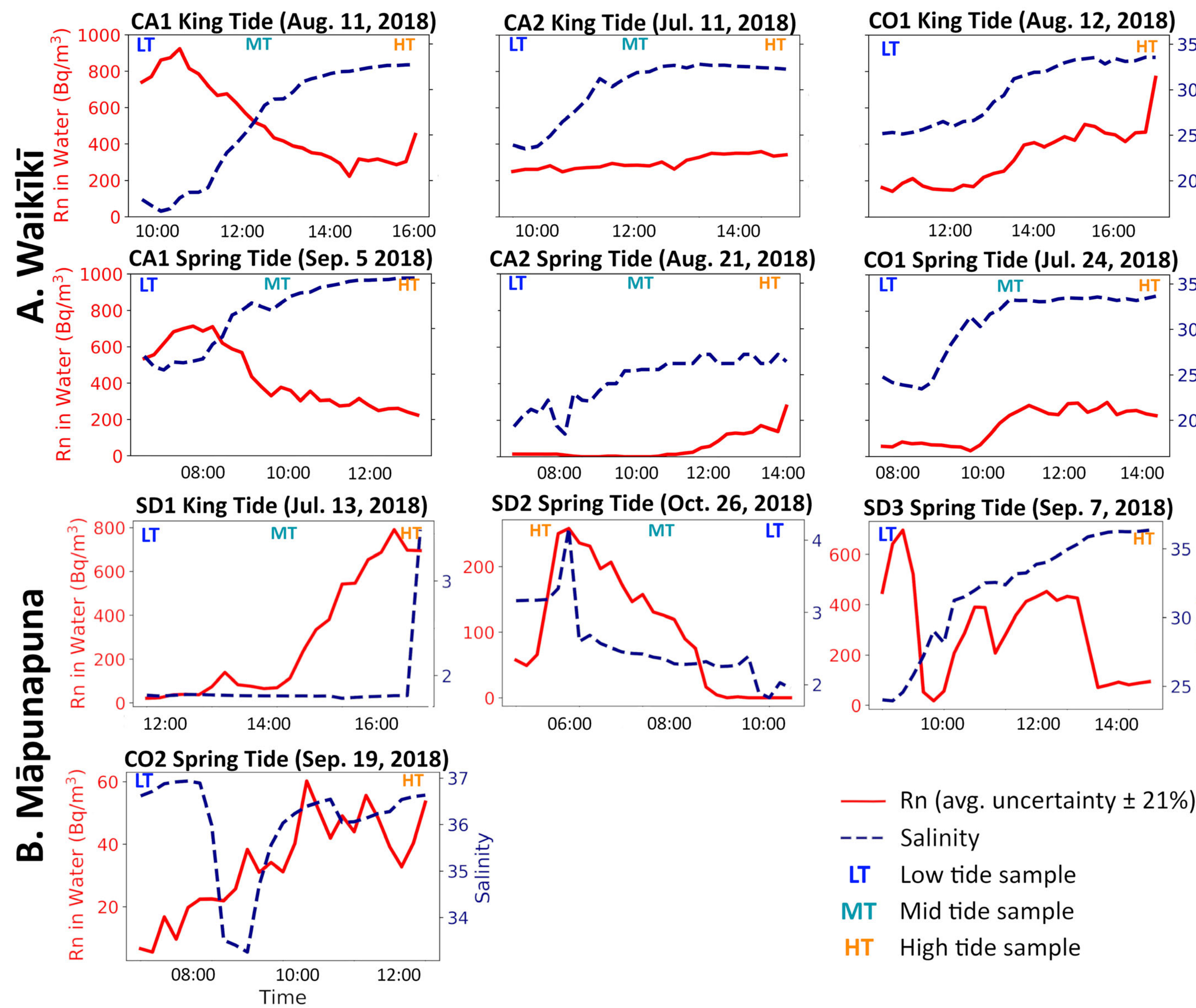


**Fig 3.** Radon (groundwater tracer; solid red line; Bq/m$^3$) and salinity (dashed blue line) over a half-tidal cycle. Timing of low tide (LT), mid tide (MT), and high tide (HT) grab samplings are indicated for each survey. Time is indicated in Hawai'i standard time. (A) Waikīkī time series by location and tide (king tide vs. spring tide). CA1, CA2, and CO1 are all coastal sites. (B) Māpunapuna time series by location, where SD1, SD2, and SD3 are all storm drain sites and CO2 is a coastal site where the storm drains discharge. The time series for SD1 was conducted during a king tide and the remaining Māpunapuna time series (SD2, SD3, and CO2) were conducted during spring tides.

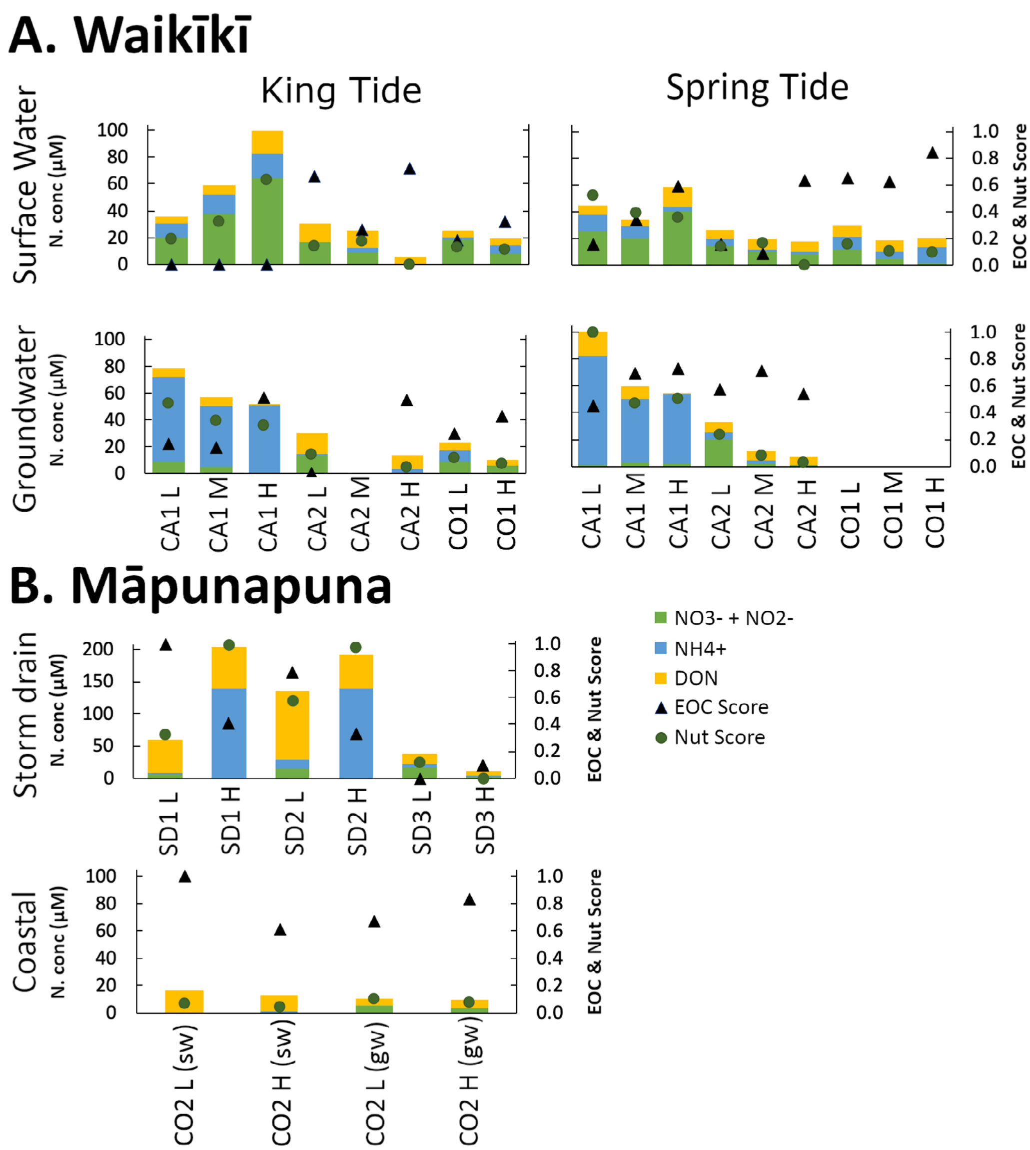


**Fig 4.** Distribution of nitrogen species ($NO_3^- + NO_2^-$, $NH_4^+$, and DON) concentrations (µM), nutrient (nut) and EOC scores. L, M, and H correspond to low, mid, and high tide samplings. (A) Waikīkī coastal sites separated by king vs. spring tide and surface water vs. groundwater. (B) Māpunapuna storm drain and coastal sites. For CO2, surface water and groundwater samples are indicated by sw and gw, respectively. Nutrient and EOC scores were normalized separately for coastal and storm drain sites.

concentrations remained mostly consistent between king and spring tide samplings.

EOC concentrations had greater variability from low to high tide. Carbamazepine and caffeine concentrations ranged from less than the method detection limit (<MDL) to 330 ng/L and <MDL to 3000 ng/L, respectively (Fig. 4; Table S4). Fluoroquinolones were only detectable at SD1 and SD2 with concentrations ranging from 19 to 61 ng/L. Detection frequencies of carbamazepine, caffeine, and fluoroquinolones were 54%, 89%, and 0% and 93%, 57%, and 16% for coastal and storm drain sites, respectively. In coastal Waikīkī surface waters, carbamazepine concentrations increased or stayed consistent from low to high tide. The same trend was observed for Waikīkī groundwater, with the exception of CA2 ST. Carbamazepine and caffeine concentrations decreased from low to high tide at SD1, SD2, and CO2 surface water. In contrast to SD3, SD1, and SD2 had increasing nutrient concentrations with decreasing EOC concentrations at high tide.

## Discussion

### Groundwater discharge

One component of SGD is tidally driven seawater intrusion and its subsequent discharge after mixing with groundwater

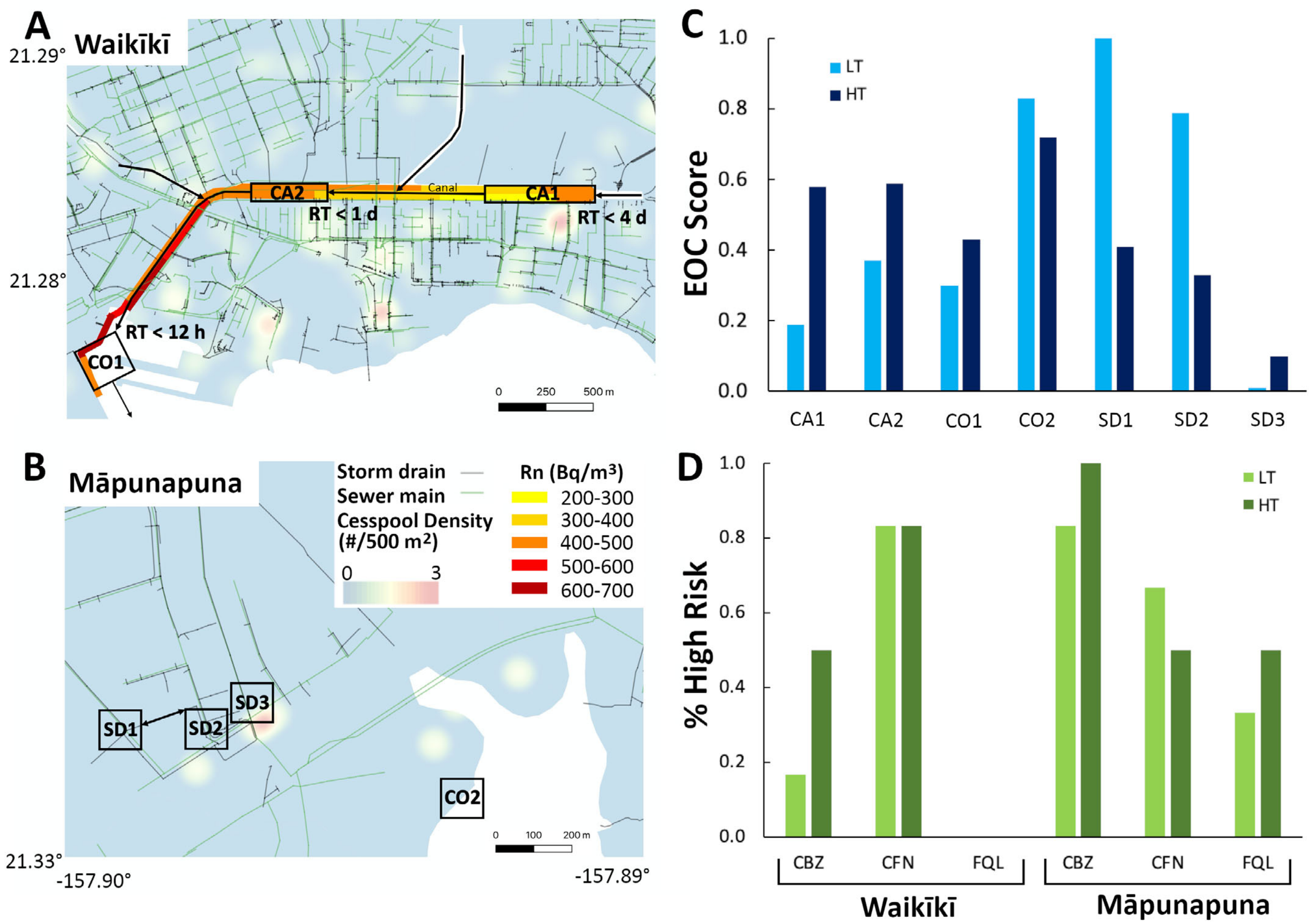


**Fig 5.** EOC scores and percentage of samples with a RQ > 1 (high ecological risk) at low and high tide. (A) Waikīkī and (B) Māpunapuna sampling sites. Storm drains and sewer mains are indicated on the map using blue and green lines, respectively. Cesspool density is indicated by the color gradient as the number of individual units per 500 m$^2$. In (A), the Ala Wai Canal is colored according to radon concentrations in water (Bq/m$^3$) from a radon survey (Fig. S1) and maximum estimated residence times (RT) are indicated by location. (C) Low (LT) vs. high (HT) tide EOC scores by sampling site. Coastal EOC scores include the median surface and groundwater results together. Waikīkī sites have median EOC scores from king and spring tides combined and EOC scores increased from low (light blue) to high (dark blue) tide for all Waikīkī sites and SD3. (D) the percentage of samples that pose a high risk to the ecosystem increase from low (light green) to high (dark green) tide for carbamazepine and fluoroquinolones where above the detection limit. For caffeine (a highly mobile and soluble compound), the percentage of samples that pose a high risk decrease or remains the same at high tide.

(Robinson et al., 2007). Infiltrating seawater causes the fresher groundwater lens to float, inundate the otherwise unsaturated zone, and in some instances rise above the ground surface. GWI also contributes significantly to nuisance flooding (Rotzoll and Fletcher 2012). Here we used geochemical tracers to document tidally driven GWI and its subsequent discharge to the ocean in two urban areas.

Radon activity in coastal and storm drain water provides direct evidence for groundwater discharge to both coastal waters and inland urban areas. In this study, radon was observed at all studied locations (Appendix S4). Increased groundwater discharge occurs into storm drains when the water table intersects the fractured storm drain network. While we were unable to quantify groundwater fluxes into storm drains due to their unknown geometry, sharp increases in radon at high tide provide clear evidence for GWI into the pipes at SD1 and SD2.

## Pollution pathways

There are multiple pathways for effluent from WIS to impact adjacent waterways (Fig. 1). Wastewater leakage may create saturated conditions in the unsaturated zone, reducing the bioremediation capacity (Elmir 2018). In a more extreme scenario, WIS can be directly flooded by either chronic (SLR; A in Fig. 1) or episodic (tidal; Fig. 1C) inundation. All of these pathways lead to treatment failure when wastewater moves unimpeded in a saturated environment.

Over 94% of coastal samples had at least one detectable EOC compound, establishing a hydrologic connection between WIS and our study sites and confirming our hypotheses (Table S1). EOC concentrations were consistent with other coastal studies conducted in areas subject to wastewater pollution (e.g., McKenzie et al. 2020*a*; Sczymycha et al., 2020). From low to high tide, EOCs increased but nutrient concentrations (Fig. S4; Appendix S4) decreased for most coastal samples. Averaging EOC concentrations by site and tide, carbamazepine consistently increased from low to high tide in both surface and groundwater for all Waikīkī sites. Caffeine also increased from low to high tide for all Waikīkī sites except for CA1 (Fig. 5). Variability in trends amongst EOC compounds likely reflects differences in their behavior in the environment (Table S2) and their consumption and release rate to wastewater. For instance, caffeine is significantly more soluble and has a lower tendency to sorb to organic matter compared to carbamazepine. This may explain why a substantially greater percentage change between low and high tide was observed for caffeine compared to carbamazepine. While we did not observe dramatic differences in nutrient concentrations between king and spring tides, nutrient fluxes (Appendix S4) were up to three times greater during king compared to spring tides, demonstrating that higher tide levels occurring today have the potential to lead to negative consequences to coastal water quality.

A strong correlation between TDN and TDP was observed for almost all groundwater ($r^2$ = 0.72, $p$ value = $7.0 \times 10^{-5}$) and surface water ($r^2$ = 0.55, $p$ value = $1.7 \times 10^{-4}$) samples, implying that dilution, not processes of nitrogen removal (e.g., denitrification), is the dominant process occurring. This further supports that inundation is actively preventing aerobic degradation as nitrifying bacteria require oxygen to produce the substrate for denitrification (Elmir 2018). The correlation between TDN and TDP was even stronger for storm drains ($r^2$ = 0.92, $p$ value = 0.0092), again supporting inundation under saturated conditions leading to dilution, and limited biogeochemical cycling of contaminants. This stronger correlation between TDN and TDP is unsurprising, as storm drains tend to be low oxygen environments.

EOC scores were calculated to compare relative wastewater presence between the study sites, Waikīkī EOC scores increased during high tide (0.53 ± 0.090) compared to low tide (0.29 ± 0.091) (Fig. 5). This implies increased flux from WIS to the Ala Wai Canal due to the tidally influenced water table.

Storm drains SD1 and SD2 exhibited the opposite trend from low to high tide compared to coastal sites, where EOC scores decreased (Fig. 5). SD1 and SD2 are directly connected to one another and are not exposed to sunlight compared to SD3. Among the EOCs studied, fluoroquinolones are particularly susceptible to rapid photodegradation (e.g., Patel et al. 2019), thus sunlight exposure at SD3 may lead to differences between EOC scores. Differences between coastal and storm drain sites likely reflect divergence in the inundation pathway and WIS source. Due to the comparitively lower density of cesspools in Māpunapuna, storm drains are more likely impacted by defective sewer lines instead of cesspools. For instance, the increase in EOCs at high tide for coastal sites may indicate increased inundation and flow of wastewater from cesspools in the subsurface. Storm drains, in comparison, experience both stormwater backflow of seawater (Fig. 1H) as well as GWI from the rising water table (Fig. 1A, C), leading to comparatively greater dilution of EOCs. The divergence in nutrient trends between most coastal sites and storm drains may also illustrate this effect because the storm drains receive seawater from Ke'ehi Lagoon and Honolulu Harbor, areas that frequently do not meet water quality standards (USDA 1999). Additionally, the storm drains are in an area with substantial industrial land use and may be receiving additional nutrients from nonwastewater sources at high tide. Distinguishing geochemical signatures between cesspools and defective sewer lines discharging to water bodies remains a challenge because EOC and nutrient concentrations are dependent on several factors, including cesspool density, distance from the WIS source, and number of people served by the sewer line or cesspool.

While EOCs are applied here as wastewater tracers, they also pose an environmental risk (Fig. 5). Average RQs for surface water and storm drain samples were above 1, demonstrating that even under current conditions, EOCs render a high risk to the ecosystem. Overall, RQs were high risk in 62% of samples for carbamazepine and caffeine and 24% for fluoroquinolones (Table S6) and may threaten growth or result in premature mortality of aquatic organisms (European Commission 2003).

## Conclusion

The frequency, duration, and severity of wastewater contamination to Waikīkī and Māpunapuna water bodies are projected to increase with SLR. Here, we focused on two different site types to study multiple mechanisms of GWI. Higher nutrient and EOC fluxes were observed for most coastal sites during king tides compared to spring tides. Additionally, higher EOC scores were observed at high tide compared to low tide for coastal Waikīkī sites. Tidally driven EOC concentrations observed in Waikīkī and Māpunapuna demonstrate the hydrologic connection between WIS and coastal waters and serves as a warning for what is becoming more frequent or even permanent problem in the future.

Of significance is that storm drains in low lying inland areas can overflow every spring tide (with even greater frequency and magnitude in the future), becoming channels for untreated wastewater onto streets and sidewalks. From an anthropogenic perspective, this flooding of contaminated water also poses a health risk to pedestrians and impedes traffic including critical operations such as emergency vehicles navigating the area during high tide. Coastal municipalities should consider infrastructure that minimizes flooding opportunities, contact with contaminated water, and decreases the number of contaminant sources, such as installation of one-way valves for storm drains, decommission of cesspools, increased monitoring for defective sewer lines, and construction of raised walkways and streets. This study confirms the hydrological connection and demonstrates that SLR leads to increased opportunities for wastewater to pose direct environmental and human health risks.

While this study was based in Honolulu, it has applications to coastal communities elsewhere. For instance, the number of days per year that U.S. coastal cities experience nuisance flooding has doubled between 2000 and 2019 and is estimated to increase to 270 $\mathrm{d\,yr^{-1}}$ in some coastal communities by 2050, particularly in areas vulnerable to storm surge (Sweet et al. 2020). SLR will expedite WIS leakage to coastal water bodies, reducing opportunities for natural remediation and potentially lead to ecological decline and increases in waterborne illness. While this study focused on contaminant pathways to surface water, coastal drinking water resources are also threatened. Moving forward, coastal municipalities should conduct SLR related risk assessments and mitigation strategies that account for increased connectivity between WIS and recreational/drinking water resources.

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