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Inflow and infiltration in coastal wastewater collection systems: effects of rainfall, temperature, and sea level

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Abstract

Wastewater collection and treatment systems are vital to public health, economic growth, and environmental quality, but do not receive as much consideration for upgrades and improvements as other forms of public infrastructure. Extraneous inputs to a wastewater collection system are caused by rainfall and submergence ("Inflow and infiltration," I&I) and other factors, such as variation in sea level in coastal settings. These factors all pose risks for system degradation, sanitary system overflows (SSOs), and water quality impairment, but remain poorly quantified. Multiple regression analyses of total flows through 19 wastewater collection systems in coastal North Carolina, all using gravity collection systems, over a 2-year period (2010–2011) demonstrated statistically significant effects of rainfall, temperature, and sea level as drivers of extraneous flows. Rainfall effects were significant for 18/19 (95%) of these systems. Temperature effects were also significant for 18/19 (95%) of these systems. Sea level effects, primarily driven by spring-neap tidal oscillations, were significant for 11/19 (58%). Further, single factor regression analyses of the effects of temperature and sea level on system flows demonstrated significant effects for 16/19 (84%) and 18/19 (95%) systems, respectively. These collective results demonstrate the potential vulnerability of coastal wastewater collection and treatment systems to breaches in system integrity that allow extraneous flows, primarily through groundwater elevation, to drive further infrastructure degradation and environmental pollution.

Practitioner points

- Heavy rainfalls drive statistically significant inflow and infiltration (I&I) in over 90% of central wastewater systems in coastal North Carolina.
- Temperature, most likely as effects of seasonal variation in groundwater levels, also had a significant effect on I&I in over 90% of these systems.
- Sea level, expressed as daily high-high tide, drove significant effects on flow through over 90% of these systems.

Key words

inflow and infiltration; rainfall; sanitary system overflows; sea level; wastewater treatment

INTRODUCTION

CENTRAL wastewater treatment systems are vulnerable to various natural hazards, but their failures are less obvious to the public, as much of their structure, particularly collection systems, lies underground and out of sight. The integrity of central wastewater collection systems can be assessed by camera inspections of mains, visual inspections of pump stations and manholes, and less direct methods like smoke tests, but these assessment tools are not quantitative and limited in their sensitivity. Opportunities for failures in system integrity are common, as each km of underground collection pipe can represent hundreds of connections and scores of ground-level openings.

Inflow and infiltration ("I&I"; US EPA 1990, 1995) can pose major challenges to the integrity of central wastewater collection systems. "Inflow" denotes water entering a system from aboveground, as in rainwater leaking through manhole covers. "Infiltration" is the seepage of groundwater through breaches in the underground collection system.

Breaches can arise from poorly fitted pipe connections, deterioration of connection seals, deterioration of the pipes themselves (many older systems have been constructed of materials like clay tile, iron, or other materials that can become fragile with age and exposure to wastewater), or mechanical breakage from improper bedding, local settling of the ground, or even earthquakes (Davies, Clarke, Whiter, & Cunningham, 2001). Consequently, I&I has been recognized as a significant source of extraneous, nonsewage flows into wastewater treatment plants. Excessive I&I can impose extra costs on sewer utilities and their customers as well as environmental impacts through enhanced risks of sanitary system overflows (SSOs), reduced treatment efficiency, flow volume-triggered requirements to expand or upgrade facilities, and costs of inspection and repair of system segments with excessive I&I. Excessive extraneous flows to coastal sewer systems have recently led in some U.S. coastal communities to installation of new technologies, including vacuum and low-pressure systems, that are much more resilient to leakage and consequent difficulties.

Most assessments of I&I are conducted by utilities themselves in response to SSOs. Visual inspection may identify particular portions of a collection system where I&I is likely to be unusually high, but quantitative assessments typically entail localized measures of in-system flows vs. local rainfall conducted by specialized contractors, for example, Nesbit (2007; http://www.globalw.com/support/inflow.html), and use intensive data collection methods (Bareš, Stránský, & Sýkora, 2009). Consequently, the cost-effectiveness of these methods in quantifying the I&I problem at larger scales is limited. Other sophisticated approaches have been developed in data-dense situations that lend themselves to detailed modeling or through application of chemical tracers (Belhadj, Joannis, & Raimbault, 2000; Kracht, Gresch, & Gujer, 2007; Zhang, 2007), but these are system-specific (Karpf & Krebs, 2011) and entail methods of limited accessibility to most utilities.

We have previously used whole-system flow data to quantify I&I responses to rainfall and temperature in an examination of central wastewater systems throughout eastern North Carolina, a Coastal Plain region with low elevations, relatively high annual rainfall, and seasonally high groundwater levels (Cahoon & Hanke, 2017). That study and an earlier one (Flood & Cahoon, 2011) found that a high percentage of coastal central sewer systems, all of which use conventional, gravity flow collection systems, were vulnerable to significant rainfall-driven I&I, but that other factors could contribute additional extraneous flows. Here, we examine rainfall, temperature, and sea level as combined and separate sources of extraneous flows to 19 municipal wastewater systems throughout coastal North Carolina. We expected that if rainfall-driven infiltration (groundwater leakage into collection systems) was broadly significant, then other factors affecting groundwater levels in coastal environments, such as temperature-associated evapotranspiration effects and groundwater level fluctuations associated with variations in tidal amplitude, might also affect flows into coastal WWTPs.

Methodology

This study employed a whole-system approach to the estimation of I&I very similar to the one used in small-scale studies, for example, Massachusetts Department of Environmental Protection (1993): the determination of flow responses to rainfall or other environmental variables. Cahoon and Hanke (2017) described this approach, but the protocol is outlined here as well to provide context for the additional analyses reported in this study. Whole-system flow data for 19 wastewater treatment plants (WWTPs) in coastal North Carolina, which are monitored as a condition of National Pollutant Discharge Elimination System (NPDES) permits under the US Clean Water Act, were used. Metered flow data for these municipal wastewater collection and treatment systems analyzed in this study were provided electronically in Excel spreadsheet format for the years 2010 and 2011 (J. Gregson, NC DENR WiRO, pers. comm.). Flow data were acquired as mgd (millions of gallons day^{-1}), standard units in the United States, but were converted to m^3 day^{-1} for these analyses. Daily flow data were generally recorded as of 8 AM (local, EST/EDT) each day. North Carolina does not permit combined sewer systems (wastewater + storm water collection and treatment), so storm water inflow is not a design feature of central wastewater systems in North Carolina.

Rainfall data were obtained from National Weather Service (NWS) meteorological stations located as closely as possible to each WWTP, ideally within the same county (or city, in the case of larger cities and WWTPs), and reported through NOAA's National Climate Data Center (www.ncdc.noaa.gov). Rainfall data were reported and downloaded as cm day^{-1} as of 7 AM local (EST) in most cases. Values for daily rainfall were added to the flow data spreadsheet, then values for cumulative rainfall over preceding 3-, 7-, 10-, and 14-day periods were calculated; rainfall data for the last 2 weeks of 2009 were included to allow calculation of cumulative rainfall as of January 1, 2010. The same stations also reported minimum and maximum daily air temperatures (°C); the average of these two values was included in subsequent analyses.

I&I results reported in Cahoon and Hanke (2017) identified significant effects of rainfall and/or temperature for 86 of 93 eastern North Carolina WWTPs. Among these, 19 central wastewater collection and treatment systems were identified as lying along oceanic and/or estuarine coastlines experiencing tidal effects and having statistically significant I&I effects. Flows through these systems were then examined statistically for effects of temperature and sea level in combination with and separately from rainfall effects.

Tide gage data from official NOAA tide gages located at Wilmington (NC State Port, 34^{o}11′51.26″ N, 77^{o}57′19.93″ W), Wrightsville Beach (US CG, 34^{o}11′20.89″ N, 77^{o}48′45.78″ W), Beaufort (NOAA-NMFS, 34^{o}43′11.27″ N, 76^{o}40′17.23″ W), and Oregon Inlet (US CG, 35^{o}46′58.70″ N, 75^{o}32′24.38 W) were downloaded for each day, January 1, 2010, through December 31, 2011. Daily high-high tide values (the higher of the semi-diurnal M2 high tides) as meters vs. local datum were extracted for each day at each location. Data points from the unusually high storm tides associated with Hurricane Irene in late August 2011 were removed and excluded from all subsequent analyses; some systems went offline and were unable to report flow data for a few days. More importantly, our intent was to focus on the effects of routine variations in sea level on system flows rather than on effects of dramatic but very rare, extreme events.

Data analyses

Multiple regression analysis was used to examine the response of daily WWTP system flow values to total rainfalls over each period (1-day rainfall to 14-day cumulative rainfall), average daily temperature, and sea level (as daily high-high tide level). Multiple regression has the advantage of considering the effects of each factor independently, allowing determination of significant responses of flow in the overall model and to each independent effect. Temperature data from the NWS data station closest to each WWTP location were used in these calculations. Sea level data were used for the tide gauge station hydrologically closest to each WWTP. For example, the Wilmington North and South WWTPs were closest to the Wilmington/State Port station, but most of the WWTPs in the Albemarle–Pamlico Sound region were closest to the Oregon Inlet station.

The two-year period for data collection and analysis allowed for up to 730 lines of data, however, all records had some gaps. When rainfall or temperature data were missing, which happened frequently owing to gauging malfunctions or other problems (tide gauge data were complete, with the exception noted above of hurricane tides), resulting incomplete data lines were excluded from regression analyses. Thus, if one day's rainfall was not reported, none of the data for the inclusive 14-day period beginning with that entry was included in the regression analysis. The regression model had the form:

$$\begin{aligned}\text{System flow}(\mathrm{m^3\,d^{-1}}) = {} & \text{base flow}(\mathrm{m^3\,d^{-1}}) + \mathrm{m}_1(1-\mathrm{DR}) \\ & + \mathrm{m}_3(3-\mathrm{DR}) + \mathrm{m}_7(7-\mathrm{DR}) + \mathrm{m}_{10}(10-\mathrm{DR}) \\ & + \mathrm{m}_{14}(14-\mathrm{DR}) + \mathrm{m}_T(\text{Temp}) \\ & + \mathrm{m}_{HH}(\text{High-high tide})\end{aligned} \tag{1}$$

where "base flow" is the y-intercept (at which all parameters in the model are set to zero), "1-DR" is rainfall on day 1 (cm), "3-DR" is cumulative 3-day rainfall as of day 1, and so on, "Temp" is average daily temperature, and "$\mathrm{m_x}$" is the corresponding regression coefficient for each term. Regression statistics (derived intercepts and coefficients) were then used to estimate *inflow* (the calculated extra system flow driven by 1-day rainfall ($\mathrm{m_1}$(1-DR) if that term was statistically significant @ $p < 0.05$), and *infiltration* (calculated and summed extra system flows driven by statistically significant cumulative rainfalls) for each WWTP, following the methods of Flood and Cahoon (2011).

We also performed single factor linear regressions of system flow vs. temperature and system flow vs. sea level, owing to gaps in the rainfall data sets, which sometimes substantially reduced the overall degrees of freedom in the multiple regression analyses, and to analyze the magnitude of these effects across the ranges of their variation. These regression models had the form:

$$\text{System flow}(\mathrm{m^3 d^{-1}}) = \text{base flow}(\mathrm{m^3 d^{-1}}) + \mathrm{m}_T(\text{Temp}) \tag{2}$$

and

$$\text{System flow}(\mathrm{m}^3 d^{-1}) = \text{base flow}(m^3 d^{-1}) + m_{HH}(\text{High-high tide}), \tag{3}$$

respectively. The magnitudes of temperature and sea level effects were estimated by calculating the effects on system flows of the 90th and 10th percentile values for temperature or sea level and then calculating the percent of average flow attributed to the difference.

Statistical analyses of these data sets were conducted using JMP Pro version 13.0. Mapping of the results used Arcview 10.5 (ESRI, Redlands, CA) to provide a geographic assessment of percent system flow effects arising from variation in temperature and sea level.

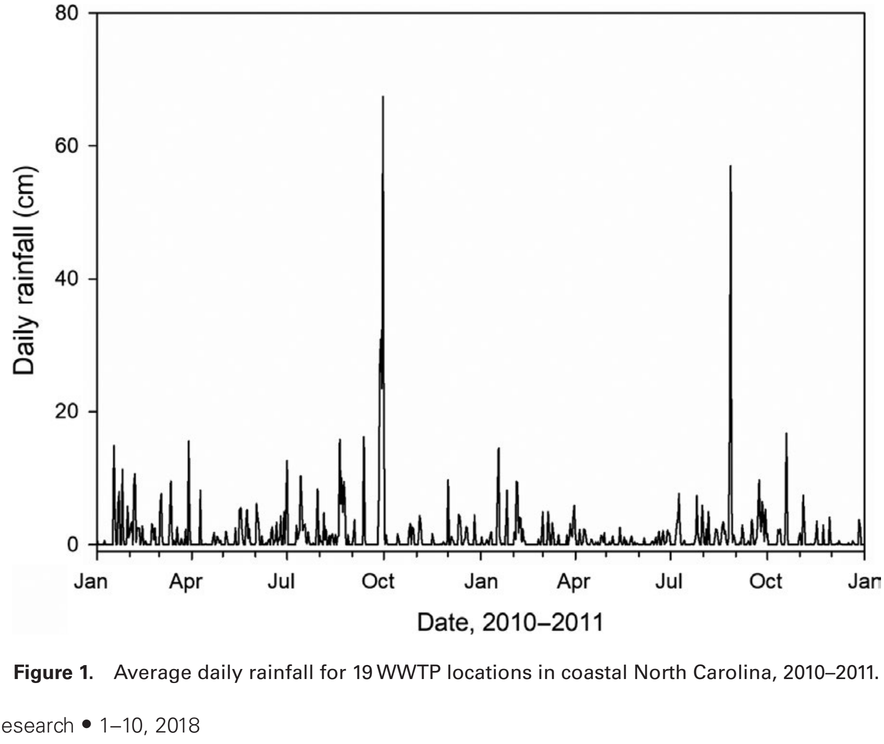

Figure 1. Average daily rainfall for 19 WWTP locations in coastal North Carolina, 2010–2011.

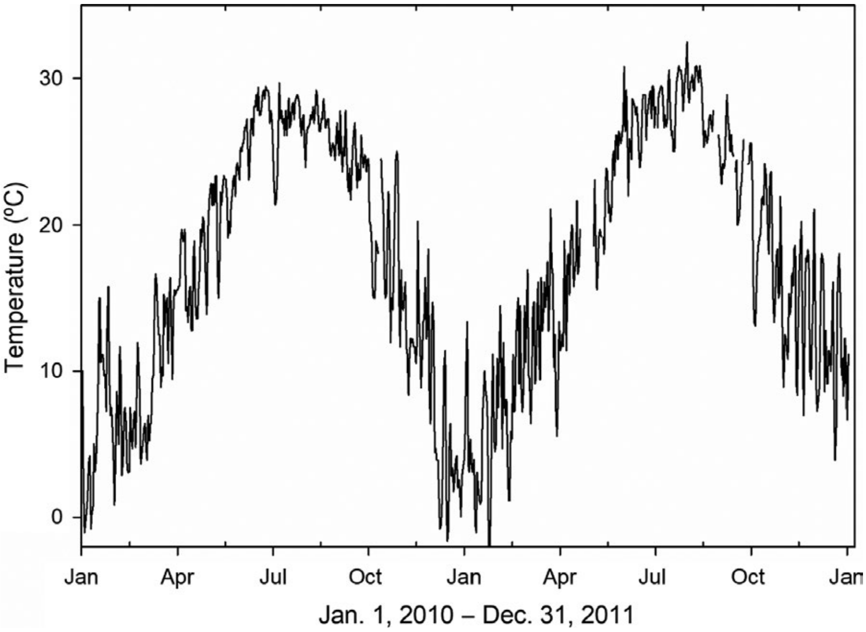

Figure 2. Average daily temperature for coastal North Carolina (at Beaufort, see Figure 4), 2010–2011.

RESULTS

Rainfall patterns during the period 2010–2011 (examined as average daily rainfall for the 19 WWTPs considered in this analysis; Figure 1) revealed no strongly seasonal patterns. Tropical systems impacting eastern North Carolina (TS Nicole in late September 2010 and landfalling Hurricane Irene in late August 2011) produced significant, but brief rainfalls, but otherwise these 2 years were not remarkably dry nor wet compared to long-term records (Cahoon & Hanke, 2017). The period, April–July 2011, appears somewhat drier than the same months in 2010, but the difference is small (Figure 1). Consequently, there was no remarkable temporal variability in rainfall except at event scales. Most rainfall in eastern North Carolina is associated with frontal systems with periodicities of 1–2/week and with local convective storm events. There were 50 days in this 2-year period with average rainfall across the region of at least 5.1 cm (2 inches) in 24 hr. A total of 239 daily rainfalls were measured at individual NWS stations exceeding 5.1 cm, excluding a very few tropical system rains, across the study area.

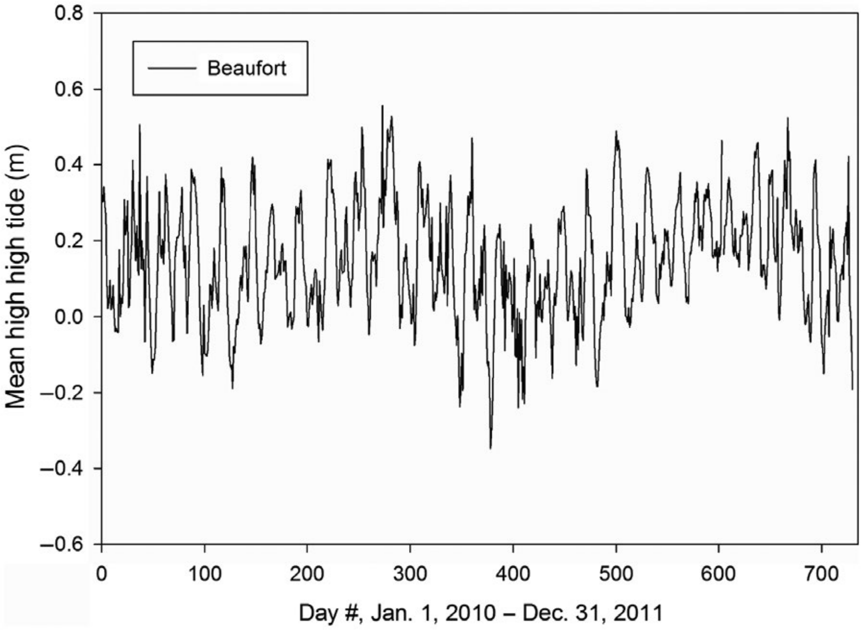

Figure 3. Daily sea level as high-high tide height vs. datum for coastal North Carolina (at Beaufort, see Figure 4), 2010–2011. Values for Hurricane Irene in late August, 2011 not included.

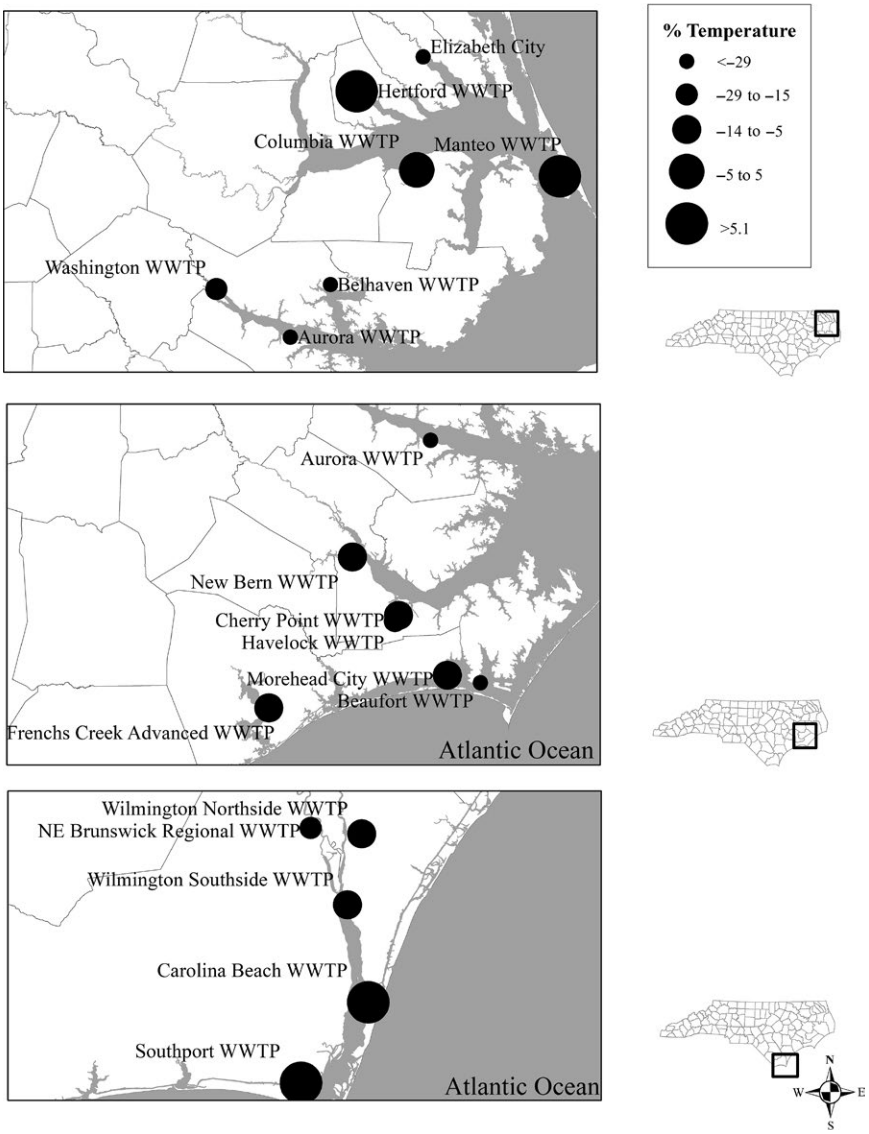

Figure 4. Geographical distribution of temperature effects on percent flow for 90th–10th percentile of temperature range for coastal NC WWTPs, 2010–2011. Data as in Table 2.

Temporal patterns of temperature and sea level reflected several major scales of variation. Seasonality was obviously the strongest source of temporal variation in temperature, followed by weather-event-scale variation (Figure 2). The differences between the 10th and 90th percentile values for temperature during 2010–2011 averaged approximately 24°C. The dominant temporal scale of variability in sea level (as daily high-high tide) was driven by the lunar fortnightly + monthly tidal components (Knauss, 1978), complemented by the annual aphelion–perihelion variation with maximum values in late summer–early fall (Wright, Collins, & Park, 1999), as well as short-term variability likely associated with regional wind events (Figure 3). The differences between the 10th and 90th percentile values during 2010–2011 for daily high-high tides were 0.302 m for Oregon Inlet, 0.388 m for Beaufort, 0.346 m for Wilmington, and 0.496 m for Wrightsville Beach.

Multiple linear regressions of 1- to 14-day integrated rainfall totals, temperature, and daily high-high tides for 19 coastal WWTPs yielded highly significant ($p < 0.0001$) overall results for all 19 systems (Table 1). Rainfall-associated extraneous flows ("inflow and infiltration") were significant for 18/19 (95%) systems, consistent with findings reported by Cahoon and Hanke (2017). Temperature effects were also significant for 17/19 (89%) systems, but 13/19 (68%) temperature effects were of negative sign, indicating lower system flows associated with higher temperatures, and 5/19 (26%) were positive, indicating higher system flows at higher temperatures. Sea level (daily high-high tide) effects were significant for 11/19 (58%) systems. Along with the actual regression equations, the magnitudes of each of these effects in Table 1 were calculated for average values of total system flow, rainfall values, temperature, and sea level. There was likely some complex covariance among

Table 1. Results of multiple linear regression of rainfall, temperature, and sea level effects on flows through coastal WWTPs. Locations ranked by R^2 values for overall regression. "Ave. flow" = average daily flow through each WWTP, calculated as y-intercept plus the sum of average values of rainfall, temperature, and sea level multiplied by coefficients for significant effects in multiple regression. The second line for each WWTP shows the multiple regression equation as Flow (m^3 day^{-1}) = Y-intercept + effects of rainfall (cm) integrated over 1-, 3-, 7-, 10, and 14-day intervals before the day of flow measurement + temperature (°C) + sea level (m above datum). Locations mapped in Figures 4 and 5; locations of tide gage stations identified in Table 3

	REGRESSION STATISTICS				AVE. FLOW	EFFECTS AT AVERAGE FLOW		
WWTP	*F*	*DF*	*P*	R^2	(M^3 D^{-1})	% RAINFALL	% TEMP.	% SEA LEVEL
Wilmington South	285	7,714	<0.0001	0.73	31570	7.2	−5.2	ns
		Flow = $30994 + 78.3_{1DR} + 49.4_{3DR} + 13.2_{7DR} + 21.6_{14DR} - 96.6_{Temp}$						
Beaufort	231	7,607	<0.0001	0.72	2370	24.4	−34.5	3.0
		Flow = $2535 + 14.6_{1DR} + 15.1_{3DR} + 4.05_{7DR} + 5.48_{14DR} - 46.8_{Temp} + 477_{Tide}$						
NE Brunswick	261	7,711	<0.0001	0.72	4690	8.7	−16.3	1.6
		Flow = $4978 + 65.8_{1DR} + 81.9_{3DR} + 45.2_{7DR} + 35_{14DR} - 43_{Temp} + 663_{Tide}$						
New Bern	192	7,543	<0.0001	0.71	14010	11.4	−8.7	3.2
		Flow = $13181 + 757_{1DR} + 382_{3DR} + 129_{7DR} + 142_{14DR} - 73.4_{Temp} + 2927_{Tide}$						
Wilmington North	195	7,711	<0.0001	0.65	28770	8.5	−10.5	2.3
		Flow = $28683 + 336_{1DR} + 488_{3DR} + 230_{7DR} + 237_{14DR} - 169_{Temp} + 5657_{Tide}$						
Havelock	152	7,552	<0.0001	0.65	5030	7.5	−21.7	ns
		Flow = $5743 + 351_{1DR} + 110_{3DR} + 35.8_{14DR} - 64.1_{Temp}$						
Morehead City	155	7,597	<0.0001	0.64	4620	11.1	−8.5	ns
		Flow = $4495 - 40.5_{1DR} + 28.8_{3DR} + 7.15_{7DR} + 6.02_{14DR} - 22.5_{Temp}$						
Belhaven	161	7,706	<0.0001	0.61	1290	24.8	−38.3	9.5
		Flow = $1335 + 5.78_{3DR} + 2.02_{7DR} + 1.39_{10DR} + 2.57_{14DR} - 28.8_{Temp} + 805_{Tide}$						
Washington	147	7,688	<0.0001	0.59	6660	12.2	−19.6	4.0
		Flow = $6861 + 254_{1DR} + 90.3_{3DR} + 92.2_{7DR} + 72.1_{14DR} - 75.3_{Temp} + 1757_{Tide}$						
Carolina Beach	147	7,713	<0.0001	0.59	5450	10.4	17.3	1.5
		Flow = $3852 + 8.1_{1DR} + 10.4_{3DR} + 3.49_{10DR} + 5.73_{14DR} + 53.1_{Temp} + 502_{Tide}$						
Kure Beach	142	7,713	<0.0001	0.58	178	26.2	ns	ns
		Flow = $138 + 14.3_{7DR} + 1.58_{14DR} - 29_{Tide}$						
Southport	28.8	7,142	<0.0001	0.57	507	13.5	16.1	ns
		Flow = $357 - 53.7_{1DR} + 35.4_{3DR} + 7.52_{14DR} + 6.27_{Temp}$						
French's Creek	81.8	7,452	<0.0001	0.55	13940	9.8	−10.6	ns
		Flow = $14128 + 1648_{1DR} + 452_{3DR} + 102_{14DR} - 87.4_{Temp}$						
Columbia	124	7,716	<0.0001	0.54	1020	16.0	3.4	2.9
		Flow = $794 + 50.1_{3DR} + 14.8_{7DR} + 8.32_{10DR} + 5.86_{14DR} + 2.05_{Temp} + 193_{Tide}$						
Cherry Point	75.7	7,556	<0.0001	0.48	6410	4.3	−5.8	ns
		Flow = $6501 + 39.7_{1DR} + 17.5_{3DR} - 21.8_{Temp}$						
Elizabeth City	49.2	7,488	<0.0001	0.41	9990	9.8	−31.0	10.3
		Flow = $11082 + 400_{3DR} + 112_{14DR} - 185_{Temp} + 6800_{Tide}$						
Manteo	30.4	7,360	<0.0001	0.36	1190	11.9	8.2	ns
		Flow = $873 + 33.4_{1DR} + 34_{14DR} + 5.55_{Temp}$						
Aurora	18.7	7,293	<0.0001	0.29	306	11.5	−29.7	12.5
		Flow = $324 + 0.76_{14DR} - 5.2_{Temp} + 252_{Tide}$						
Hertford	4.88	7,718	<0.0001	0.036	1850	ns	8.4	5.7
		Flow = $1592 + 9.36_{Temp} + 691_{Tide}$						

rainfall, temperature, and sea level values at several time scales, particularly seasonal and weather-event scales, which would be aliased to some degree by gaps in the rainfall data.

Single factor linear regressions of system flows vs. temperature were significant for 16/19 (84%) systems, with temperature effects, expressed as the % change in flow across the 90th–10th percentile range of temperatures, varying from +25.9% to −47.2% of average system flow (Table 2). Eleven of these 16 significant temperature effects were negative, indicating lower system flows at higher temperatures, a result similar but not identical to the patterns observed using multiple regression analysis. These patterns of both negative and positive temperature effects likely reflect some balance of seasonal evapotranspiration vs. summer visitation impacts in coastal communities. The geographic pattern of temperature effects offers some support to the hypothesis that locations with

Table 2. Single factor linear regression of temperature effects on flows through coastal WWTPs. Locations ranked by magnitude of temperature effect. Temperature effect as % change between 10th and 90th percentiles of temperature range, calculated as: (temp. coeff. × (90%ile – 10%ile temp)/(Y-int. + (temp. coeff. × (90%ile – 10%ile temp))*100). Locations mapped in Figures 4 and 5

	REGRESSION STATISTICS				Y-INT.	TEMPERATURE		TEMPERATURE EFFECT
WWTP	*F*	*DF*	*P*	R^2	($M^3\ D^{-1}$)	COEFF. ($^{O}C^{-1}$)	90%ILE/10%ILE	% FLOW CHANGE
Carolina Beach	134	1,726	<0.0001	0.15	4360	63.9	28.6/4.6825.9	
Southport	19.6	1,246	<0.0001	0.07	437	6.02	26.9/1.95	25.6
Hertford	16.7	1,727	<0.0001	0.02	1690	11.7	28.1/3.6	14.5
Columbia	10.1	1,725	0.0015	0.01	938	4.73	27.8/3.3	11.0
Manteo	5.16 1,470	0.0236	0.01	1070	3.66	28.1/5.85	7.06	
Cherry Point	(n.s.)							0
Kure Beach	(n.s.)							0
New Bern	(n.s.)							0
Wilmington South	9.33	1,726	0.0023	0.01	32720	−58.2	28.6/4.68	−4.45
French's Creek	9.87	1,691	0.0018	0.01	14470	−46.5	28.1/3.65	−8.51
Wilmington North	23.0	1,717	<0.0001	0.03	30660	−112	28.6/4.45	−9.68
Morehead City	34.4	1,695	<0.0001	0.05	5145	−28.3	28.1/4.66-14.8	
NE Brunswick	93.7	1,717	<0.0001	0.11	5270	−34.7	28.6/4.45	−18.9
Washington	53.7	1,725	<0.0001	0.07	7670	−57.6	28.4/3.64	−22.9
Aurora	6.84	1,429	0.0092	0.01	368	−2.81	28.6/3.92	−23.2
Havelock	176	1,708	<0.0001	0.20	6030	−55.5	27.8/3.65	−28.6
Elizabeth City	74.7	1,568	<0.0001	0.11	12680	−156	28.1/3.9	−42.3
Beaufort	83.7	1,703	<0.0001	0.11	3140	−41.2	28.1/4.76	−44.0
Belhaven	64.7	1,715	<0.0001	0.08	1660	−21.8	28.1/3.65	−47.2

highly seasonal residential populations, for example, Manteo, Carolina Beach, Southport, might exhibit a positive relationship between extraneous flows and temperature, while locations with more constant population patterns, for example, Wilmington North, may reveal seasonality effects on evapotranspiration and groundwater levels more clearly (Figure 4).

Single factor linear regressions of system flows vs. daily high-high tide levels were significant for 18/19 (95%) systems, with sea level effects, expressed as the % change in flow across the 90th–10th percentile range of daily high-high tide levels, varying from 4.8 to 34.8% of average system flow (Table 3). These effects are more dramatic than indicated by the multiple regression analyses for sea level effects, but these separate analyses were utilized to understand how these variables specifically influenced flow rates based on the nature of the data set. Note that degrees of freedom for the single factor regressions were sometimes much larger than in the multiple regression analyses (Tables 1 and 3), owing mostly to gaps in rainfall records used in the multiple regressions. The greatest tide range effects are skewed toward locations well away from ocean inlets that therefore have dampened tidal amplitudes, in contrast to locations closer to the coast or along the strongly tidal Cape Fear River Estuary in southern North Carolina (Figure 5). Unfortunately, the most reliable tide gages are all located along the coast or at the state port in Wilmington, leaving many estuarine areas only indirectly gaged. Thus, the magnitude of sea level effects at locations well away from coastal tide gages may be imprecisely estimated in these analyses, but the operation of such effects clearly cannot be ruled out and must be considered further.

Discussion

Extraneous flows into central wastewater collection and treatment systems can create a variety of management problems for coastal communities. Unusually high flow volumes can impel regulators to require system upgrades, which can be expensive and sometimes unforeseen, putting burdens on local budgets and ratepayers. Intrusions of seawater, in particular, can support production of corrosive and annoying hydrogen sulfide gas from sea salt sulfate (Pikar et al., 2014). In extreme circumstances, elevated salinity may also affect the integrity of microbial processes used in most wastewater treatment systems. Sanitary system overflows (SSOs) are likely the most frequent consequence of extraneous flows but are most likely underreported, as North Carolina requires that only SSOs of more than 1,000 gallons (3,700 L) be notified to the public (N.C. General Statute § 143-215.1 C.). As SSOs are most frequently associated with heavy rain events, distinguishing between coastal water quality impairment caused by "storm water runoff" as opposed to SSOs in coastal areas becomes difficult. The challenge is that limiting these two co-occurring sources of water quality impairment requires very different management remedies.

Calculated values of extraneous flows through WWTPs in this study are almost certainly underestimates. The regression approach utilized in these analyses examined differences in flows attributable to variable external effects and assumed zero I&I when no rainfall occurred in the previous 14 days and zero extraneous flow when temperature and sea level values were

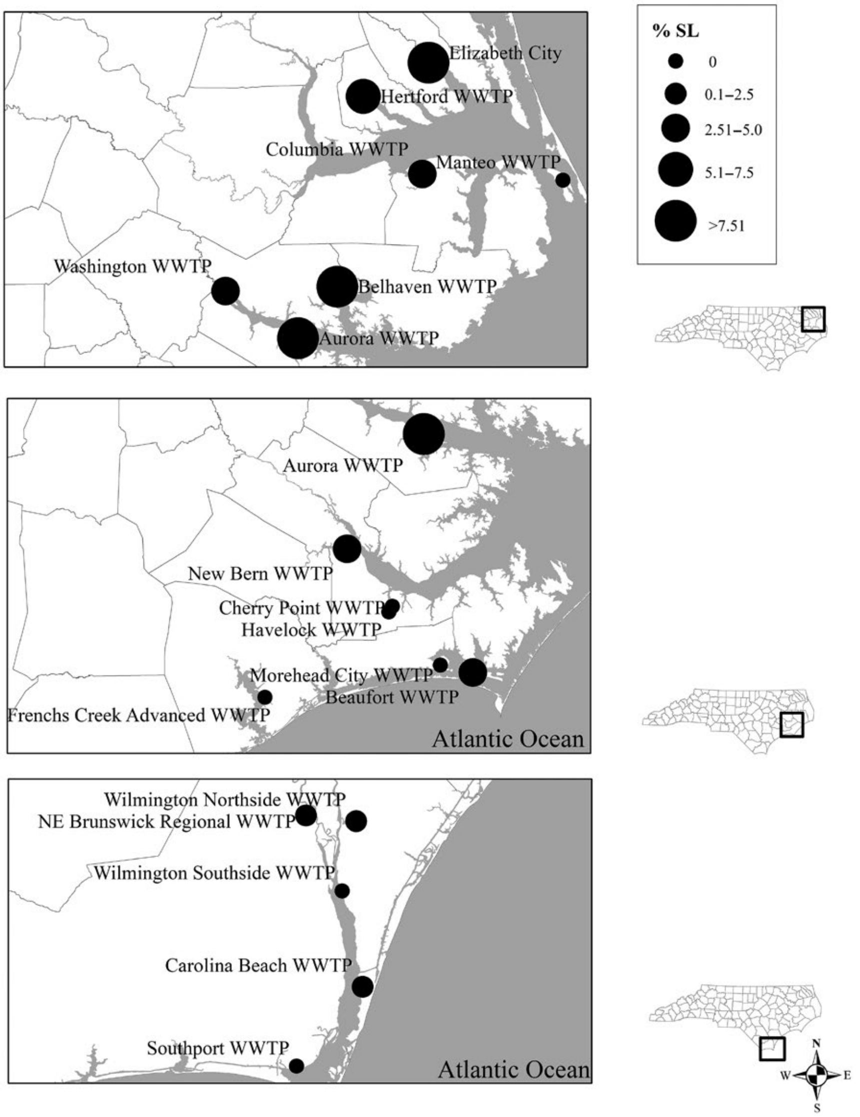

Figure 5. Geographical distribution of sea level effects on percent flow for 90th–10th percentile of daily high-high tide range for coastal NC, 2010–2011. Data as in Table 3.

zero as well. Some sources, for example, groundwater infiltration into portions of sewer collection systems lying below the normal groundwater table, are probably constant except when groundwater tables are unusually low, as in severe drought, which did not occur during 2010–2011. To that extent, therefore, that some flow sources occur continuously, those flows would not be captured in estimates of flow variation responses to external effects. Moreover, any extraneous flows driving water discharges from central sewer systems by SSOs would, by definition, not appear as measured flows at the intake of a WWTP. Anecdotal information, for example, news reports of SSOs during major rain events, provides evidence of such effects. Thus, the estimates here of extraneous flows in these central sewer systems are likely conservative.

The importance of rainfall-driven effects on central sewer system flows in coastal North Carolina has been addressed in earlier studies (Cahoon & Hanke, 2017; Flood & Cahoon, 2011). Inflow and infiltration as drivers for extraneous flows and SSOs are relatively well discussed in the literature (Kaczor & Bugajski, 2012; Karpf & Krebs, 2011; Staufer, Scheidegger, & Rieckermann, 2012). The importance of rainfall-driven extraneous flows in this study is to demonstrate the very common vulnerability of central sewer systems to extraneous flows through breaches in the collection system, a vulnerability that also exposes these systems to effects of seasonal variations in groundwater levels and at several temporal scales owing to tidal inundation.

Temperature effects varied across the study area, with significant negative and positive effects estimated across the 19 systems we examined. Negative effects, that is, increases in extraneous flows with declining temperatures, are highly likely to be a signal of groundwater elevation as the effects of evapotranspiration diminish in colder times, coupled with potential

Table 3. Single factor linear regression of sea level (daily high-high tide) effects on flows through coastal WWTPs. Locations ranked by magnitude of sea level effect. Tide Stations: B = Beaufort; OI = Oregon Inlet; W = Wilmington; WB = Wrightsville Beach. Sea level effect as % change between 10th and 90th percentiles of sea level range, calculated as: (sea level coeff. × (90%ile – 10%ile temp)/(Y-int. + (sea level coeff. × (90%ile – 10%ile sea level))*100). Locations mapped in Figures 4 and 5

	REGRESSION STATISTICS				Y-INT.	SEA LEVEL		SEA LEVEL EFFECT
WWTP/TIDE STATION	*F*	*DF*	*P*	R^2	$(M^3 D^{-1})$	COEFF. (M^{-1})	90%ILE/10%ILE	% FLOW CHANGE
Aurora/OI	48.5	1,435	<0.0001	0.10	260	458	0.3/−0.002	34.8
Belhaven/OI	73.9	1,724	<0.0001	0.09	1035	1670	0.3/−0.002	32.8
Columbia/OI	83.2	1,724	<0.0001	0.10	873	953	0.3/−0.002	24.8
Elizabeth City/OI	35.9	1,724	<0.0001	0.05	8540	7020	0.3/−0.002	19.9
New Bern/OI	68.4	1,575	<0.0001	0.10	12450	1000	0.3/−0.002	19.5
Beaufort/B	23.6	1,726	<0.0001	0.03	2230	1285	0.348/−0.04	18.3
Manteo/OI	76.7	1,725	<0.0001	0.09	1000	746	0.3/−0.002	18.3
Washington/OI	51.8	1,724	<0.0001	0.065	6020	4090	0.3/−0.002	17.1
Carolina Beach/WB	46.9	1,720	<0.0001	0.06	5160	1825	0.425/−0.071	14.9
Hertford/OI	19.7	1,724	<0.0001	0.025	1740	959	0.3/−0.002	14.2
Wilmington North/W	59.6	1,717	<0.0001	0.075	27400	11120	0.299/−0.048	12.3
Southport/WB	7.35	1,389	0.007	0.016	500	118	0.425/−0.071	10.5
NE Brunswick/W	28.1	1,717	<0.0001	0.036	4510	1250	0.299/−0.048	8.8
Cherry Point/OI	25.2	1,724	<0.0001	0.03	6390	1935	0.3/−0.002	8.4
Morehead City/B	10.7	1,714	0.0011	0.013	4510	916	0.348/−0.04	7.3
French's Creek/B	4.25	1,725	0.0397	0.004	13400	1800	0.348/−0.04	5.0
Havelock/OI	6.41	1,720	0.0115	0.007	4960	850	0.3/−0.002	4.9
Wilmington South/W	13.0	1,721	0.0003	0.016	31140	3150	0.425/−0.071	4.8
Kure Beach/WB	n.s.	–	–	–	–	0.0	–	0

seasonal variability in rainfall. The frequently observed negative sign of temperature effects (Tables 1 and 2) suggests that heavy rains in the summer may be less likely to drive SSOs in at least some locations, reducing the impact on body contact recreational uses of coastal waters. Conversely, heavy winter rains may be more likely to drive SSOs when effects of low temperatures and evapotranspiration allow higher groundwater levels, with potential negative impacts on oyster harvest, a winter season activity (15A NCAC 03K .0201).

Sea level effects on extraneous flows through coastal WWTPs have not previously been quantified to the best of our knowledge, although seawater intrusion into collection systems is not unknown, for example, King County (2011). Most such reports, however, come from locations experiencing local flooding associated with storms or unusually high tides. Our analyses indicate that the potential for sea level-driven extraneous flows is temporally and geographically broader than has been appreciated. Of particular interest is the observation that municipalities in coastal North Carolina well inland from the ocean experience significant effects of sea level variation, even though tidal amplitudes are damped with distance from the ocean. It is possible that placement of residences and wastewater infrastructure to serve them in areas with low tidal amplitudes has historically been closer to mean water levels than in areas with higher tidal amplitudes, which might yield the increased effects of higher high tides detected in this analysis, but detailed engineering data would be required to test that possibility. The relative age of each wastewater collection system may also be a factor, as newer systems might have employed better materials, that is, PVC pipe, and better engineering than older ones, with relatively less risk of extraneous flows. Many if not all the municipalities lying along inland coasts in North Carolina are relatively old, whereas development along North Carolina's ocean coast has accelerated recently. Sea level rise, although approximately 15 cm since 1960 (with considerable latitudinal variation; Kopp, Horton, Kemp, & Tebaldi, 2015), when some of the older systems might have been completed, could have had a correspondingly greater impact on those systems than on newer ones.

Future projections of sea level rise (SLR) along the North Carolina coast create disturbing scenarios for coastal wastewater systems. Existing collection systems will be more frequently and extensively located below rising groundwater levels, driven in part by local sea level rise. Extraneous flows will therefore increase with rising sea levels, barring system improvements that reduce extraneous flows. Projections of sea level rise vary along the state's ~520 km coastline, with higher values projected in the northeast and lower in the southern region (Kopp et al., 2015). Projections also vary among climate and general SLR model projections as well, with published ranges of 42–132 cm rise for North Carolina by 2100 under the high-end representative concentration pathway (RCP) 8.5 scenario (Kopp et al., 2015). Compared to the rise observed over the last six decades, such projected increases would clearly expose coastal wastewater systems to significant inundation problems.

We think that sea level effects manifest primarily through changes in groundwater levels in coastal areas that correspond most closely with the bimonthly spring-neap tidal cycle. Extraneous flows associated with sea level variation might not, therefore, necessarily yield a salinity signal at a WWTP, but salinity measurements over a bimonthly cycle might examine this proposition. Seawater itself can cause significant problems for wastewater collection systems, including corrosion of metal components, generation of sulfide gas that can degrade concrete, and effects on the microbiota responsible for biological wastewater treatment.

Accelerating sea level rise creates two additional wastewater management challenges for coastal communities in North Carolina. First, most but not all barrier island communities, especially the most northeastern coastal part of the state, use on-site wastewater treatment systems (“septic systems”), which require some minimum clearance between groundwater elevation and the soil surface to function properly. As groundwater levels rise with rising sea levels, increased rates of failure by on-site systems coupled with ongoing development on barrier islands will increase pressure to switch over to central wastewater collection and treatment systems, although costs would be high. Alternatives to conventional gravity collection systems are now being implemented in a few coastal North Carolina communities, such as a vacuum collection system installed in Oak Island, a barrier island community in Brunswick County, southeastern North Carolina, to offset major water quality problems caused by on-site system failures. Such systems would substantially reduce I&I issues and resulting impairments of WWTP performance (except in major storm events that cause flooding or overwash), but are relatively costly alternatives to conventional gravity collection systems. Second, North Carolina has adopted guidelines that sea level projections for only 30 years may be used in coastal permitting decisions (NC CRC Science Panel, 2016), whereas central wastewater and collection systems are expected to have much longer service lives, thus creating a situation in which accelerating sea level rise can compromise the integrity of sewer infrastructure only a few decades into the future. Finally, we note that the various manifestations of climate change that may occur in North Carolina and elsewhere, in addition to sea level rise, including heavier and more frequent rain events and changes in temperature regimes, will exert significant impacts on coastal central sewer systems, even without considering possible changes in extreme storm event intensity and frequency.

Conclusions

Extraneous flows into wastewater collection systems in coastal North Carolina are driven by varying combinations of rainfall, seasonal temperature effects on groundwater levels, and variation in sea level owing to tidal height variations. These effects are sufficiently significant and widespread to challenge the ability of coastal communities to mitigate them. Climate change will add to the magnitude of this challenge, as heavier rainfall events, potentially more extreme seasonality, and rising sea levels will increase environmental impacts on wastewater collection system performance.

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