Water table dynamics beneath onsite wastewater systems in eastern North Carolina in response to Hurricane Florence
Charles Humphrey Jr., Danielle Dillane, Guy Iverson and Michael O’Driscoll

ABSTRACT
Onsite wastewater treatment systems (OWSs) are commonly used in eastern North Carolina. A vadose zone or vertical separation distance (VSD) between the OWS drainfield trenches and groundwater is required for effective aerobic wastewater treatment. Extreme weather events, including hurricanes, can deliver significant rainfall that influences groundwater levels and reduces the VSD, thus also influencing the treatment of wastewater by the OWS. Few studies have quantified the effects of storms on the VSD. Groundwater levels at three sites with the OWS were monitored before, during, and after Hurricane Florence. Groundwater rose over 1.5 m within 9 h at the sites in response to rain from the hurricane but took more than 3.5 weeks to return to prestorm levels. Groundwater inundated the drainfield trenches for several days at two sites leading to direct discharge of wastewater to groundwater. The hydraulic gradient and the groundwater velocity increased during the storm and the groundwater flow direction shifted, leading to greater dispersion of wastewater impacted groundwater. The wastewater treatment efficiency of the soil-based OWS in coastal areas may lessen over time because of rising water tables and reduced VSD. Individual pretreatment OWSs, elevated drainfields, or centralized sewage treatment may be required in regions with shrinking VSDs.

Key words | climate change, groundwater, hurricane, onsite wastewater, vadose zone

HIGHLIGHTS
- Groundwater levels directly beneath three onsite wastewater systems were monitored during Hurricane Florence.
- A vertical separation distance decreased by more than 1.5 m at each site in response to rain from the hurricane.
- Direct discharge of wastewater to groundwater occurred at two of three sites.
- The onsite wastewater treatment efficiency may diminish in coastal areas in response to more frequent intense storms.

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INTRODUCTION

Onsite wastewater treatment systems (OWSs) are a common means of wastewater treatment and dispersal in rural regions of many countries, including the USA (US EPA 2002), Australia (Gunady et al. 2015; Geary & Lucas 2018), Canada (Harman et al. 2019), and Ireland (Gill et al. 2007). Most OWSs include a septic tank, drainfield trenches, and soil beneath the trenches. The septic tank typically has a large capacity (>3,700 L) that enables the sedimentation or separation of solids and liquids (US EPA 2002). Raw wastewater entering the tank contains high concentrations of pathogens, nutrients, pharmaceuticals, and other chemicals (US EPA 2002; Lowe et al. 2007) that may pose significant threats to public and environmental health if not effectively treated. While some pollutants in wastewater are removed in the septic tank, most wastewater treatment occurs in the vadose zone (aerated soil) beneath the drainfield trenches. The vertical separation distance (VSD) is the thickness of unsaturated soil between the OWS drainfield trenches and the water table. The VSD influences the treatment efficiency of the OWS. For example, research has shown that when the VSD is reduced to less than 60 cm, bacteria reductions (Karathanasis et al. 2006; Conn et al. 2011; Humphrey et al. 2011, 2015a; Stall et al. 2014) and nutrient transformations and removal (Del Rosario et al. 2014; O’Driscoll et al. 2014; Humphrey et al. 2015b, 2017; Cooper et al. 2016) are negatively influenced. The excess loading of nitrogen, phosphorus, and bacteria often causes impairment of water resources (US EPA 2002; Lusk et al. 2017), and thus understanding the factors that control the fate and transport of these pollutants is an important step in developing effective environmental policies.

NITROGEN TREATMENT BY ONSITE WASTEWATER SYSTEMS

Nitrogen is one of the most commonly observed pollutants in groundwater (Naylor et al. 2018) and surface waters (Paerl et al. 2019) and may be attributed to various sources, including wastewater. Nitrogen concentrations in wastewater typically range between 33 and 171 mg/L (Lowe et al. 2007). Organic nitrogen and ammonium (NH4+) are the dominant forms of nitrogen found in raw wastewater that enters the septic tank. Anaerobic digestion of organic matter results in ammonification, and thus NH4+ becomes the dominant form of nitrogen in septic effluent that enters the drainfield trenches (Lowe et al. 2007; O’Driscoll et al. 2014). If OWS drainfield trenches are installed in oxic soils, then NH4+ may be converted into NO3⁻ by soil microorganisms via nitrification (Humphrey et al. 2010; Lusk et al. 2017). Denitrification, the transformation of NO3⁻ to N2 or N2O, can be a significant removal mechanism of OWS-derived nitrogen if suitable environmental conditions are present beneath the OWS drainfield trenches or within the groundwater flow path of the OWS (Del Rosario et al. 2014; O’Driscoll et al. 2014). Denitrification requires NO3⁻, a source of labile carbon, and anaerobic conditions (Lusk et al. 2017). Where there is typically a small
(<30 cm) separation from the OWS to the water table, elevated concentrations of NH₄⁺ have been observed in groundwater beneath the systems, likely due to inhibition of nitrification (Humphrey et al. 2010; O’Driscoll et al. 2014). Denitrification and mass removal of nitrogen may be limited by the availability of nitrate in areas where OWS drainfield trenches are too close to groundwater for aerobic conditions and nitrification to occur (Humphrey et al. 2010).

PHOSPHORUS TREATMENT BY ONSITE WASTEWATER SYSTEMS

Excess phosphorus loading to surface waters may also cause environmental and public health concerns via the stimulation of harmful algal blooms and the impairment of aquatic habitat (Paerl et al. 2019). Concentrations of phosphorus in wastewater, typically 5–15 mg/L for total phosphorous and 1.2–12.1 mg/L for reactive phosphate (US EPA 2002; Humphrey et al. 2015b), are much higher than concentrations observed to increase algal production in freshwater lakes and rivers. The dominant phosphate removal processes are mineral precipitation and adsorption, which primarily occur in oxic soil immediately beneath the drainfield trenches (Robertson & Harman 1999; Gill et al. 2007; Humphrey et al. 2015b; Lusk et al. 2017). While the significant (>90%) attenuation of OWS-derived phosphate may occur in some settings, groundwater plumes enriched with phosphate, and extending more than 15 m down-gradient from the OWS, have been observed in coastal areas where the vadose zone was less than 60 cm (Humphrey et al. 2014, 2015b).

BACTERIA TREATMENT BY ONSITE WASTEWATER SYSTEMS

The treatment of pathogens and indicator bacteria in wastewater, including Escherichia coli, is also influenced by the VSD between OWS drainfield trenches and groundwater (Karathanasis et al. 2006; Conn et al. 2011; Humphrey et al. 2011). Field-based studies where groundwater samples for bacteria analyses were collected near the OWS (Conn et al. 2011; Humphrey et al. 2011, 2015a) and lab-based experiments where wastewater was leached through soil columns of different thicknesses (Karathanasis et al. 2006; Stall et al. 2014) have shown that bacteria treatment is typically better when the vadose zone is thicker than 60 cm. Thus, rising groundwater levels during storm events may result in reductions in pollutant treatment by the OWS due to the corresponding declines in the VSD.

VSD AND ONSITE WASTEWATER TREATMENT

While studies have shown that separation distances of 60 cm or more are often needed for effective wastewater treatment, North Carolina (NC) requires a minimum of 30–45 cm of aerated soil beneath drainfield trenches, depending on soil and system type (North Carolina Division of Environmental Health 2007). The OWS in coastal regions may see a gradual diminishment of the VSD due to sea-level rise and a corresponding increase in water table elevation (Cooper et al. 2016; Cox et al. 2019). Furthermore, coastal NC is prone to extreme weather events such as hurricanes which can deliver significant rainfall over a short period (Paerl et al. 2019). During or after some storms, groundwater flow rates may increase if there is a corresponding increase in the hydraulic gradient which can result in groundwater discharge of wastewater pollutants to nearby waterways (O’Driscoll et al. 2014). Some climate models suggest that extreme weather events that produce intense rainfall may become even more common (Field et al. 2014), and the recent work has shown that the number of catastrophic tropical storm flooding events has increased along the NC coast since the late 1990s (Paerl et al. 2019). The influence that large storms have on groundwater levels and the VSD, hydraulic gradient, and groundwater flow direction near the OWS is unknown, but these factors influence wastewater treatment.

The goal of this project was to characterize the groundwater hydrology beneath three OWSs in eastern NC during an extreme weather event (Hurricane Florence) to improve the understanding of VSD dynamics and OWS function during storm events. Groundwater characteristics, including the water level, VSD, hydraulic gradient, and flow direction, were monitored for each system to provide insights into system performance during an intense hydrologic episode.
METHODS

Site selection

The study sites were located in Craven County (n = 2) and Pitt County (n = 1) within the Coastal Plain of NC (Figure 1). This region was chosen because over 60% of the population of eastern NC use the OWS (Hoover & Godfrey 2016), and the area has experienced the impacts of several major tropical systems within the past 20 years (Paerl et al. 2019). The Coastal Plain of NC covers about 45% of the state and can be characterized as a wedge of mostly marine sediments and sedimentary rocks that gradually thicken to the east, with sediment types consisting primarily of sand and clay (Daniels et al. 1999). The mean annual rainfall for the study area is approximately 130 cm, with a mean monthly range of 8–17 cm (US Climate Data 2020). The mean high temperature is greatest in July (32 °C), and lowest in January (12 °C) (US Climate Data 2020). Rainfall exceeds evapotranspiration for the Coastal Plain, thus resulting in relatively shallow groundwater, especially along the broad flats between rivers (Daniels et al. 1999).

The three research sites include schools that use the large OWS. The sites were instrumented with wells for groundwater monitoring in 2011 (Sites 1 and 2) and 2013 (Site 3). Monitoring wells were installed between drainfield trenches of the OWS. Characteristics of each site are listed in Table 1.

Instrumentation of sites

The groundwater wells were constructed using a 5-cm diameter solid PVC pipe connected to 0.9 m of well screen. Well sand was poured around the screen portion of the wells, and a mix of sand and bentonite was used to seal the annular space between the well casing and the outside edge of the borehole for each well. A topographic map was used to determine the approximate elevation of the surface at each site, and a laser level was used to determine the relative elevation of the top of each well casing. The depth to groundwater at each well was measured using a Solinst temperature, level, and conductivity meter (Solinst, Canada). The depth to water was subtracted from the relative elevation of the well casing to determine groundwater elevation. The distances between wells were measured using pull tapes, and well locations were plotted on aerial photographs. Manual, discrete groundwater depths from the wells were determined over the past several years, and these data were used to show typical groundwater-level ranges for comparison to water levels during an extreme event (Figure 2).

Groundwater monitoring

Hurricane Florence was projected to make landfall along the NC coast on Friday, 18 September 2018, and contribute significant rainfall to the eastern part of the state. On 11 September 2018 prior to the anticipated arrival of the storm, automated loggers (onset corporation) were programmed to record pressure every 20 min and were placed at the bottom of all three of the monitoring wells (labeled A, B, and C) at each site (Figure 1). Barometric pressure was also recorded at the same time interval. The loggers were deployed to allow the observation of pressure fluctuations due to changes in the water level associated with rainfall from Hurricane Florence. The loggers from the sites were
retrieved 2 months later on 21 November 2018. Manual measurements of groundwater depth on 21 November were noted and used along with barometric pressure data to calibrate and correct the water-level logger readings (Spane 2002). One of the loggers failed during the measurement period at Site 1 (Well C), so data were gathered and

Table 1 | Site and wastewater system characteristics

| Site | County  | USDA soil series | Install date | Total dispersal area (m²) | Maximum design flow (L day⁻¹) | Landscape position | Surface elevation (m) for A, B, C* | Well depths (m) for A, B, C* | Distance to surface water (m) |
|------|---------|------------------|--------------|---------------------------|-------------------------------|--------------------|-----------------------------------|-------------------------------|-----------------------------|
| 1    | Craven  | Autryville       | 1987         | 892                       | 37,800                        | Shoulder Slope     | 10                                | 5.7, 5.8, 6.8               | 60                          |
| 2    | Craven  | Conetoe          | 1997         | 1,115                     | 73,827                        | Broad flat         | 3.1                               | 3.6, 2.4, 2.5               | 160                         |
| 3    | Pitt    | Exum             | 2001         | 560                       | 9,500                         | Broad flat         | 24.8                              | 2.4, 2.8, 2.7               | 290                         |

*Each site had three wells labeled as A, B, and C.

Figure 2 | Historical depth to groundwater data used to show typical ranges of the water level throughout the year at Site 1 (S1), Site 2 (S2), and Site 3 (S3), with A, B, and C denoting the three wells at each site. Well A for Sites 1 and 3 was not within the drainfield area and thus should not be used to assess the VSD from drainfield trenches. Well B for Site 2 was not monitored during 2017.
subsequently analyzed for only two of the three initial loggers at that site. Groundwater-level data from the wells at each location were plotted to show fluctuations in response to the rainfall associated with the hurricane. The groundwater flow direction and the hydraulic gradient were calculated using the water-level data and three-point contouring (Domenico & Schwartz 1998). A flow chart illustrating these steps can be accessed in Supplementary Material.

RESULTS

Groundwater flow direction and hydraulic gradients

The groundwater flow direction and the hydraulic gradient changed at each site in response to recharge associated with rainfall from the hurricane. At Site 1, the groundwater elevation was initially higher at Well A in comparison to Well B, suggesting that the groundwater flow direction was north. However, during the storm and the rising limb of the hydrograph, groundwater was higher at Well B relative to Well A for 24 h (south) before ultimately shifting back for the duration of the study (Figures 1 and 3). The groundwater flow direction at Site 2 was northeast (Well A toward Well B) prior to the storm. During the rising limb of the hydrograph on 14 September, the flow shifted to the northwest (Well A toward Well C) for 6 h and then moved to the north (Well B to Well C) and remained oriented in that direction for 18 days (14 September–2 October). Between 2 October and 21 November (50 days), the flow direction shifted from northeast to north a few times. However, during 32 of those 50 days, the flow direction was northeast. The groundwater flow direction at Site 3 was east (Well B toward Well C) prior to the storm, but shifted to the northeast (Well A to Well C) a few times, for several hours during the rising limb of the hydrograph on 13 September and 14 September. Between 15 September and 25

![Figure 3](http://iwaponline.com/jwcc/article-pdf/doi/10.2166/wcc.2021.303/843929/jwc2021303.pdf)
September, the flow direction alternated between east (Well B to Well C) and southeast (Well A to Well B) five times. After 25 September and until the end of the study on 21 November, the flow direction remained oriented toward the east. Thus, the shift in the direction of groundwater flow lasted much longer at Site 2 in comparison to Sites 1 and 3. The shift in the flow direction during and after the hurricane may have resulted in a larger area of influence for wastewater plumes emanating from the OWS. A summary table with the specific dates and times of flow direction shifts may be viewed in Supplementary Material.

The hydraulic gradient at each site showed similar general trends during and after the storm. More specifically, there were two to three series of quick gradient increases and decreases, followed by an increase and then gradual decline back toward a prestorm value. Overall, for each site, the storm resulted in a net increase in the hydraulic gradient relative to prestorm conditions. For example, the hydraulic gradient at Site 1 initially increased from the prestorm condition of 0.014 on 11 September at 9:20 pm to 0.020 on 15 September at 12:20 pm, and 8 h later (12 September at 8:20 pm), the gradient was the lowest recorded (0.000), followed by an increase to 0.007 early 14 September and a decrease back to 0.000 later the same day (Figure 3). Between 14 September and 21 September, the gradient at Site 1 increased to a level greater than the prestorm value and remained elevated until 2 November. The maximum hydraulic gradient of approximately 0.020 occurred during and after the storm on 13 September and 10 October. The minimum and maximum hydraulic gradients at Site 2 were <0.001 to almost 0.005, respectively, and both occurred on 14 September 2018 (Figure 3). After a few series of increases and decreases in the gradient between 11 September and 17 September, the gradient increased to 0.003 and steadily declined over a 2-week period to the prestorm condition (0.001). During the 2-week period after the hurricane, the mean hydraulic gradient at Site 2 was 64% greater relative to the prestorm value. The hydraulic gradient range at Site 3 was 0.003–0.025, with the smallest gradient occurring during the rising limb of the hydrograph on 12 September, and the largest gradient occurring a few days later on 14 September (Figure 3). The gradient at Site 3 demonstrated a series of increases and decreases during and after the storm, and the mean gradient between 13 September and 25 September (0.008) was more than 2.6 times greater than the prestorm value (0.003). Because the hydraulic gradient increased at each site during and after the storm, the groundwater velocity and flow (and pollutant transport) also increased during that period.

**Groundwater-level dynamics**

Groundwater levels rose over 1.5, 1.7, and 1.8 m at Sites 1, 2, and 3, respectively, within 9 h in response to rainfall associated with Hurricane Florence. The hurricane made landfall on the coast of NC on 14 September 2018, but rain bands from the storm reached the region earlier. Sites 1 and 2 in Craven County received over 40 cm of rain, while Site 3 in Pitt County received over 30 cm during a 3–4-day period leading up to and following landfall of Hurricane Florence. Historical trends (Figure 2) show that separation distances to groundwater are typically within compliance levels with regard to NC requirements of at least 30–45 cm for the sites; however, there are many occasions at Site 3 when the suggested 60 cm or more separation distance to effectively treat wastewater (Karathanasis et al. 2006; Humphrey et al. 2011; Stall et al. 2014) would not have been met.

**VSD and wastewater treatment**

During and after Hurricane Florence, elevated groundwater levels caused the NC separation distance requirement to be violated and inundation of the drainfield trenches at Sites 2 and 3 (Figure 3). Groundwater never inundated the drainfield trenches nor encroached upon the VSD requirement at Site 1 due to the system being located near a shoulder slope, which influenced the thickness of the unsaturated zone (~4 m). The systems at Sites 2 and 3, however, are located on broad, flat, interstream divides with relatively shallow groundwater depths (Table 1). The groundwater elevation was equal to or greater than the bottom of the drainfield trenches at Site 2 for 7.5 days (14 September–22 September 2018) and at Site 3 for 4 days (14 September–18 September 2018). During the trench inundation period at Sites 2 and 3, wastewater in the trenches was mixing directly with groundwater. The NC separation distance requirement of 30 cm was violated for 2.5 weeks at Site 2 (14 September–2 October 2018) and 1 week at Site 3.
(14 September–22 September 2018). Groundwater levels even rose above the ground surface at Site 2 for 12 continuous hours. Groundwater was within 60 cm of the drainfield trenches at Site 2 for 67 consecutive days and Site 3 for 9 consecutive days. While groundwater rose over 1.5 m within 9 h at each site, it took 635 h (26.5 days), 948 (39.5 days), and 604 h (25.2 days) to return to prestorm levels, at Sites 1, 2, and 3, respectively. Thus, extreme storms may disrupt the routine operation of the OWS for weeks after the storm ends.

DISCUSSION

Overall, the hydraulic gradient at each site increased in response to rainfall from Hurricane Florence, and groundwater flow directions shifted from the historical orientations. The groundwater velocity is directly related to the hydraulic conductivity and gradient, thus the groundwater velocity increased during and after the storm in comparison to antecedent conditions. O’Driscoll et al. (2014) also reported an increase in the hydraulic gradient and the groundwater velocity near the OWS in coastal NC during periods of elevated water tables associated with intense rains. In humid environments like NC, groundwater typically moves along a slope (gradient) and eventually discharges to a stream or other surface waters (O’Driscoll et al. 2014), thus increasing streamflow (Humphrey et al. 2016). This process is characteristic of a ‘gaining stream’ (Young et al. 2018). During stormflow and surge events, groundwater and surface water interactions may temporarily reverse the trend, thus switching from a gaining (groundwater feeding streams) to a losing system (stream feeding groundwater) (O’Driscoll et al. 2014). This may have occurred at Site 1 when the groundwater elevation at Well B was greater than at Well A (losing) for 24 h during the storm (Figure 2) before changing back to a gaining system (Well A toward Well B) more typical of the site. Excessive runoff from the intense rain may have caused a quick rise in the stage of the stream, inundation of the floodplain, and reversal of the direction of groundwater flow (Young et al. 2018). Site 1 was located closest to a stream (60 m), and there was more than 6 m difference in elevation between the stream bottom and land surface near the wells at the site. Thus, there was a large floodplain with significant bank storage capacity at the site to enable a ‘losing stream’ scenario following intense rains.

Groundwater levels receded to antecedent conditions over similar time frames for Site 3 (25.2 days) and Site 1 (26.5 days) but took much longer for Site 2 (39.5 days). The soils at Sites 1 and 2 are classified as well drained, and at Site 3, they are moderately well drained. Based on the drainage class alone, groundwater levels should recess quicker at Sites 1 and 2 in comparison to Site 3. However, this was not the case, so other factors must have influenced the hydrology at the sites. While soils at Site 2 are well drained, the elevation was only 3.1 m above mean sea level, and surface flooding occurred. The topographic relief (less than 0.5% slope) and the elevation (3.1 m) were likely insufficient to allow quick drainage after the storm. The stream at Site 2 is a tributary of Swift Creek, which is approximately 650 m from the site. Backwater flooding from Swift Creek may have influenced drainage and groundwater recession at this site. The stream stage for Swift Creek during and after the hurricane exceeded 2.4 m for almost 1 week (15 September–21 September) (USGS 2020). There was less than 0.8 m difference in elevation between the soil surface at Site 2 and the stream stage for Swift Creek during that time. While Site 3 is also flat (<1% slope), it has the highest surface elevation (24.8 m) and is the furthest from an adjacent surface water body. The stream at Site 3 drains to the Tar River approximately 3.5 km away. The maximum stage for the Tar following the hurricane was less than 4 m (USGS 2020b). Site 3, therefore, would not be as influenced by backwater conditions as Site 2. Stream outflow and groundwater-level recession at Site 1 may have been influenced by the partial restriction of streamflow from felled trees. The floodplain at Site 1 is heavily forested, and several fallen trees were noticed within the floodplain after the storm. The stream at Site 1 is a tributary of the Neuse River. The stage of the Neuse River near Fort Barnwell (~3 km away) exceeded the flood level for just over 2 weeks (USGS 2020c). While backwater from the Neuse may have influenced drainage during that period, there was a larger difference in elevation between the land surface at Site 1 (10 m) and the peak stage of the Neuse in Fort Barnwell during and after the hurricane (5.2 m). Thus, factors, including surface elevation, relief, distance to nearest
surface water, and soil drainage class, likely influenced the hydrological response to the storm at each site.

Antecedent groundwater depth as influenced by the landscape position was important regarding OWS vertical separation compliance during and after the intense rainfall. The prestorm water table depths at Sites 2 and 3 were both less than 1.6 m, and these sites experienced direct discharge of septic tank effluent to groundwater. The prestorm water table depth at Site 1 was more than 4 m, and the OWS maintained the required separation to groundwater throughout the study. While only three sites were evaluated, the specific soil series at the sites are found across large portions of eastern NC and in Virginia and South Carolina (USDA soil series at the sites are found across large portions of eastern NC and in Virginia and South Carolina (USDA 2020). Specifically, these soil series cover estimated 1,063 km² (Autryville), 204 km² (Conetoe), and 464 km² (Exum) areas, respectively, of the USA (USDA 2020). Previous research (Cox et al. 2020) has shown that OWSs in low-elevation, waterfront areas are vulnerable to the effects of sea-level rise and coastal storms, and this study has shown that regions with elevations greater than 20 m above sea level and on broad, flat, interstream divides may also be negatively affected by intense rain events.

Most contaminants in wastewater are removed or transformed through various processes if there is 60 cm or more aerated soil beneath OWS drainfield trenches (Karathanasis et al. 2006; Humphrey et al. 2010, 2011; Del Rosario et al. 2014; Stall et al. 2014). Research in several states, including Rhode Island (Cox et al. 2019, 2020), New York and New Jersey (Fisher et al. 2016), Florida (Meeroff et al. 2018), and Colorado (Kohler et al. 2020), has shown that the OWS treatment and/or function is negatively influenced by storms and/or periods of elevated groundwater levels and reduced VSD. During periods of elevated water tables, groundwater and adjacent surface waters may become enriched with wastewater constituents, thus posing a threat to public and environmental health (Conn et al. 2017; Humphrey et al. 2015a, 2015b; Meeroff et al. 2018). For Sites 2 and 3, there was less than 60 cm of the VSD for 67 and 9 days, respectively, following the storm. During and after the hurricane, the VSD was the lowest, and the hydraulic gradient was the highest at each site. There were also shifts in the groundwater flow direction during the storm. Thus, the period of poorest wastewater treatment (the smallest VSD) coincided with the period of highest groundwater flow rate away from the OWS, and a shift in the groundwater flow direction. The Hurricane Florence groundwater data in this study reveal that the OWS treatment was negatively influenced by the storm. The OWS at Sites 2 and 3 experienced several days of direct discharge of wastewater to groundwater, thus no removal of bacteria, nutrients, or pharmaceuticals occurred prior to septic tank effluent reaching groundwater. During periods of drainfield inundation, the North Carolina Department of Health and Human Services suggests that the OWS should not be used, especially if sewage backs up into the home (NC DHHS 2018). Flooding in some regions has led to an increase in OWS repairs due to severe malfunctions (Kohler et al. 2020). Coastal communities that are served by the OWS may be confronted with diminished access to wastewater treatment and/or reduced treatment capacity due to sea-level rise and more frequent, high-intensity rain events (Humphrey et al. 2017; Cox et al. 2020).

CONCLUSIONS

OWSs are the most common means of wastewater treatment in coastal NC, and these systems require unsaturated soil conditions beneath their drainfield trenches for the effective treatment of wastewater. This research has shown that extreme weather events can cause quick (<9 h) rises in groundwater levels that encroach on separation distance requirements and cause direct discharge of wastewater to groundwater for weeks afterward. Some OWS drainfields may even experience flooding. A network of wells installed adjacent to the OWS across a transect of topographic landscapes of coastal regions is suggested to allow the monitoring of groundwater levels during intense rains, storm surge, and other climatic events. Data from the monitoring wells may help to pinpoint regions most vulnerable to groundwater pollution from the OWS, and this information will be vital in developing remediation strategies for the most impacted areas. The OWS treatment efficiencies in coastal areas may diminish from climate-induced hydrogeological changes. The elevation of OWS drainfields (Conn et al. 2011), the incorporation of advanced pretreatment (Amador et al. 2017), and the extension of centralized sewer to the most impacted areas may be necessary in
regions projected to experience rising seas, shallower groundwater tables, and/or more frequent intense rains.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.

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