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Rainfall effects on inflow and infiltration in wastewater treatment systems in a coastal plain region

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ABSTRACT

Aging wastewater collection and treatment systems have not received as much attention as other forms of infrastructure, even though they are vital to public health, economic growth, and environmental quality. Inflow and infiltration (I&I) are among potentially widespread problems facing central sewage collection and treatment systems, posing risks of sanitary system overflows (SSOs), system degradation, and water quality impairment, but remain poorly quantified. Whole-system analyses of I&I were conducted by regression analyses of system flow responses to rainfall and temperature for 93 wastewater treatment plants in 23 counties in eastern North Carolina, USA, a coastal plain region with high water tables and generally higher rainfalls than the continental interior. Statistically significant flow responses to rainfall were found in 92% of these systems, with 2-year average I&I values exceeding 10% of rainless system flow in over 40% of them. The effects of rainfall, which can be intense in this coastal region, have region-wide implications for sewer system performance and environmental management. The positive association between rainfall and excessive I&I parallels the effects of storm water runoff on water quality, in that excessive I&I can also drive SSOs, thus confounding water quality protection efforts.

Key words | inflow and infiltration, rainfall, sanitary system overflows, wastewater treatment

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INTRODUCTION

Engineered public infrastructure is vulnerable to natural hazards and must consequently be evaluated in terms of failure risks. Some infrastructure failure modes and risks, e.g., potholes in roadways, are relatively visible and easy to assess, while others, such as central sewer systems with much of their collection systems underground, are less accessible for inspection and assessment, and therefore often ignored until actual failure has occurred. The integrity of central sewer 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 limited in their sensitivity (Global Water: 'Inflow and Infiltration': http://www.globalw.com/support/inflow.html; accessed 8 June 2016). Given that each mile of underground collection main can represent hundreds of pipe connections and scores of ground-level openings, the opportunities for breaches in system integrity are myriad.

Inflow and infiltration ('I&I'; US EPA 1990, 1995) can be a major problem for central sewer collection systems (Strifling 2003). 'Inflow' denotes water entering a system from above ground, as in rain water leaking through manhole covers or water in storm drains entering sewer systems. 'Infiltration' is the seepage of groundwater through breaches in the collection system. Such 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 sewage), or mechanical breakage from improper bedding, local settling of the ground, or even earthquakes. Moreover, changes in rainfall patterns and local hydrology can affect groundwater levels and surface sources of inflow, compounding the effects of infrastructure defects (Semadeni-Davies *et al.* 2008). Consequently, I&I has been recognized as a significant source of extra, non-sewage flows into sewage treatment plants, imposing extra costs on sewer utilities and their customers through enhanced risks of sanitary system overflows (SSOs), reduced treatment efficiency, flow volume-triggered requirements to

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expand or upgrade facilities, and costs of inspection and repair of system segments with excessive I&I. Central sewer collection systems include three major components: gravity lines that passively collect sewage, which flows downhill to pump stations that then pump it through force mains uphill, and so forth until flows eventually reach a central wastewater treatment plant (WWTP). It is also necessary to distinguish here between dedicated sewage collection systems that are designed and permitted solely for that purpose, and so-called 'combined sewer systems', in which both sewage and storm water runoff are collected. Changes in rainfall patterns and local hydrology clearly have major effects on system flows in combined sewer systems (Weiss *et al.* 2002). Combined sewer systems are no longer permitted in most of the United States and have never been permitted in North Carolina, the geographic locus of this study (R. Shiver, NC DENR, pers. comm.).

Most assessments of I&I are conducted by sewer utilities themselves in response to SSOs. Visual inspection often identifies particular portions of a collection system where I&I are likely to be unusually high. These assessments typically entail highly localized measures of in-system flows vs. local rainfall conducted by specialized contractors, e.g., Nesbit (2007; Global Water: 'Inflow and Infiltration': http://www.globalw.com/support/inflow.html; accessed 8 June 2016), and use intensive data collection methods (Bareš *et al.* 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 and environmental tracers (Belhadj *et al.* 2000; Kracht *et al.* 2007; Zhang 2007; Caschetto *et al.* 2016), but these must necessarily be system-specific (Karpf & Krebs 2011).

A previous study of four central sewer systems in coastal North Carolina used whole-system flow data to examine I&I responses to rainfall and coastal sea levels, finding significant effects of both in all four systems (Flood & Cahoon 2011), posing the question of how widespread such effects might be. Here we extend that approach to an examination of central sewer systems throughout eastern North Carolina, a Coastal Plain region with low elevations, relatively high annual rainfall, high groundwater levels, and, in some cases, vulnerability to coastal flooding. Our goal was to derive a more complete assessment of I&I problems for the systems in this region in order to have a more insightful and predictive understanding of the magnitude of the infrastructure problem we face. This study examined I&I responses to rainfall patterns in order to determine the extent of I&I in a broader region, and generate a more quantitative assessment of the nature of the problems I&I pose to central sewer integrity and water quality management.

METHODS

Data sources

This study employed a whole-system approach to the estimation of I&I very similar to the one used in small-scale studies, e.g., Massachusetts Department of Environmental Protection (1993): the determination of flow responses to rainfall. Whole-system flow data for WWTPs, which are monitored as a condition of National Pollutant Discharge Elimination System (NPDES) permits, were used in this case. Metered flow data for 220 water and wastewater treatment plants (WTPs and WWTPs, respectively) in the 28 eastern North Carolina counties administered by the Wilmington Regional Office (WiRO) and the Washington Regional Office (WaRO) of the North Carolina Department of Environment and Natural Resources (NC DENR; now the Department of Environmental Quality) were provided electronically in Excel spreadsheet format for the years 2010 and 2011 (J. Gregson, NC DENR WiRO, pers. comm.). This study examined the subset consisting of municipal and residential WWTPs, but not industrial facilities or WTPs that provided drinking water and generated effluents. Several very small residential WWTPs were required to report inflow data on only a weekly or weekday only basis, which was not suitable for the analysis conducted subsequently, so those systems were excluded from further analysis. Daily inflow data were generally recorded as of 8 AM (local, EST/EDT) each day. All WWTP flow meters were calibrated by state-certified procedures; all data reported under NPDES permits must pass rigorous QA/QC procedures.

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 units of 0.01 cm day^{-1} as of 7 AM local (EST) in most cases, then converted to mm day^{-1} for analysis here. Values for daily rainfall were added to the flow data spreadsheet, then values for cumulative rainfall over the 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 1 January 2010. The same NWS stations also reported minimum and maximum daily air temperatures (°C); the average of these two values was included in subsequent analyses.

Data analyses

Multiple regression analysis was used to examine the response of daily system flow values to average daily temperature and total rainfalls over each period (1-day rainfall to 14-day cumulative rainfall). Multiple regression has the advantage of considering the effects of each cumulative rainfall period independently, allowing determination of significant responses of flow in the overall model and to each independent effect (temperature and cumulative rainfall totals). The 2-year period for data collection and analysis allowed for up to 730 lines of data, although almost all records had some gaps. When rainfall or temperature data were missing, which happened frequently owing to gauging malfunctions or failure to meet other QA/QC standards, the resulting incomplete data lines were excluded from regression analyses. Thus, if 1 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. In every instance, however, relatively large data sets remained that could be analyzed with sufficient replication. Rainfall data are always skewed, with many zero values, but transformation of these data was not undertaken, in order to facilitate simpler interpretation of the resulting regression models. The regression model had the form:

$$\text{System flow}(\mathrm{m^3\,d^{-1}}) = \mathit{base\,flow}\,(\mathrm{m^3\,d^{-1}}) + \mathrm{m}_1(1-DR) + \mathrm{m}_3(3-DR) + \mathrm{m}_7(7-DR) + \mathrm{m}_{10}(10-DR) + \mathrm{m}_{14}(14-DR) + \mathrm{m}_T(\mathit{Temp})$$

where system flow data were converted to $\mathrm{m^3\,d^{-1}}$ from 'mgd' (million gallons $\mathrm{day^{-1}}$, the standard reporting unit for US WWTPs, equal to ~3,785 $\mathrm{m^3}$), '*base flow*' is the Y-intercept, '*1-DR*' is rainfall on day 1 (mm), '*3-DR*' is cumulative 3-day rainfall as of day 1, and so on, '*Temp*' is average daily temperature, and 'mx' is the corresponding regression coefficient, m, for each term, x. Regression statistics (derived intercepts and coefficients) were then used to estimate *rainless flow* (*base flow* when all rainfall amounts were zero plus the 2010–2011 average temperature effect), *inflow* (the calculated extra system flow driven by 1-day rainfall ($\mathrm{m}_1(1\text{-}DR)$ if that term was statistically significant at $p < 0.05$), and *infiltration* (calculated and summed extra system flows driven by statistically significant cumulative rainfalls) for each WWTP, following the methods of Flood & Cahoon (2011).

Statistical analyses of these data sets were conducted using JMP, PRO version. Mapping of the results used Arcview 10.2 (ESRI, Redlands, CA) to provide a geographical assessment of percent I&I among WWTPs in eastern North Carolina. Geographic patterns of average annual rainfall for the study period were also mapped from the available data; however, only 32 rainfall stations were available and the broad scale spatial patterns were extrapolated utilizing nearest neighbor interpolation from the Spatial Analyst Toolbox in Arcview 10.2.

RESULTS

WWTP overview

The Washington and Wilmington Regional Offices of NC DENR (WaRO and WiRO) reported a total of 220 NPDES-permitted discharges in eastern North Carolina as of 2010–2011. This total included a large number of industrial dischargers without extensive collection systems as well as drinking WTPs that generate discharges from water treatment operations, none of which were examined in this analysis. Among the 28 eastern North Carolina counties administered by the WiRO and WaRO, all but five (Camden, Chowan, Currituck, Hyde, and Pamlico) had one or more permitted WWTPs serving residential and municipal customers. A total of 93 WWTPs in these 23 counties yielded data suitable for complete analyses of I&I. Seven of these, all low volume systems, yielded no significant effects of rainfall or temperature on system flows, likely as all would have had minimal collection systems, e.g., North Lenoir High School WWTP or Hermitage House Rest Home WWTP. The remaining 86 (92%) systems all exhibited statistically significant effects of rainfall and/or temperature on system flows (Table 1).

Rainless flow values for these 86 systems varied over three orders of magnitude, from 3.9 to 33,480 $\mathrm{m^3\,d^{-1}}$, reflecting the very different circumstances in which central sewage treatment systems have been employed (Table 1). The substantial variation in system flow volumes reflected the fact that state-permitted WWTPs serve a wide range of residential customers, ranging from small residential communities and schools to larger incorporated municipalities, including relatively large coastal cities such as Wilmington, New Bern, and Greenville. The smallest

Table 1 | Effects of environmental factors (rainfall and temperature) on WWTP system flows in eastern NC, 2010–2011, as determined by multiple regression analyses

County WWTP	Regression statistics	Base flow ($m^3\ d^{-1}$), rain and temp. effects	Rainless flow ($m^3\ d^{-1}$)	Inflow (%)	Infiltration %
Beaufort					
Aurora	35.9; 6,434; 0.32	$319 + 1.13_{24DR} - 8.85_{^\circ C}$	157	0	33.5
Belhaven	173.3; 6,710; 0.59	$1{,}413 - 2.7_{1DR} + 5.822_{3DR} + 2.27_{7DR} + 1.46_{10DR} + 2.76_{14DR} - 26.7_{^\circ C}$	958	−1.1	35.2
4-Dowry Creek	4.29; 6,710; 0.03;0.0003	$13.8 + 0.08_{30DR}$	13.8	0	8.5
1-Pantego Mun. Ctr.	20.6; 6,709; 0.14	$5.09 - 0.07_{^\circ C}$	3.9	0	0
80-Washington	195; 6,692; 0.62	$7{,}006 + 21.8_{1DR} + 10.7_{3DR} + 8.89_{7DR} + 7.71_{14DR} - 70.8_{^\circ C}$	5,776	1.4	13.1
Bertie					
Lewiston-Woodville	121.4; 6,722; 0.50	$291 + 1.12_{7DR} + 0.69_{14DR} - 7.62_{^\circ C}$	167	0	35.4
68-Windsor	81.1; 6,709; 0.40	$2{,}612 + 8.87_{1DR} + 4.81_{3DR} + 2.59_{7DR} - 27.8_{^\circ C}$	2,137	1.6	6.0
Brunswick					
49-Belville	22.6; 6,711; 0.15	$730 + 0.74_{1DR} + 3.62_{^\circ C}$	794	0.3	0.0
63-Carolina Shores	38.1; 6,675; 0.25	$1{,}880 - 2.57_{1DR} + 1.57_{3DR} + 1.55_{7DR} + 0.8_{14DR} - 8.9_{^\circ C}$	1,726	−0.5	5.2
74-NE Brunswick Reg.	293; 6,712; 0.71	$4{,}999 + 6.8_{1DR} + 7.95_{3DR} + 4.24_{7DR} + 3.97_{14DR} - 41.2_{^\circ C}$	4,265	0.6	9.3
39-Southport	33.8; 6,143; 0.57	$359 - 5.36_{1DR} + 3.54_{3DR} + 0.77_{14DR} + 6.25_{^\circ C}$	441	−4.3	19.8
3-Waccamaw Elemen.	2.95; 6,691; 0.02, 0.0076	$12.9 + 0.04_{7DR}$	12.9	0	6.4
Carteret					
Beaufort	266; 6,608; 0.72	$2{,}561 + 15.1_{1DR} + 15.2_{3DR} + 3.77_{7DR} + 5.81_{14DR} - 45.3_{^\circ C}$	1,777	2.9	30.5
73-Morehead City	181; 6,598; 0.64	$4{,}507 - 40.4_{1DR} + 29_{3DR} + 7.0_{7DR} + 6.1_{14DR} - 21.8_{^\circ C}$	4,127	−2.5	15.0
59-Newport	51.9; 6,722; 0.30	$1{,}701 + 5.94_{3DR} + 1.33_{14DR} - 23.5_{^\circ C}$	1,319	0	10.3
6-Taylor Ext. Care	3.99; 6,343; 0.05; 0.0007	$24.1 + 0.06_{14DR} - 0.05_{^\circ C}$	23.2	0	14.2
Columbus					
52-Chadbourn	20.8; 6,537; 0.18	$901 + 17.7_{1DR} + 8.53_{10DR} - 1.73_{^\circ C}$	868	6.1	28.6
9-Columbus County	5.21; 6,493; 0.05	76.3	76.3	0	0
47-Lake Waccamaw	9.19; 6,538; 0.08	$722 + 6.01_{1DR}$	722	2.5	0
56-Tabor City	22.4; 6,708; 0.16	$1{,}292 + 6.55_{3DR} - 3.66_{^\circ C}$	1,255	0	4.7
72-Whiteville	25.7; 6,537; 0.21	$4{,}056 + 24.5_{3DR} + 14.4_{7DR} - 16.1_{^\circ C}$	3,773	0	13.4
Craven					
18-Bridgeton	20.3; 6,661; 0.15	$152 - 1.1_{^\circ C}$	134	0	0
21-Carolina Pines Est.	11.9; 6,663; 0.09	$153 + 0.36_{1DR} + 0.28_{3DR} + 0.12_{^\circ C}$	155	0.8	18.0
79-Cherry Point	78.6; 6,562; 0.45	$6{,}231 + 34.2_{1DR} + 21.7_{3DR} - 1.97_{^\circ C}$	6,189	1.7	3.3

(*continued*)

Table 1 | continued

County WWTP	Regression statistics	Base flow ($m^3 d^{-1}$), rain and temp. effects	Rainless flow ($m^3 d^{-1}$)	Inflow (%)	Infiltration %
50-Fairfield Harbour	35.8; 6,657; 0.24	$798 - 0.6_{3\mathrm{DR}} + 0.75_{10\mathrm{DR}} + 0.68_{14\mathrm{DR}} + 1.61_{^\circ\mathrm{C}}$	826	0	7.1
89-First Craven San.	4.71; 6,670; 0.03; 0.0001	$104 + 0.25_{10\mathrm{DR}} + 1.44_{^\circ\mathrm{C}}$	129	0	7.4
76-Havelock	157; 6,556; 0.63	$5{,}768 + 32.7_{1\mathrm{DR}} + 11_{3\mathrm{DR}} + 3.5_{14\mathrm{DR}} - 65.4_{^\circ\mathrm{C}}$	4,663	2.1	5.6
82-New Bern	122; 6,585; 0.55	$14{,}550 + 113_{1\mathrm{DR}} + 34_{3\mathrm{DR}} + 17.1_{7\mathrm{DR}} + 17.8_{14\mathrm{DR}} - 194_{^\circ\mathrm{C}}$	11,316	3.4	13.9
37-River Bend	24.3; 6,647; 0.18	$443 + 4.6_{1\mathrm{DR}} - 0.52_{^\circ\mathrm{C}}$	433	3.6	0
51-Vanceboro	87.3; 6,655; 0.44	$1{,}093 + 4.41_{1\mathrm{DR}} + 1.28_{7\mathrm{DR}} + 1.06_{10\mathrm{DR}} + 0.49_{14\mathrm{DR}} - 17.1_{^\circ\mathrm{C}}$	808	1.8	10.9
Dare					
54-Manteo	32.7; 6,362; 0.34	$969 + 3.23_{1\mathrm{DR}} + 3.44_{14\mathrm{DR}}$	969	0.9	13.9
7-Stumpy Point	54.6; 6,444; 0.42	$13.6 + 0.17_{1\mathrm{DR}} + 0.17_{3\mathrm{DR}} + 0.7_{14\mathrm{DR}} + 0.33_{^\circ\mathrm{C}}$	18.5	3.2	28.3
Duplin					
43-Beulaville	69.5; 6,518; 0.44	$716 + 4.47_{1\mathrm{DR}} + 2.54_{3\mathrm{DR}} + 0.95_{7\mathrm{DR}} - 7.7_{^\circ\mathrm{C}}$	597	2.0	6.5
42-Kenansville	24.4; 6,520; 0.21	$589 + 1.6_{1\mathrm{DR}} + 1.53_{3\mathrm{DR}} + 0.48_{14\mathrm{DR}} - 0.23_{^\circ\mathrm{C}}$	585	0.7	5.2
32-Magnolia	33.7; 6,520; 0.27	$257 - 2.76_{1\mathrm{DR}} + 0.7_{3\mathrm{DR}} + 1.01_{7\mathrm{DR}} + 0.43_{14\mathrm{DR}}$	257	−2.8	16.1
Rose Hill	173; 6,670; 0.60	$1{,}037 + 2.27_{1\mathrm{DR}} + 2.88_{3\mathrm{DR}} + 1.59_{7\mathrm{DR}} + 2_{14\mathrm{DR}} - 26_{^\circ\mathrm{C}}$	604	1.3	28.1
Warsaw	122; 6,518; 0.58	$1{,}809 + 8.11_{1\mathrm{DR}} + 10.2_{3\mathrm{DR}} + 3.22_{7\mathrm{DR}} + 3.22_{14\mathrm{DR}} - 38.7_{^\circ\mathrm{C}}$	1,210	1.8	22.1
Greene					
40-Maury San. Land.	20.0; 6,561; 0.17	$551 + 0.92_{3\mathrm{DR}} - 2.6_{^\circ\mathrm{C}}$	509	0	2.0
44-Snow Hill	6.60; 6,643; 0.05	$676 - 1.81_{^\circ\mathrm{C}}$	647	0	0
Hertford					
70-Ahoskie	24.1; 6,156; 0.46	$1{,}748 + 3.83_{3\mathrm{DR}} + 3.07_{7\mathrm{DR}} + 6.21_{^\circ\mathrm{C}}$	1,864	0	7.2
Jones					
Maysville	95.3; 6,609; 0.48	$459 + 3.29_{3\mathrm{DR}} + 1.81_{7\mathrm{DR}} + 1.31_{14\mathrm{DR}} - 8.43_{^\circ\mathrm{C}}$	323	0	34.1
Trenton	100; 6,304; 0.66	$207 + 0.9_{1\mathrm{DR}} + 0.35_{7\mathrm{DR}} + 0.84_{14\mathrm{DR}} - 3.72_{^\circ\mathrm{C}}$	144	2.2	34.8
Lenoir					
Kinston Reg. W. Recl.	142; 6,723; 0.54	$20{,}296 + 31.1_{3\mathrm{DR}} + 35.4_{7\mathrm{DR}} + 36.1_{14\mathrm{DR}} - 328_{^\circ\mathrm{C}}$	14,482	0	21.5
61-La Grange	36.7; 6,630; 0.25	$1{,}644 + 2.9_{3\mathrm{DR}} + 3.31_{14\mathrm{DR}} - 26.8_{^\circ\mathrm{C}}$	1,216	0	16.9
Martin					
19-Hamilton	33.0; 6,705; 0.21	$109 + 0.55_{1\mathrm{DR}} + 0.23_{3\mathrm{DR}} + 0.12_{14\mathrm{DR}} + 1.08_{^\circ\mathrm{C}}$	127	1.7	7.2
23-Jamesville	16.2; 6,710; 0.11	$177 + 1.67_{1\mathrm{DR}} + 0.46_{3\mathrm{DR}} - 1.31_{^\circ\mathrm{C}}$	155	4.2	3.5
Robersonville	122; 6,707; 0.50	$2{,}439 + 21.7_{1\mathrm{DR}} + 24.8_{3\mathrm{DR}} + 3.72_{14\mathrm{DR}} - 44.2_{^\circ\mathrm{C}}$	1,718	4.8	28.3
71-Williamston	138; 6,707; 0.54	$4{,}148 + 29.2_{1\mathrm{DR}} + 8.31_{3\mathrm{DR}} + 5.17_{7\mathrm{DR}} + 7.55_{14\mathrm{DR}} - 66.3_{^\circ\mathrm{C}}$	3,067	3.7	21.0
New Hanover					
33-Beau Rivage Plant.	25.1; 6,705; 0.17	$277 + 0.2_{14\mathrm{DR}}$	277	0	3.7
77-Carolina Beach	121; 6,722; 0.50	$4{,}624 + 9.27_{1\mathrm{DR}} + 10.4_{3\mathrm{DR}} + 6.68_{14\mathrm{DR}} + 12_{^\circ\mathrm{C}}$	4,844	0.7	9.5

(*continued*)

Table 1 | continued

County WWTP	Regression statistics	Base flow ($m^3\ d^{-1}$), rain and temp. effects	Rainless flow ($m^3\ d^{-1}$)	Inflow (%)	Infiltration %
15-Dolphin Bay	22.3; 6,714; 0.15	$128 + 0.62_{3DR} - 1.21_{^\circ C}$	107	0	6.4
Kure Beach	162; 6,722; 0.57	$128 - 0.5_{1DR} + 0.37_{3DR} + 1.26_{7DR} + 0.135_{14DR}$	128	−1.5	33.9
41-The Cape	99.4; 6,720; 0.45	$534 + 0.66_{3DR} + 0.36_{14DR}$	534	0	4.9
25-Walnut Hills	16.6; 6,712; 0.12	$181 - 0.3_{1DR} + 0.28_{3DR} + 0.12_{7DR}$	181	−0.6	3.4
85-Wilmington North	212; 6,712; 0.64	$28{,}860 + 36_{1DR} + 46.7_{3DR} + 20.6_{7DR} + 27.6_{14DR} - 153_{^\circ C}$	26,135	0.5	9.4
87-Wilmington South	294; 6,722; 0.71	$29{,}780 + 77.5_{1DR} + 50.4_{3DR} + 10.7_{7DR} + 20.4_{14DR} - 20.8_{^\circ C}$	29,397	1.0	6.4
Onslow					
10-Beacham Apts. #1	9.50; 6,462; 0.10	$82.5 + 0.27_{3DR}$	82.5	0	3.0
16-Beacham Apts. #2	8.14; 6,465; 0.08	$91.5 + 0.46_{1DR} - 0.3_{3DR} + 0.28_{14DR}$	91.5	1.6	10.6
20-Blue Creek	8.00; 6,465; 0.08	$140 + 1.8_{1DR}$	140	4.0	0
Cabin Ck. Camp.	5.52; 6,351; 0.07	$7.34 + 0.09_{7DR}$	7.34	0	25.2
83-French's Creek Adv.	95.6; 6,453; 0.55	$14{,}110 + 164_{1DR} + 45.1_{3DR} + 10.1_{14DR} - 88_{^\circ C}$	12,556	4.0	6.7
31-Horse Creek Farms	42.7; 6,660; 0.27	$275 + 0.89_{1DR} + 0.14_{14DR} - 1.77_{^\circ C}$	245	1.2	2.7
N-Hunters Creek	2.71; 6,48; 0.16; 0.0239	$903 + 17.7_{1DR} + (-8.65)_{14DR}$	0.239	6.9	−52.8
17-Kenwood	2.98; 6,628; 0.02; 0.007	$133 - 0.77_{^\circ C}$	121	0	0
55-Lauradale	8.05; 6,470; 0.08	$1{,}196 - 3.31_{^\circ C}$	1,138	0	0
Regalwood	25.6; 6,365; 0.28	$271 + 3.64_{1DR} + 2.52_{3DR} + 0.97_{10DR}$	271	5.3	27.5
45-Richlands	74.5; 6,382; 0.53	$854 + 5.59_{1DR} + 1.71_{3DR} + 0.93_{14DR} - 17.2_{^\circ C}$	557	3.9	14.0
24-Rock Creek G&CC	45.6; 6,369; 0.42	$165 + 3.39_{1DR} + 1.13_{3DR}$	165	6.3	6.3
28-Sherwood Mobile H.	8.10; 6,271; 0.13	$183 + 1.67_{^\circ C}$	212	0	0
Springdale Acres	95.9; 6,472; 0.54	$351 - 2.59_{1DR} + 2.74_{3DR} + 1.16_{14DR} - 2.84_{^\circ C}$	301	−2.7	24.8
46-Webb Creek	52.0; 6,466; 0.39	$699 + 0.83_{3DR} + 0.42_{7DR} + 0.61_{14DR} - 3.25_{^\circ C}$	642	0	6.7
38-White Oak Estates	51.5; 6,371; 0.45	$553 + 6.01_{1DR} + 2.6_{3DR} - 6.1_{^\circ C}$	448	5.3	7.1
Pasquotank					
81-Elizabeth City	29.6; 6,490; 0.26	$8{,}731 + 38.8_{3DR} + 14.1_{14DR}$	8,731	0	12.7
Pender					
62-Burgaw	49.6; 6,518; 0.36	$1{,}645 - 14.1_{1DR} + 16.2_{3DR} + 5.06_{7DR} - 8.99_{^\circ C}$	1,506	−2.4	15.1
5-Pender H.S.	10.2; 6,565; 0.09	$20.6 + 0.22_{3DR}$	20.6	0	11.4
8-Penderlea Elementary	3.09; 6,548; 0.02; 0.0055	$26.5 + 0.23_{3DR}$	26.5	0	9.2
Perquimans					

(*continued*)

Table 1 | continued

County WWTP	Regression statistics	Base flow ($m^3\ d^{-1}$), rain and temp. effects	Rainless flow ($m^3\ d^{-1}$)	Inflow (%)	Infiltration %
64-Hertford	3.59; 6,722; 0.02; 0.0016	$1,659 + 11_{^\circ C}$	1,842	0	0
Pitt					
78-Contentnea Sew. D.	47.8; 6,617; 0.31	$7,153 + 8.64_{14DR} - 94.1_{^\circ C}$	5,661	0	8.2
75-Farmville	21.2; 6,508; 0.19	$5,797 + 15.9_{7DR} - 82.1_{^\circ C}$	4,395	0	8.0
88-GUC	248; 6,690; 0.68	$37,365 + 42.9_{3DR} + 48_{7DR} + 20.7_{10DR} + 31.9_{14DR} - 230_{^\circ C}$	33,480	0	11.8
Tyrell					
53-Columbia	145; 6,719; 0.54	$814 + 2.43_{1DR} + 4.21_{3DR} + 1.57_{7DR} + 0.85_{10DR} + 0.63_{14DR} + 2.41_{^\circ C}$	855	0.1	1.9
Washington					
14-Creswell	119; 6,706; 0.50	$101 + 2.36_{1DR} + 0.68_{3DR} + 0.52_{^\circ C}$	110	8.4	7.3
65-Plymouth	94.1; 6,709; 0.44	$2,010 + 15.6_{1DR} + 7.44_{3DR} + 2.82_{DR} - 14.4_{^\circ C}$	1,768	3.4	9.2
30-Roper	11.8; 6,707; 0.08	$280 + 1.47_{1DR} + 1.39_{3DR} - 3.82_{^\circ C}$	215	2.7	7.6
Wayne					
86-Goldsboro	65.5; 6,683; 0.36	$31,040 + 53.7_{7DR} + 43.9_{10DR} + 33_{14DR} - 385_{^\circ C}$	24,672	0	17.5
66-Mount Olive	19.8; 6,223; 0.33	$2,577 + 14.6_{1DR} - 37.7_{^\circ C}$	1,944	2.1	0

Regression statistics are F value; df for overall model; R^2_{Adj}; *p* values (all <0.0001 unless otherwise included). Intercepts and coefficients significant @$p < 0.05$ in regression model equations are shown as 'Base flow, rain and temp effects'. Numbers preceding WWTP names indicate locations in Figure 3.

systems tended to have been built as discrete collection and treatment units (so-called 'package plants'), whereas the large municipal systems were generally built, expanded, and upgraded over longer periods of time.

NPDES permits typically specify that a WWTP must be sized so that its average treatment volume in practice should be no more than 80% of its rated capacity (the '80/90% rule'; 15A NCAC 02H .0223). The arithmetic mean rainless flow volume for all 86 WWTPs was 3,240 $m^3\ d^{-1}$, meaning that an 'average' WWTP would be permitted to treat >4,050 $m^3\ d^{-1}$, but this metric inadequately represented the widespread, low density population typical of eastern North Carolina. Given the wide variance and non-normal distribution of system sizes in eastern North Carolina, the geometric mean rainless flow volume of 650 $m^3\ d^{-1}$ was more representative of WWTPs in this setting, meaning that a more typical WWTP would be permitted to treat more than 760 $m^3\ d^{-1}$ (~202,000 gallons d^{-1}).

Inflow and infiltration

System designs allow for modest I&I, but excessive I&I could cause flow volumes into WWTPs to exceed the 80% standard and even the full treatment capacity. Eighty (93%) of these 86 systems exhibited statistically significant I&I, with 40 of those 86 systems exhibiting statistically significant inflow in 2010–2011, defined as increases in system flow associated with 1-day (same-day) rainfall (Table 1; nine calculated negative inflow values likely reflect artifacts of differences in flow and rainfall measurement times at small individual WWTPs and nearby rain gauging stations). Forty-six of the 86 systems had no significant inflow values. Average inflow percentage in 2010–2011 for all 86 systems was ~1% of rainless flow. Significant inflow values varied from essentially nil to 9.6% of rainless flow. Maximum inflow volume was 68 $m^3\ d^{-1}$, in a system averaging almost 11,350 $m^3\ d^{-1}$ of rainless flow (New Bern WWTP). Overall, inflow did not contribute in a major way to flow variation for most WWTPs.

Seventy-two of those 86 systems (=84%) exhibited statistically significant infiltration effects in 2010–2011, defined as increases in system flow associated with cumulative rainfall over 3-day, 7-day, 10-day and/or 14-day periods (Table 1; the negative value for the small Hunters Creek WWTP is almost certainly an artifact of a very limited data set, with daily record $n < 60$). Infiltration averaged

11.5% of rainless flow overall, and infiltration values varied from 0 to 35.2% of rainless flow volumes. Seven of the 86 systems examined had average I&I percentages >30% of rainless flow, another 10 had average I&I between 20 and 30% of rainless flow, and an additional 19 systems had average I&I between 10 and 20%. Thus, 36 of 86 systems (42%) had average I&I exceeding 10% of average rainless flow during the 2-year period, 2010–2011. The highest value for average infiltration volume was 4,320 $m^3\ d^{-1}$ in a system averaging 28,810 $m^3\ d^{-1}$ total system flow (17.5% of rainless flow), Goldsboro WWTP. Consequently, infiltration effects on total system flows through these WWTPs were much more widespread and important than inflow effects. The highest values of I&I as a portion of rainless flow occurred in medium-sized systems. Overall, higher I&I volumes were associated with larger sewage treatment systems, as expected, but I&I percentages of rainless flow were not (Figure 1).

Rainfall in 2010 and 2011 averaged 125 cm (49.2″), ranging from a low of 94 cm (37″) to a high of 151 cm (59.4″) at the rain gaging stations of eastern North Carolina accessed for this study (Figure 2). Temperature effects on system flows were statistically significant in 66 (77%) of 86 systems that had significant overall flow effects. Most (55 of 66) significant temperature effect coefficients were negative, implying that flows decreased as temperature increased. We interpreted that as the effect of warm-season evapotranspiration driving lower groundwater levels, i.e., another infiltration signal.

DISCUSSION

Inflow and infiltration (I&I) can cause SSOs during rain events, degrade the performance of central wastewater treatment systems, and force significant and costly mitigation efforts. Eighty-six of 93 residential sewage collection systems in eastern North Carolina (Table 1) exhibited statistically significant I&I effects on system flows, which we interpreted largely as deriving from issues with collection system integrity. North Carolina does not permit inter-connected storm water and sewage systems, so I&I effects must reflect some degree of failure of collection systems to meet the environmental challenges inherent in their below-ground setting. System integrity varied considerably among the systems examined in this study. Some I&I is to be expected under almost all circumstances (excepting the small contained systems, e.g., individual schools served by an on-site WWTP), and is factored into system design, flow calculations, and permitting (typically assumed to be <10%). Some levels of I&I calculated in this study are clearly excessive, however, and demonstrate more problematic system vulnerability to environmental effects. This study found that approximately 40% of central waste water systems had average I&I exceeding 10% of rainless flows under the average conditions occurring in 2010–2011. It is also important to consider that SSOs actually divert sewage flows from WWTP metering locations, so I&I that drives SSOs is systematically underestimated by the approach used in this analysis. Similarly, subsurface leaks of sewage out of the system under the influence

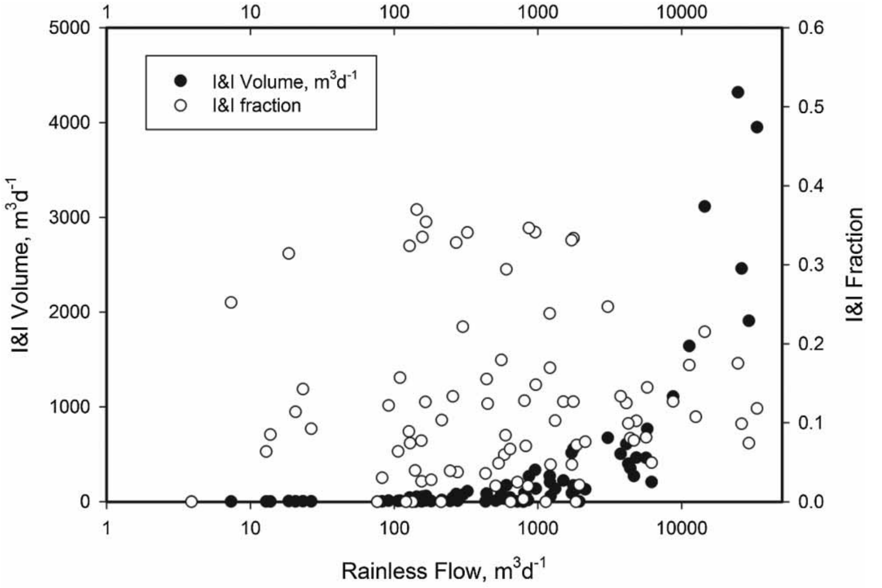

Figure 1 | Comparisons of inflow and infiltration (I&I) volume and fraction of rainless flow vs. rainless flows into WWTPs serving residential communities in eastern North Carolina.

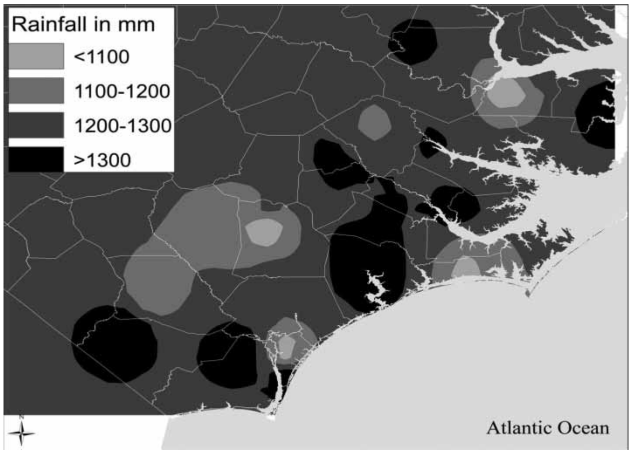

Figure 2 | Geographic pattern of extrapolated average rainfall for the study period from 32 rainfall stations in eastern North Carolina.

of gravity when groundwater levels are low, i.e., times of little rain, or out of force mains under pressure would also underestimate I&I using our approach. Such leakage might not drive immediate surface water quality degradation, but would cause localized contamination of groundwater.

Long-term average rainfalls in coastal North Carolina are generally higher than the values we obtained for 2010–2011 (source: http://www.currentresults.com/Weather/North-Carolina/average-yearly-precipitation.php; accessed 8 June 2016), however, ranging from 1,230 mm year^{-1} in Edenton to 1,500 mm year^{-1} in Morehead City (Table 2), reflecting generally wetter conditions in much of the coastal plain. Thus, estimates of rainfall-driven inflow and infiltration obtained in this study are likely somewhat conservative in a longer-term perspective. Persistent dry conditions predating the period 2010–2011 (average Palmer Hydrological Drought Index value in January 2007–December 2009 = −0.86: http://www.nc-climate.ncsu.edu/climate/climdiv.php; accessed 8 June 2016) for NC may have also aliased I&I responses in the study period by depressing groundwater levels over a longer preceding period.

Inflow effects on system flow were generally a small portion of total system flow and a small fraction of total I&I. Only 9 of 86 systems had inflow values that exceeded infiltration values. Inflow, the incursion of surface water into a sewage collection system, is usually easy to control by relatively simple measures such as grading manhole locations to avoid surface ponding and sealing manhole covers with gaskets. The latter measure is an example of a cheap retrofitting option that can be taken if I&I have been problematic; commercial vendors advertise such gaskets as 'inflow preventers'. Drainage improvements to reduce ponding problems are more expensive but often justified by other considerations.

Infiltration, the leakage of groundwater into sewage collection systems, is a much tougher problem to address. The inherent design criteria for sewage collection systems require that pipes be laid underground and, in many cases, well below groundwater tables. Moreover, one of the factors driving construction of central sewage treatment systems is the presence of high groundwater tables that render on-site wastewater treatment systems (septic tanks) impermissible options for development of otherwise suitable landscapes. Even when collection systems are well-constructed, aging and settling can induce cracks and joint problems (Terry 2008). The expense of sewage collection systems, often on the order of $1 million per mile (1.67 km) of collection main (www.werf.org/c/decentralizedcost/c1_gravity_sewers.aspx; accessed 8 June 2016), can lead to shortcuts in construction and material quality that raise the risks of system leaks. The most daunting costs, however, arise when defective sections of existing collection lines must be replaced, driving an understandable tendency to forego such improvements. Unfortunately, social and political considerations often work against rapid repairs of faulty sewage collection systems, requiring external enforcement actions. For example, the US EPA recently entered into a Consent Decree with the city of Wilmington, New Hanover County, and the Cape Fear Public Utility Authority to decrease and eliminate SSOs in their service district (http://www.cfpua.org/index.aspx?NID=461; accessed 8 June 2016). Consequently, it is not at all surprising that infiltration is a widespread and serious problem in eastern North Carolina.

Rainfall effects on I&I were significant in 79 of those 86 systems, averaged 11.8% over and above rainless flow values, and ranged from 0 to 37.1% for the period 2010–2011. One implication of the relationships between I&I and rainfall is that wetter conditions, either from longer-term patterns or major rain events, such as stalled fronts or tropical systems, might seriously overtax the capacity of a significant portion of wastewater systems in eastern North Carolina. For example, we used the regression equations developed by this study to examine I&I in all 86 systems for two hypothetical situations, one a 50 mm (~2 inch) rain event occurring after an otherwise rainless 14-day period, and the second a series of 50 mm (~2 inch) rain events occurring on days 1, 7, and 14 of an otherwise rainless period, each assuming effects of average temperature. A single 50 mm (~2-inch) event in 1 day of a 14-day period corresponds approximately to average annual rainfall in eastern North Carolina (Table 2): 1,320 mm yr^{-1}, although rainfall of 50 mm in 1

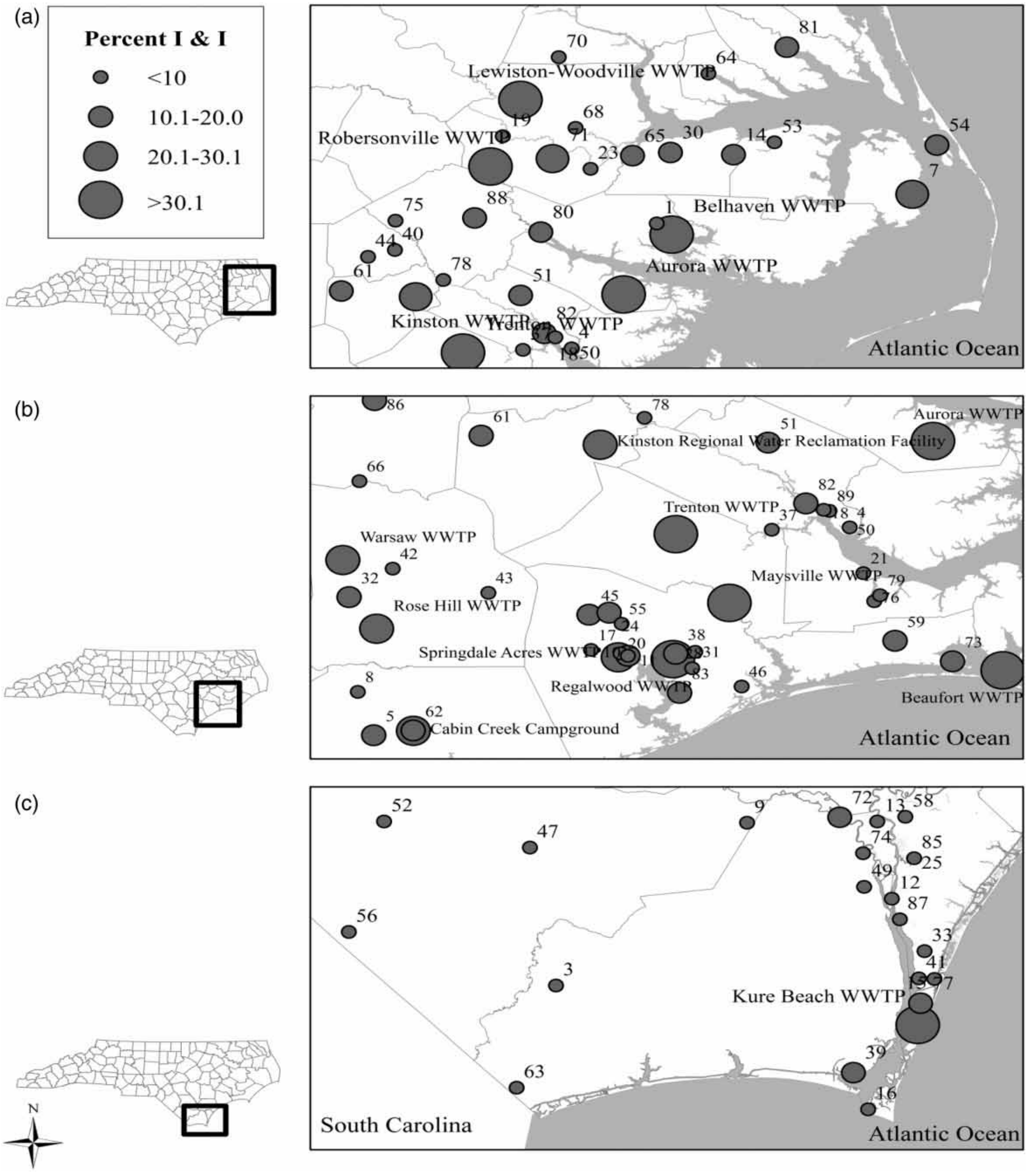

Figure 3 | Maps of eastern North Carolina illustrating locations of WWTPs serving residential communities and proportions of inflow and infiltration (I&I) as a percent of rainless flow. WWTPs numbered as in Table 1, except those with I&I >20% named in figure. The single WWTP with a 'negative' I&I (N-Hunter's Creek, Table 1) was not plotted.

day is an above normal event. Modeling such an event produced an average I&I of over 42% for these 86 WWTPs according to our regression analyses. The second scenario reflects rain patterns that can occur during wetter than normal conditions, but well within the bounds of what has been observed historically. In this case, average I&I was 66%. These simulations illustrate the potential vulnerability of central sewage collection systems to heavy, but plausible, rainfall patterns in eastern North Carolina. For example, the Town of Lake Waccamaw (#47 in Figure 3; Columbus County) collection system reported 60 SSOs between April, 2002 and September, 2014, many of them attributed to 'excessive rainfall' (J. Gregson, NC DENR WiRO, pers. comm.). Moreover, the heavy rainfalls that can drive SSOs also generally exceed the design capacity for storm water management systems, usually 25 mm (1 inch) or 38 mm (1.5 inches) rainfall in 24 hr, creating confounded effects on water quality.

A variety of weather and climate situations can influence rainfall patterns in eastern North Carolina and other coastal regions. Thunderstorm (convective) rains can frequently inundate small areas and create significant local flooding, with localized SSOs as one consequence. Some

Table 2 | Long-term average annual precipitation (mm) vs. 2010–2011 precipitation in cities of eastern North Carolina determined from NOAA's National Climate Data Center (www.ncdc.noaa.gov)

City/County	Average precipitation	2010–2011 annual precipitation
Beaufort/Carteret	1,390	1,230
Belhaven/Beaufort	1,230	1,430
Greenville/Pitt	1,260	1,310
Manteo/Dare	1,270	950
Morehead City/Carteret	1,500	1,240
New Bern/Craven	1,340	1,230
Wilmington/New Hanover	1,460	1,320

frontal systems, particularly if they stall over the region, can deliver significant rainfall. Tropical storm systems with rainfall effects are frequent in eastern North Carolina (averaging >1 event per year since 1851; 'Climatology of tropical cyclones in eastern North Carolina': http://www.weather.gov/mhx//TropicalClimatology; accessed 8 June 2016), as along much of the southeastern USA, and can generate significant regional flooding, with the worst of them completely flooding entire towns and their wastewater systems, e.g., Hurricane Floyd in 1999 (Bales *et al.* 2000). Rainfall varies seasonally in eastern North Carolina, with generally wetter summers and drier winter, spring and fall conditions (http://www.nc-climate.ncsu.edu/climate/monthlyprecip.html; accessed 8 June 2016). Inter-annual variability in rainfall is pronounced, as weather records and climate proxy studies have shown (Stahle *et al.* 1988; Wang *et al.* 2010), and the frequency of heavy rainfall has increased in recent decades (http://www.cisa.sc.edu/ccrc/pdfs/Presentations/Konrad_The%20Climate%20of%20the%20Carolinas%20Past,%20present,%20Future.pdf; accessed 8 June 2016). Eastern North Carolina (and much of the southeastern USA) also experiences heavier sustained rainfall associated with warm phase El Niño-Southern Oscillation events (Savidge & Cahoon 2002; Cahoon 2012). Longer-term projections of changes in precipitation patterns owing to global climate change suggest that eastern North Carolina may lie between areas of expected significantly increased or decreased precipitation (Christensen *et al.* 2007), so long-term average rainfall patterns may not change much, although the frequency of intense rainfall may increase. Recent analyses suggest that warming-induced increases in evapo-transpiration may actually draw down groundwater tables and soil moisture (Sherwood & Fu 2014), thereby lowering I&I, but forecasts specific to eastern NC are not available, and coastal regions may respond differently than more continental climate regimes in general.

Significant temperature effects on system flows were also observed in 78% of collection systems, and were the sole significant environmental influences on system flow in six systems (7%). Eighty-three percent of temperature effects on system flows were negative, meaning that rising temperatures drove reduced system flows. We interpreted that pattern as the effect of evapotranspiration, which is much stronger during the warm vegetation growing season, and the resulting drawdown of groundwater levels, which would reduce infiltration. The widespread inverse relationship between temperature and system flow indicates that high rainfall events in cooler months are more likely to drive excessive I&I and concomitant problems. We speculate that the fewer positive temperature coefficients might reflect seasonal tourism (more sewer flow in warmer months as tourists arrive, e.g., Carolina Beach WWTP), but would need occupancy and other data to test that proposition more explicitly. That positive effect appears limited, however, to a few locations likely visited seasonally as well as a handful of smaller collection systems (Table 1; Figure 3).

Groundwater levels are a function of rainfall inputs, evapotranspiration drawdowns, human effects, soil types and elevations, and proximity to surface waters. Humans affect groundwater tables and, therefore, the potential for infiltration into sewage collection systems in several ways. Direct water withdrawals, such as by shallow wells, would tend to lower groundwater tables, particularly if well water is used for lawn irrigation. Central sewer collection systems rarely overlap in space with agricultural areas in which water withdrawals for irrigation are significant, but that may happen in a few circumstances, especially if urban sprawl into agricultural areas creates a patchwork of land uses requiring extensions of central sewer systems to serve suburban developments. Humans also ditch and drain the landscape, so groundwater tables in such manipulated settings are likely to decline, which would act to reduce the frequency of excessive I&I. Finally, humans enjoy living close to surface waters and have developed extensive portions of North Carolina's and other coastal regions' riparian zones accordingly, creating both a necessity for central sewers to serve many of these areas and exposing collection systems to inundation from their horizontal and vertical proximity to saturated soils and water.

Soils also play an important role in setting risk levels for I&I. Soil composition, drainage, and permeability all act to control the degree of soil saturation at a given depth. Surface maps of soils in North Carolina show that many common soil types are 'poorly drained', 'impermeable', or otherwise capable of creating high groundwater tables that effectively submerge sewer collection system pipes (e.g., Weaver 1977; Barnhill 1986; Goodwin 1987). As stated above, well drained soils are generally suitable for on-site wastewater systems, so there may be a tendency for central sewers to be located in poorly drained areas in addition to areas of high population density. Thorough analysis of the effects of soil distributions on I&I at large scale is very difficult; however, as surface soil maps may not be sufficiently precise at relevant spatial scales, soil composition can change dramatically with depth, and landscape alteration can affect groundwater hydrology significantly.

An obvious factor affecting the risk of I&I is the quality of the sewage collection systems themselves. Central sewer systems are expensive to design, construct, and maintain (Gravity Sewer Systems, Water Environment Research Foundation Fact Sheet C1: www.werf.org/c/decentralized-cost/c1_gravity_sewers.aspx; accessed 8 June 2016). Sewer customers can be very sensitive to their utility bills and resist high costs. Central sewer systems are also subject to inherent hazards, ranging from poor construction practices to natural phenomena like settling, that can raise the risks of excessive I&I. Design and construction criteria for central sewer systems continue to evolve; for example, the use of PVC pipe in collection systems has been widespread in only the past few decades, but many systems predate that and use more brittle or degradable materials. Experience has shown that cast iron and concrete, for example, can be vulnerable to the effects of sewage gases over time (Terry 2008). There is increasingly broad recognition of critical national needs with respect to maintenance and upgrades of wastewater infrastructure, although the estimated costs are staggering (https://knowledge.wharton.upenn.edu/article/americas-neglected-water-systems-face-a-reckoning/; accessed 8 June 2016).

The quantitative analyses presented here demonstrate that I&I is a widespread problem in this coastal region, as has been known for urban areas throughout the USA for many years (Strifling 2003). The association of excessive I&I with heavy rainfall presents a particularly serious problem when the results are SSOs, as spills of raw sewage pose serious threats to public health and water quality. It is likely that not all SSOs caused by excessive I&I are actually detected and reported, as many might be relatively small events, masked by other consequences of heavy rains. North Carolina requires reporting of SSOs over 1,000 gallons (http://portal.ncdenr.org/web/wq/swp/ps/npdes/guidance; accessed 8 June 2016), so smaller spills would not be reportable. We should consider, however, how much of the pollution attributed to storm water runoff is actually caused by SSOs driven by excessive I&I. Recent studies employing human-specific bacterial markers have shown that human waste contamination of storm water runoff is apparently widespread, but otherwise cryptic (Sauer *et al.* 2011). How much 'non-point' source water pollution is actually caused by sewer infrastructure failures?

CONCLUSIONS

Statistically significant increases in flow from central sewage collection systems into WWTPs in eastern North Carolina are common, and are driven by rainfall. Infiltration of groundwater into sewage collection systems appears to be more pronounced than surface inflows. I&I together exceed 10% of rainless flows into WWTPs in over 40% of the systems examined over a 2-year period with approximately average rainfalls. Excessive flows into WWTPs pose several problems for sewage management, particularly elevated risks of SSOs, the effects of which may be easily confounded with storm water runoff.

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