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Multiple modes of water quality impairment by fecal contamination in a rapidly developing coastal area: Southwest Brunswick County, North Carolina

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Abstract: Fecal contamination of surface waters is a significant problem, particularly in rapidly developing coastal watersheds. Data from a water quality monitoring program in southwest Brunswick County, North Carolina, gathered in support of a regional wastewater and storm water management program were used to examine likely modes and sources of fecal contamination. Sampling was conducted at 42 locations at 3-4 week intervals between 1996 and 2003, including streams, ponds, and estuarine waters in a variety of land use settings. Expected fecal sources included human wastewater systems (on-site and central), storm water runoff, and direct deposition by animals. Fecal coliform levels were positively associated with rainfall measures, but frequent high fecal coliform concentrations at times of no rain indicated other modes of contamination as well. Fecal coliform levels were also positively associated with silicate levels, a groundwater source signal, indicating that flux of fecal-contaminated groundwater was a mode of contamination, potentially elevating FC levels in impacted waters independent of storm water runoff. Fecal contamination by failing septic or sewer systems at many locations was significant and in addition to effects of storm water runoff. Rainfall was also linked to fecal contamination by central sewage treatment system failures. These results highlight the importance of considering multiple modes of water pollution and different ways in which human activities cause water quality degradation. Management of water quality in coastal regions must therefore recognize diverse drivers of fecal contamination to surface waters.

Key words: Storm water, sewage, septic tanks, fecal coliform bacteria, groundwater, silicate

1. INTRODUCTION

Fecal pollution of coastal waters is perhaps one of the most widespread and problematic forms of water quality impairment. Extensive human development and alteration of coastal watersheds coupled with intimate human use of coastal water resources for bathing and shellfish harvest create a situation in which overall risk to the population has become unacceptable. In the United States the Clean Water Act (CWA) of 1972 and subsequent revisions specify policy and practice for regulating the effects of point sources and non-point sources of such pollutants on surface water quality. Point sources require permitting under the National Pollutant Discharge Elimination System (NPDES), which regulates the nature and quantities of pollutants discharged through outfall pipes by industries and waste treatment systems. Recognition of pollutant contributions from non-point sources led to storm water management regulations promulgated by the U.S. E.P.A. as Phase I and Phase II rules (http://www.epa.gov/npdes/pubs/fact1-0.pdf). Management of fecal pollution is one of the principal aims of effective point source and storm water controls.

Storm water runoff is clearly very important to water quality (Wanielista and Yousef, 1993; Whitman et al., 2006; Parker et al., 2010) but is not the only source of non-point water quality impairment, as wet and dry deposition of airborne pollutants (Andersen and Hovmand, 1995) and discharges of contaminated groundwater (Winter et al., 1998) are also “non-point” sources. The Clean Water Act does not as thoroughly regulate these other sources of non-point source pollution, however. Consequently, the focus of non-point source research and regulation on storm water management may not adequately recognize the contributions of these other non-point sources. Moreover, the relative effectiveness of point source controls vs. non-point controls (U.S. E.P.A., 1996) must not be taken for granted, as all engineered human systems are prone to at least occasional failures.

Human development poses myriad challenges to water quality management. Human waste itself is a significant potential source of fecal pollution, so regulations mandate either on-site waste treatment systems, typically septic tanks with associated drain fields, or central sewage collection and treatment systems. Most rural areas rely on the former and most incorporated municipalities on the latter approach, primarily owing to cost and suitability. Humans bring with them pets and other domestic animals, as well as associated wildlife, whose wastes are deposited on the landscape and lead frequently to elevated contamination of runoff. Moreover, humans alter the hydrology of developed landscapes by creation of impervious cover, removal of vegetative cover, and drainage "improvements" that act to accelerate runoff and the delivery of its contents to surface waters. Coastal environments, with human development occurring in close proximity to extensive, high value surface waters, are particularly vulnerable to such multiple impacts. Various studies have demonstrated fecal contamination from central sewage systems, septic systems, and stormwater runoff in coastal North Carolina (Mallin et al., 2007; Mallin, 2013; Mallin et al. 2000; Parker et al., 2010) and elsewhere (Futch et al., 2011; Rippy et al., 2014; Byappanahalli et al., 2015).

The study presented here addressed these issues and is based on water quality monitoring data collected as part of a comprehensive program to manage human wastewater and storm water pollution in southwest Brunswick County, a rapidly developing portion of the North Carolina coast just northeast of Myrtle Beach, South Carolina. This program was undertaken starting in 1994 by the South Brunswick Water and Sewer Authority (SBWSA) for a CWA Section 201 Facilities Planning Area that included the incorporated towns of Calabash, Carolina Shores and Sunset Beach, as well as contiguous, unincorporated portions of Brunswick County. Previous studies had established the likelihood that poorly performing septic systems were responsible for shellfishing closures in the estuarine waters of this area (US EPA, 1980; NC DNRCD, 1980), providing a rationale for central sewer service to the area. Subsequent legal challenges to SBWSA's original plans to provide only sewer service led to incorporation of a storm water management program and a comprehensive water quality monitoring program into SBWSA's overall mission. Water quality monitoring was then contracted by SBWSA to the University of North Carolina Wilmington (UNCW).

Water quality monitoring was undertaken starting in 1996 with several goals: 1) development of an Environmental Impact Statement (EIS) and Phase II Storm Water permit application; 2) comprehensive evaluation of existing water quality conditions, with particular attention to locations with problems; 3) identification, when possible, of causes or sources of water quality impairment; 4) evaluation of remediation, mitigation, and enforcement measures taken in direct response to identified problems, and 5) evaluation of the effectiveness of SBWSA's wastewater and storm water programs as they were implemented. Brunswick County's government decided in 2003 to incorporate SBWSA's regional efforts into a broader county-wide wastewater and storm water program, so SBWSA was disestablished and UNCW's water quality monitoring was terminated.

A previously published study (Cahoon et al., 2006), based on a subset of these water quality monitoring data, addressed the issue of shell-fishing closures in the estuarine portions of the SBWSA 201 Area, and determined that both poor septic tank performance and storm water runoff contributed to fecal contamination of estuarine waters. Water quality impairment was defined as non-attainment of numerical standards adopted by North Carolina for fecal coliform bacteria. Fecal coliform bacteria concentrations are used as indicators of fecal contamination by human and/or animal sources. Relevant standards in the SBWSA 201 Area for fresh surface waters included: fecal coliform bacteria not to exceed a median value of 200 colony-forming units (CFU) $(100\ \text{ml})^{-1}$, although expected higher after rain (15A NCAC 02B .0211). Relevant standards for the estuarine surface waters included: fecal coliform bacteria not to exceed a median value of 14 CFU $(100\ \text{ml})^{-1}$ (15A NCAC 02B .0221). The aims of this study were to identify the likely modes of fecal contamination to fresh and estuarine waters in this coastal region responsible for non-attainment of water quality standards for fecal coliforms.

2. METHODS and MATERIALS

2.1 Geographical Setting

Southwest Brunswick County, North Carolina, is situated between the heavily developed Myrtle Beach, S.C. region and the rapidly growing city of Wilmington, N.C., and is one of the fastest growing coastal communities in North Carolina and along the U.S. East Coast (population: +54.8%, 2000-2010, http://accessnc.commerce.state.nc.us/docs/countyProfile/NC/37019.pdf). This coastal plain region (maximum elevation < 20 m) is in a warm temperate climate zone, receiving approximately 1.5 m rainfall yr^{-1}. Much of this rainfall is associated with local, intense thunderstorms during the warmer months, frontal rain events throughout the year, occasional tropical storms during the late summer and early fall, and inter-annually variable rainfall associated with the ENSO climate cycle (Savidge and Cahoon, 2002).

Data describing the characteristics of the SBWSA 201 Facilities Planning Area and its human and natural environment were obtained from the SBWSA Environmental Impact Statement

(URS Greiner, 1998). SBWSA's 201 Area encompassed a 161 km^2 area, including the incorporated towns of Calabash, Carolina Shores and Sunset Beach, adjoining unincorporated portions of Brunswick County, and surface waters (Figure 1). Human population of this area was approximately 8,000 year-round and 25,000 peak seasonal residents in 1997. The area included residential developments of varying density, golf courses, rural and agricultural areas, as well as a small commercial area in downtown Calabash, in addition to extensive forested areas and other undeveloped tracts of land. The 201 Area included portions of 7 hydrological units, with the largest portions of the total area draining into the Cawcaw River or into coastal waters (NCDENR, 1998). Impervious cover in these hydrological units varied from essentially zero in a small swamp forest unit to 18% for the Sunset Beach watershed. Soils in this region included a variety of coastal types, all but one of which were classified as "severe" for septic tank performance, as either excessively or poorly drained (Barnhill, 1986). Waste treatment systems serving the human population in this area as of 1996 included a large number of septic systems and four central sewer systems serving small portions of the area, with only one of the latter (Carolina Shores WWTP) having a permitted discharge (<0.53 million gallons per day, mgd) to surface waters, the others using sub-surface drainage fields. Storm water management facilities in the area included 3 permitted discharge facilities (wet detention basins), 5 infiltration basins, 19 storm drain pipes on the island of Sunset Beach, and various roadside ditches, swales, and associated culverts. All estuarine waters in this area, including Calabash Creek, the AICW, and waters behind Sunset Beach, were classified as "SA" (shellfishing) waters, but were closed to shellfishing by fecal coliform contamination prior to and throughout the study period (N.C. Division of Shellfish Sanitation, Map 50, Area A-1).

2.2 Methods and Techniques

Water quality monitoring began in October, 1996 at 22 monitoring locations (ML) throughout the SBWSA 201 Area, with twenty additional ML subsequently added and some ML dropped for various reasons (Figure 1). Monitoring locations were numbered in sequence of selection, and were selected to represent all drainage basins and types of surface water bodies in the 201 Area. All ML were located within waters of the state or tributaries to these waters, and were accessed through public rights of way or with permission of private owners. Each ML was sampled every 3-4 weeks, always in mid-morning hours, 0900 to 1200 local time, and without regard to tidal stage in the case of estuarine ML. In some instances, additional sampling was conducted at and near ML where data indicated special concerns.

Values of twelve water quality parameters were measured either *in situ* or from samples collected and returned to the laboratory for each sampling location and time. All parameters were measured by standard methods with rigorous QA/QC measures in place; the UNCW laboratory became state-certified for these protocols during the course of this project. Salinity (Sal), dissolved oxygen (DO), temperature (Temp), and percent oxygen saturation (%Sat) were measured and logged *in situ* using a YSI 85 multi-parameter water quality meter, which was calibrated before each daily sampling trip. Water for fecal coliform analyses was collected in triplicate sterile bottles dipped at the surface to avoid sediment disturbance, iced immediately, and returned to the laboratory within 6 hours, in accordance with accepted sampling protocols. Fecal coliform (Fecal) analyses employed the membrane filtration method (MFC, method 9222D, APHA, 1998). We filtered, incubated, and counted five filtered subsamples (3 x 10 ml, 1 x 1 ml, and 1x 100 ml) from each sample, reporting a mean value +/- one std. dev. for the three 10 ml subsamples as CFU (100 ml)$^{-1}$. We measured total nitrogen (TN) and total phosphorus (TP) in triplicate using a persulfate digestion method (Valderrama, 1981) followed by analysis as nitrate and phosphate by standard colorimetric methods with an Alpkem Flow Solution 3000 AutoAnalyzer, and reported as µg N or P L^{-1}. Reactive silicate (Si) was measured using the molybdate-blue method of Strickland and Parsons (1972) in triplicate samples and reported as µM Si. Chlorophyll *a* (Chla) was measured in triplicate for 200 ml samples returned to the lab, filtered through glass fiber filters, analyzed fluorometrically following Welschmeyer (1994), and reported as µg L^{-1}. Total suspended solids (TSS) were measured in triplicate water samples by filtration through ashed 47 mm glass fiber filters and gravimetry and expressed as mg L^{-1}; TSS measurements were suspended in 2000 in deference to turbidity measures to reduce costs, as NC has no ambient TSS standard for surface waters. Turbidity (Turb) was measured as NTU on a single separate water sample using a DRT-15CE nephelometer (Fisher Scientific) that was calibrated regularly with manufacturer's formazin standards. pH (pH) was measured on a single separate sample using a Fisher Accumet AB15 pH meter calibrated each day with pH 4.0, 7.0 and 10.0 standards from Fisher. Data on daily (@ 0700 hours) rainfall in the SBWSA 201 Area were obtained from the National Weather Service's weather station at Longwood (COOP ID #315116; 34^{o}01'N, 78^{o}33'W), ~4 km north of the SBWSA 201 Area. Rainfall data were examined as same-day rainfall (24HR) and rainfall summed over the previous 3 days (3DR). Discharge Monitoring Reports (DMRs) and the NPDES Violations file for the one central sewer system with a surface water discharge in the SBWSA 201 Area (Carolina Shores WWTP, NPDES Permit #NC004873) were obtained from the NC Division of Water Quality Wilmington Regional Office.

Monitoring activity was conducted between October, 1996 and July, 2003, yielding over 42,500 ML- and time-specific measures of 12 water quality parameters at a total of 2435 sampling times and places. Values for 6 of those parameters (TN, TP, Si, TSS, Chla, and Fecal) included 3 or more replicate measures that were averaged for each sampling time and place, then entered into the master data set for analysis. All averages except for pH were calculated as arithmetic means; average pH was calculated after conversion to $[H^+]$ and re-conversion of the resulting value to a pH value.

Observations in the field by sampling teams and inspection of the data occasionally revealed evidence of specific water quality impairments by human activities, e.g., spills from central sewer facilities, acute failure of septic tanks in some locations, and land disturbance activity causing sedimentation problems. For example, a sanitary system overflow (SSO) in the Carolina Shores sewer system on April 29, 1997 yielded fecal coliform counts in a receiving stream in excess of 600,000 CFU $(100\ ml)^{-1}$, the highest value observed in 7 years of monitoring and almost an order of magnitude higher than any of the other 2300+ fecal coliform counts obtained. These incidents were reported to proper authorities for investigation, remediation, and, if appropriate, enforcement actions. The data arising from these incidents were retained in the overall data set for further analysis, however, as they represented observed, if unusual, effects on water quality.

2.3 Data Analysis

The large size of the data sets and the skewness deriving from frequent zero values in some cases and occasional extreme values frequently precluded the data sets for the measured parameters from satisfying tests for normality. Data for DO, %Sat, Temp and pH were unimodal and approximately normally distributed. Data for Turb, Chla, TSS, TP, TN, Fecal, and Si were transformed logarithmically (Log_{10}). Data for Sal, 24HR, and 3DR were transformed by the formula: $Log_{10}(X+1)$, where X is the raw value, as many values for these parameters were zero. All subsequent statistical analyses therefore used raw data for DO, %Sat, pH and Temp, as well as the log-transformed values for other parameters, designated as LTurb, LChla, LTSS, LTP, LTN, LFecal, LSi, LSal, L24HR, and L3DR, respectively.

Principal components analysis (PCA) was used initially to examine the correlation structure of the overall data set. Specific hypotheses about associations between fecal coliform concentrations and related parameters derived from PCA were then tested by ANOVA and multiple regression. The effects on fecal coliform levels of other characteristics of the environmental settings in which ML were located were examined using one-way ANOVA. All statistical analyses were conducted using JMP 9.0 (SAS Institute).

3. RESULTS

There were multiple likely modes of fecal coliform contamination across the watersheds sampled in the SBWSA 201 Area, including storm water runoff, inputs from poorly performing septic systems, effluent and spills from central sewer systems, and direct deposition by wild and domestic animals. Fecal coliform concentrations were frequently (480/2335) above the NC state standard for human body contact of 200 CFU $(100\ ml)^{-1}$, with 319/487 samples at estuarine sites above the shellfishing standard of 14 CFU $(100\ ml)^{-1}$, so fecal coliform contamination was a common and widespread problem. Prior assessments and investigations had established that several sites had clear evidence of ongoing septic tank inputs causing elevated fecal coliform bacteria concentrations with no correlation to rainfall (Cahoon et al., 2006). Field observations and results of incident investigations established that occasional problems with central sewage treatment caused high fecal coliform incidents (>5,000 CFU $(100\ ml)^{-1}$) at downstream ML. There were a few instances of high fecal coliform counts (>5,000 CFU $(100\ ml)^{-1}$) at other sites when no proximal human source could be identified, and field observations pointed to wild and/or domestic animal waste as a likely cause. There were no large-scale agricultural sources, such as confined animal feeding operations (CAFOs), of animal waste in the 201 Area, although a few domestic farm animals were observed in rural locations. Not surprisingly, one-way ANOVA followed by Tukey's HSD *a posteriori* tests ($\alpha<0.05$) comparing fecal coliform concentrations among all 42 ML individually revealed a large number of significant differences among ML (overall F=8.51, df= 41, 2037, $p<0.0001$).Consequently, ML were grouped in 3 ways to facilitate evaluation of contamination modes: a) fresh water or seawater ML, b) pond or stream ML, and c) ML proximal to septic tanks, ML downstream of a surface-discharging central sewer system, or ML with no proximal human waste sources. Resulting categories based on actual field conditions were: ponds ("Pond") with no proximal human waste sources, ponds with proximal septic systems ("Pond/SP"), seawater ("Seawater") with no proximal human waste inputs, seawater with proximal septic systems ("Seawater/SP"), streams ("Stream") with no proximal human waste systems, streams with proximal septic systems ("Stream/SP"), and streams receiving sewer discharges ("Stream/SE"). A major reason for distinguishing groups of ML by septic tank and sewer proximity was the expectation that these potential sources of fecal coliform pollution might otherwise mask rainfall and runoff effects as sources. Analyses of these location-based effects on fecal coliform levels, other water quality parameters, and rainfall were therefore conducted for data grouped by these ML categories as well as for the overall data set (Table 1). One-way ANOVAs and Tukey's HSD tests demonstrated significant differences among ML groups with regard to all parameters except the rainfall measures, L24HR and L3DR, indicating similarity of rainfall patterns and effects throughout the sampling area as well as significant location-based effects on other parameters (Table 1). Overall average values for each of these 12 parameters plus rainfall, (L24HR) and (L3DR), are also presented in Table 1 for each ML group and for the overall data set. As expected, ML in close proximity to central sewer or septic systems generally had higher average fecal coliform concentrations than ML situated otherwise.

PCA revealed several kinds of information about the correlation structure of the overall data set. Eigenvalues exceeded a numerical score of 1.0 for the first 5 principal components (PC) and accounted for 18.6, 15.0, 14.2, 12.2, and 9.4 percent (total = 69.4%) of total variance, respectively (Table 2). Examination of eigenvectors and the loading matrix revealed that the fecal coliform parameter (LFecal) loaded most heavily in PC3, for which the parameters LTurb, LTSS, LTP, LTN, and LSi also loaded heavily, followed by PC4, for which L24HR, L3DR, and LTP also loaded heavily. The pair-wise correlation matrix for LFecal identified much the same set of significantly correlated parameters (Table 3). Several hypotheses of cause and effect for fecal coliform concentrations were thus derived from this correlative approach to analysis of the overall data set, but we interpreted relationships between fecal coliforms and salinity, turbidity, total phosphorus and total nitrogen as correlative and not causative. Higher salinity is associated with greater dilution by seawater, exposure to sunlight, and the negative effects of salinity on fecal coliform viability (Hanes and Fragala, 1967). Turbidity, total phosphorus and total nitrogen are associated with runoff and fecal wastes, without necessarily driving fecal coliform levels independently.

We expected that if storm water runoff was an important mode of fecal contamination there would be a significant positive association between fecal coliforms and the rainfall indicators. Rising fecal coliform concentrations were in fact driven by increasing rainfall amounts (Figs. 2 and 3), although it should be noted that high fecal coliform concentrations occurred at many times and ML when there had been no rainfall and therefore no storm water runoff, indicating confounding effects that reduced the overall robustness of simple pairwise analyses. Silicate concentrations are typically very low in rainwater but elevated in groundwater owing to dissolution of silicate minerals (Loucaides et al., 2007), so we considered silicate as an indicator of the relative contributions of the two water sources. We expected that silicate concentrations would rise at times of no rainfall as groundwater inflow dominated these shallow water areas, and that fecal coliforms would then decline owing to lack of runoff, yielding a negative relationship between fecal coliform concentrations and silicate. There was no significant effect of either same-day (L24HR) rain or 3-day (L3DR) rain on silicate (LSi) for all ML by simple linear regression (p values = 0.538 and 0.458, respectively), indicating a more complex relationship between rainfall and groundwater contributions to surface waters. Regression of fecal coliform concentrations against silicate concentrations for the entire data set yielded a significant positive relationship, however, meaning that silicate-enriched groundwater appeared to be broadly contaminated by fecal coliforms (Fig. 4), although, again, simple pairwise analysis is confounded by covarying effects. The relationships between fecal coliform concentrations and rainfall or silicate, although statistically significant, yielded low values of explained variance (R^2_{Adj}), which illustrated the confounding nature of the independent effects of rainfall and groundwater in driving fecal contamination, along with what are likely in-stream factors as well, particularly regrowth of fecal coliforms (Surbeck et al., 2010), which was most likely during low-flow conditions, although sediment disturbance would be minimal then and sampling methods specifically avoided sediment disturbance.

ML within the SBWSA 201 Planning Area were located either in areas served by septic tanks, however densely situated or proximal to nearby ML, or by central sewer in the Carolina

Shores community, so we examined relationships among fecal coliform concentrations and the hypothesized drivers separately for ML potentially affected by septic tanks and those potentially affected by central sewer using multiple regression analysis. Multiple regression of fecal coliform concentrations (LFecal) against rainfall (L24HR and L3DR) and silicate (LSi) for the 7 ML associated with central sewer (ML#3, 4, 5, 6, 7, 32, and 38; Fig. 1) was significant ($F=13.65$, $df=3,188$, $p<0.0001$) and identified same-day rain, cumulative 3-day rain and silicate as all having significant ($p<0.05$) and positive effects on fecal coliform concentrations: LFecal = 1.20 + 1.20L24HR + 0.79L3DR + 0.31LSi. A similar multiple regression for the 35 ML in areas served by septic tanks was also significant ($F=49.75$, $df=3,1334$, $p<0.0001$) with all three independent parameters having significant ($p<0.05$) and positive effects on fecal coliform concentrations: LFecal = 1.17 + 1.06L24HR + 0.37L3DR+ 0.28LSi. When the effects of rainfall and silicate on fecal coliform concentrations were analyzed for each individual ML, 6 ML (ML#2, 8, 9, 12, 21, and 22) exhibited significant ($p<0.05$) effects of same-day rain, 2 ML (ML#6 and 19) exhibited significant effects of 3-day rain, and 10 ML (ML#3, 8, 15, 16, 17, 22, 26, 32, 35, and 38) exhibited significant and positive effects of silicate.

These observations that rainfall measures and silicate all had statistically positive effects on fecal coliform concentrations prompted further examination of the relationships between silicate and rainfall parameters. When ML were grouped as those served by central sewer or by septic tanks, there was no significant effect of same day or 3-day cumulative rain on silicate levels for the septic tank group, but there were significant negative effects of same-day rain and 3-day rain on silicate for the sewer group ($F=8.49$, $df=1, 229$, $p=0.0039$; ($F=6.69$, $df=1,232$, $p=0.0103$, respectively), indicating dilution of silicate-enriched groundwater by silicate-depleted rainwater. Thus, when rainfall or silicate had significant effects on fecal coliform concentrations, those effects were positive, but the only significant effects of rainfall on silicate were negative, and only in areas served by central sewer. Rainfall did not significantly dilute silicate concentrations at ML in areas served by septic tanks, an effect we interpreted as enhanced pumping of silicate-enriched groundwater by rainwater infiltration. All of the 201 Area was served by well water, which is highly enriched in silicate by dissolution of silicate minerals into groundwater. Thus, increasing rainfall or silicate caused higher fecal coliform concentrations, but did so in distinct ways, with the presence of septic systems apparently driving a positive relationship between silicate and fecal coliform levels, and masking the expected inverse relationship between rainfall and silicate levels.

Causes of frequent fecal contamination for ML group Stream/SE arising from the Carolina Shores WWTP were investigated by examining the facility's DMRs. Two causes of fecal contamination were hypothesized: 1) high fecal coliform concentrations in treated effluent, indicating treatment failure, and 2) sanitary system overflows (SSOs) upstream of the facility's final chlorination system. Fecal coliform values reported in 27 monthly DMRs between Jan., 1996 and March, 1999 (after which the system was expanded to collect and treat waste from a large development) ranged from 0.5 to 372 and averaged 38.5 CFU $(100\ ml)^{-1}$. These results appeared to rule out treatment system failure as a routine source of fecal contamination downstream, but an unannounced inspection by NC DENR personnel in Sept., 1997 reported fecal coliform counts in plant effluent at 18,000 CFU $(100\ ml)^{-1}$, suggesting either poor quality control or questionable reporting practices. Subsequent investigation revealed that inadequate chlorination could occur when influent volumes rose during rainy weather, causing poor control of fecal bacteria in effluents (R. Shiver, NC DENR, pers. comm.). This also suggested that excessive inflow and infiltration (I&I) from leaks in the gravity-fed sewage collection system could be a factor. Multiple regression of daily influent flow (millions of gallons per day, mgd) reported in 27 monthly DMRs against rainfall reported for the same day (24HR) and integrated over 3- (3DR), 7- (7DR), 14- (14DR), and 30- (30DR) day periods as well as daily temperature (from DMRs) yielded the following relationships (only parameters significant at $p<0.05$ shown): Flow (mgd) = 0.140 +0.0025(3DR) + 0.0018(7DR) + 0.0021(30DR) – 0.0023(Temp). The overall regression was highly significant: F= 84.9, df= 6,632, $p<0.0001$, $R^2_{Adj} = 0.44$. Same day rain (24HR) was not significant in this analysis. Thus, cumulative effects of rainfall, but not immediate effects, drove significantly higher flows through the collection system ("infiltration"), as did lower temperatures, which we interpreted as a temperature-driven, seasonal evapotranspiration effect by vegetation on groundwater levels. This pattern of higher infiltration during rainy, cooler periods could have driven 1) more frequent treatment system failures when chlorination rates were inadequate to handle higher flows and/or 2) more frequent SSOs from the collection system. Thus, rain may have driven fecal contamination indirectly and with a time lag for the ML associated with this sewer system.

4. DISCUSSION

Fecal contamination of surface waters is one of the most troubling aspects of water quality, as it is the principal cause of closures for human uses (shellfishing and bathing) in almost all coastal settings (NOAA, 1998; Dorfman and Rosselot, 2011). Fecal contamination of surface waters in the SBWSA 201 Area was widespread and had three dominant features: frequent central sewer system failures, complemented by a broad storm water runoff signal, and confounded by inputs of contaminated groundwater indicated by the positive relationship between silicate (groundwater discharge) and fecal coliform concentrations.

A previous study explored the role of poorly performing septic systems in the estuarine watersheds of the SBWSA 201 area (Cahoon et al., 2006), showing that high areal densities of septic systems (up to 8 systems per acre, or almost 20 per hectare), unsuitable soils (Barnhill, 1986), high littoral zone elevation gradients, and facilitated drainage all likely contributed to widespread fecal contamination of estuarine waters independent of direct storm water runoff effects. This broad failure of septic systems to prevent off-site fecal contamination is a common feature of coastal regions, unfortunately, as extensive literature now shows (Moe et al., 1985; Cogger, 1988; Lapointe et al., 1990; White et al., 2000; Lipp et al., 2001; Reay, 2004; Cahoon et al., 2006; Del Rosario et al., 2013; Mallin, 2013). U.S. E.P.A. has recommended that septic densities should not exceed 1 per 16 acres, or about 1 per ~6.5 hectares to avoid groundwater contamination (Yates, 1985). Continued pressure from increasing coastal development to install additional septic systems under conditions likely to cause significant off-site groundwater contamination must consequently be viewed as a serious potential threat to surface water quality when any combination of these conditions occurs. The data and analyses presented here confirmed the problem, but demonstrated that it extended far beyond the issue of ‘failing’ septic systems that could be identified by standard inspections, which look for surface ponding and other overt signs of septic tank failure. Studies elsewhere have demonstrated groundwater contamination by septic tanks (Katz et al., 2011). Our results point strongly to fecal contamination of groundwater by septic tanks as a significant source of fecal contamination to surface waters in this coastal region, independent of and in addition to storm water runoff.

Our results also demonstrated a clear impact of storm water runoff on fecal coliform contamination of surface waters in the SBWSA 201 Planning Area, a result that was not at all surprising. Extensive literature demonstrates such effects in many settings, e.g., Schueler, 1994; Weiskel et al., 1996; Scandura and Sobsey, 1997; Mallin et al., 2000, 2001, 2009; Surbeck et al.,

2010. Our results also show, however, that the impacts of fecal-contaminated groundwater discharges and fecal-contaminated runoff were statistically independent of each other. Moreover, there was no significant correlation between silicate concentrations and either 1-day rainfall or cumulative 3-day rainfall in areas served by septic systems. If silicate-depleted rainwater and silicate-enriched groundwater were completely distinct sources to surface waters, however, one would expect an inverse relationship, i.e., a dilution of silicate in surface waters by rainwater. The lack of such a negative relationship in areas served by septic tanks suggests an additional mechanism of water input: rainfall-enhanced flushing of shallow groundwater. Incoming rain would partially soak into the ground, raising groundwater levels and enhancing discharge of groundwater into surface waters. This additional groundwater flow, which Loucaides et al. (2007) termed “interflow”, would be difficult to distinguish from storm water runoff by conventional flow measurements, but would contain intermediate concentrations of silicate and fecal coliforms. This mechanism further confounds the notion of storm water runoff as an easily characterized source of water contamination: fecal pollution of surface waters during and after rain events may reflect both surface runoff and enhanced discharges of polluted groundwater. In situations like this one, where the widespread use of septic systems has apparently led to widespread groundwater contamination by fecal coliforms, measures to manage storm water runoff alone would be insufficiently protective of surface water quality.

We note that the confounded nature of rainfall-driven surface and sub-surface flows to surface waters makes clear delineation of their relative contributions to surface water contamination by fecal coliforms (or other pollutants) quite problematic. One can estimate groundwater discharge to surface waters when rainfall is not occurring, and can estimate surface runoff during rainfall by methods that are now more or less standard, but estimates of “interflow” contributions are clearly more difficult. We suggest that silicate concentrations, although not completely conservative in natural aquatic ecosystems, may allow at least approximate constraints on the volume of interflow contributions to surface waters.

The alternative to reliance on septic systems under inappropriate circumstances, the installation of central sewage collection and treatment systems, was the primary rationale for the formation of SBWSA, as in many other coastal settings where development pressure has posed challenges to water quality. Unfortunately, performance of the one existing WWTP with a surface discharge in the SBWSA 201 Area, the Carolina Shores WWTP, yielded little confidence that central waste treatment had been sufficiently protective of water quality in this area. The town of Carolina Shores was built in a perched wetland area, with seasonally high groundwater levels, which rationalized use of central sewer in preference to septic tanks (Bicki and Brown, 1990), but potentially exposed the collection system to enhanced risk of I&I. Aside from any aspects of the WWTP operations that may have contributed to the observed loadings of fecal coliform bacteria to receiving waters, the demonstrated vulnerability of the system to excessive I&I and resulting higher risk of poor system performance and SSOs must raise questions about the reliability of central waste treatment systems as a means to protect water quality in low-lying coastal areas. Another study in coastal North Carolina has shown that excessive I&I may be a common feature of central waste treatment systems in low-lying coastal areas (Flood and Cahoon, 2011). Sauer et al. (2011) demonstrated contamination of stormwater runoff by human sewage from leaking sewer systems. Consequently, direct impacts of human waste generation appear difficult to avoid in coastal ecosystems, although the worst may be limited by effective system construction, performance and enforcement.

The coincidence of some failure modes for central sewer systems, such as SSOs driven by excessive I&I, with rain events makes the management challenge even greater. Further evaluations of the incidence of excessive I&I, its response to rainfall, and the effectiveness of mitigation measures are clearly required. Inter-annual variability in rainfall patterns, e.g., Chigbu et al. (2004), can alias the results of shorter-term studies, so that resolution of different source signals might be difficult. Continuing water quality impairment after implementation of storm water regulations may therefore not imply failure of those regulations as much as failure to recognize and control other sources of impairment from on-site and central waste treatment systems, even though regulations current at the time addressed them. Therefore, remediation of impaired water quality requires more effective recognition and management of multiple, confounded sources of impairment from human waste in coastal settings.

5. CONCLUSIONS

Multivariate statistical analyses of monitoring data collected over 7 years demonstrated significant effects of stormwater runoff, central sewage system failures, and percolation of groundwater (using silicate levels as a tracer) contaminated by fecal coliform bacteria into surface waters of a rapidly developing coastal region in North Carolina, USA. These different modes of contamination were confounded by the effects of rainfall on central sewage system performance and on groundwater flushing. Water quality management is therefore a more complex problem than current regulations and waste treatment practices recognize.

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FIGURES

Figure 1. Map showing the SBWSA 201 Planning Area with monitoring locations (ML) denoted as numbers. Dotted lines are major roads, solid lines are streams, slant-lined areas are open waters.

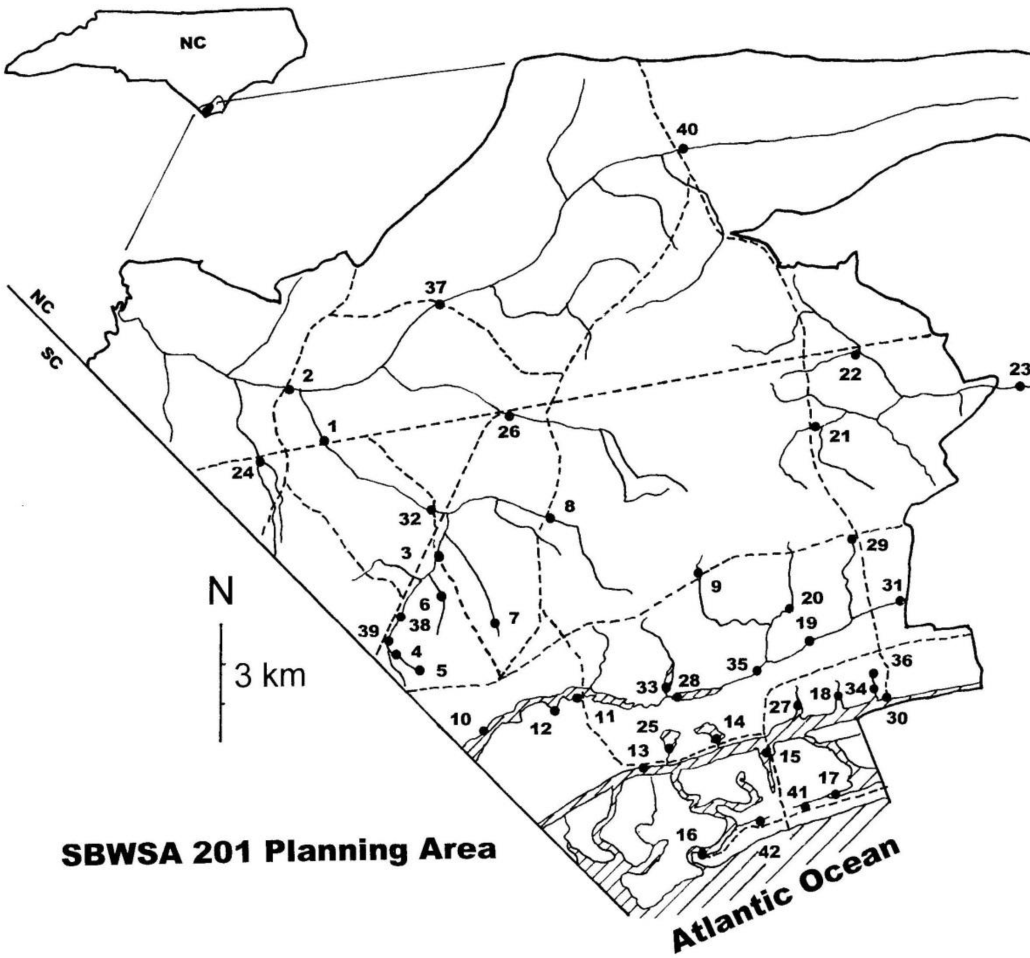

Figure 2. Response of fecal coliform concentrations (LFecal) to same-day rainfall (L24HR) for all sampling times and places. Linear regression was highly significant ($F=120.7$, $df=1, 2066$, $p<0.0001$, $R^2_{Adj}=0.055$); $LFecal = 1.66 + 1.57(L24HR)$.

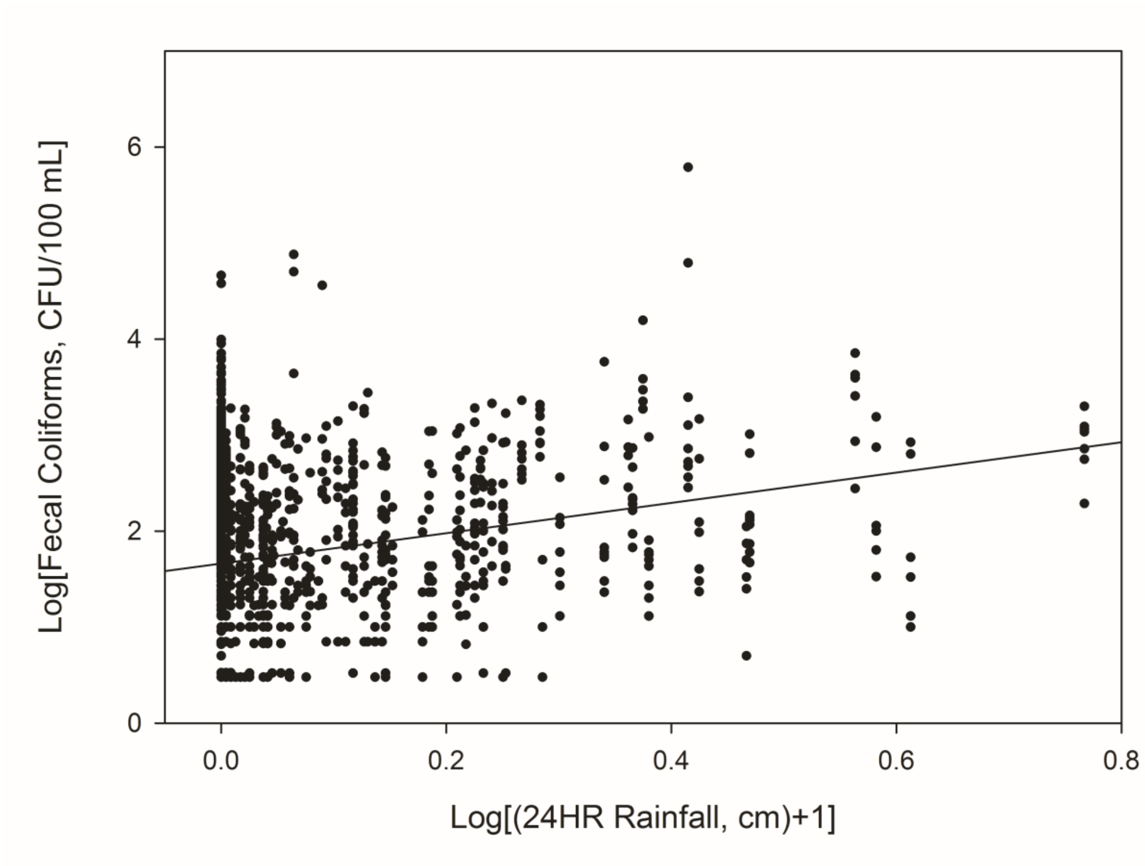

Figure 3. Response of fecal coliform concentrations (LFecal) to 3-day cumulative rainfall (L3DR) for all sampling times and places. Linear regression was highly significant ($F=85.8$, $df=1,2082$, $p<0.0001$, $R^2_{Adj}=0.039$); LFecal = 1.63 + 0.87 (L3DR).

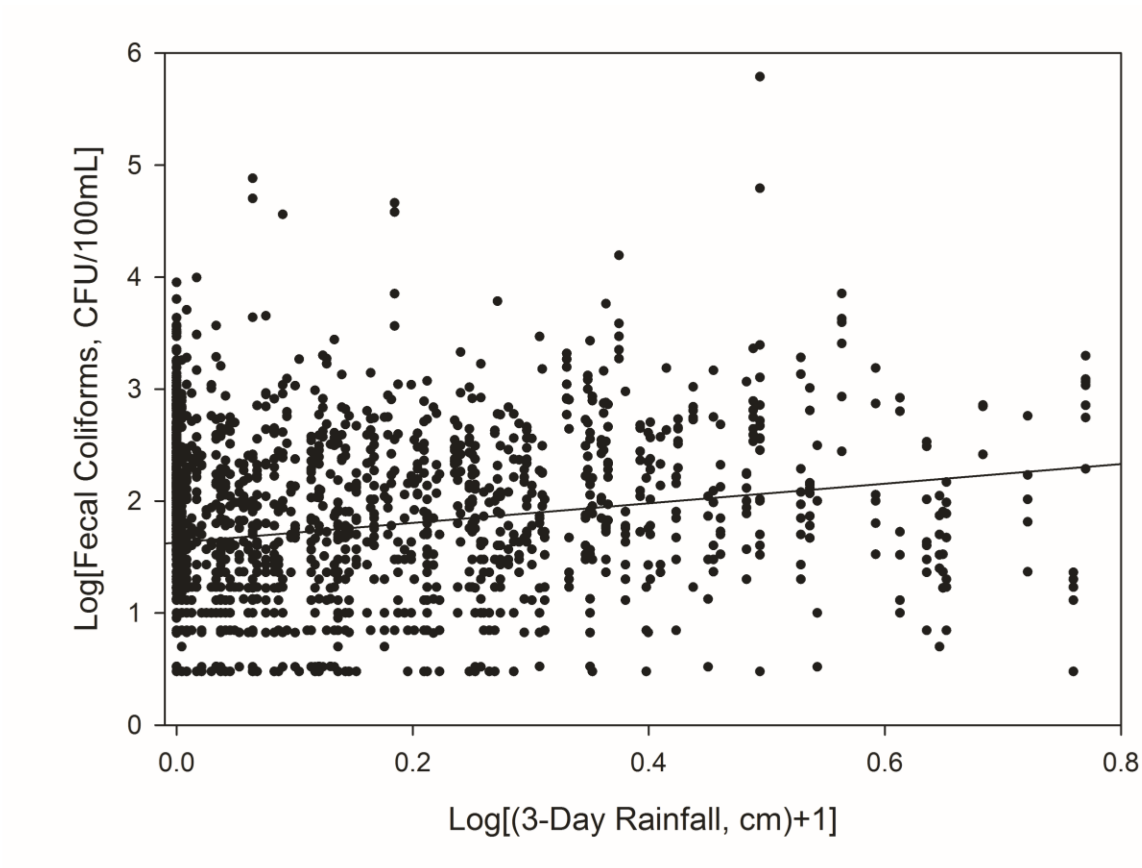

Figure 4. Response of fecal coliform concentrations (LFecal) to silicate concentrations (LSi) for all sampling times and places. Linear regression was highly significant ($F=67.8$, $df=1,1520$, $p<0.0001$, $R^2_{Adj}=0.042$); LFecal = 1.31 + 0.27 (LSi).

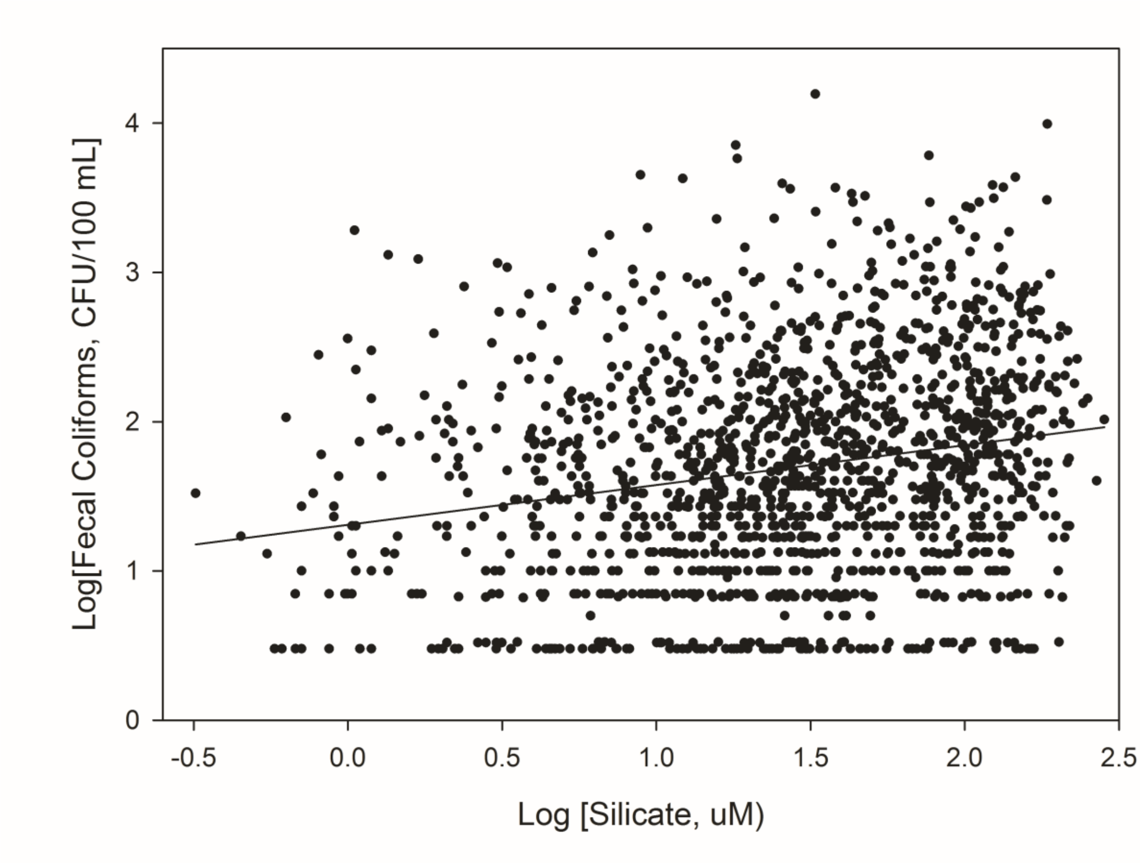

Table 1. Groupings and geometric mean values of water quality parameters of Monitoring Locations (ML) in the SBWSA 201 Planning Area, 1996-2003. Letters below values denote Tukey's HSD *post hoc* groupings for comparisons of each parameter among ML groupings by 1-way ANOVA. N = number of samples taken for each ML grouping. All statistical comparisons used $Log_{10}[X]$ values for Chla, Fecal, Turb, TSS, TP, TN, and Si and $Log_{10}[X+1]$ for Sal, 24HR and 3DR.

Group	Description (ML#)	DO mg/L	%Sat	Chla ug/L	Fecal # /100 mL	Turb NTU	Sal PSU	pH	Temp °C	TSS mg/L	TP ug/L	TN ug/L	Si uM	24HR cm	3DR cm
Pond: N=514	w/o septic (14, 18, 21, 22, 25, 28, 33)	5.09 BC	54.2 B	4.89 B	32.4 D	7.24 C	0.95 C	4.71 CD	19.0 AB	5.75 B	68.2 B	562 B	16.2 C	0.25 A	0.81 A
Pond/SP: N=249	w/septic (12, 27, 34)	4.89 BC	52.1 B	4.07 BC	79.4 AB	7.24 BC	1.69 B	4.87 BC	18.9 AB	6.46 B	49.0 B	589 B	28.2 AB	0.30 A	0.89 A
Seawater: N=312	w/o septic (13, 15, 16, 17, 30)	4.84 C	55.3 B	7.24 A	45.7 CD	7.76 BC	5.31 A	6.72 A	19.8 A	18.6 A	47.9 B	427 C	23.4 B	0.25 A	0.81 A
Seawater/SP: N=195	w/ septic (10, 11, 41, 42)	5.16 BC	55.1 B	5.01 B	38.9 CD	8.51 BC	1.63 B	6.78 AB	19.7 AB	14.1 A	58.9 B	759 B	29.5 AB	0.25 A	0.89 A
Stream: N=818	w/o sewer or septic (1, 2, 6, 7, 8, 9, 19, 20, 24, 26, 35, 37, 39, 40)	5.34 B	54.5 B	3.55 C	54.9 BC	11.5 A	0.32 D	4.58 E	18.1 B	6.45 B	60.3 B	617 B	29.5 AB	0.30 A	0.74 A
Stream/SP: N=70	w/ septic (31)	5.45 ABC	54.5 AB	2.69 BC	107 A	14.1 A	0.12 D	5.54 DE	17.6 AB	5.75 B	74.1 B	813 AB	47.9 A	0.25 A	0.81 A
Stream/SE: N=277	w/ sewer (3, 4, 5, 32, 38)	6.06 A	63.4 A	3.72 C	126 A	9.12 B	1.14 BC	6.06 BC	18.0 B	6.03 B	204 A	1230 A	26.3 B	0.38 A	0.81 A
Overall N=2435	(All)	5.25	55.3	4.36	54.9	9.12	1.09	4.84	18.7	7.58	66.1	631	25.1	0.30	0.81

Table 2. Results of Principal Components Analysis of SBWSA 201 Area monitoring data; Results for principal components with eigenvalues > 1.0. Eigenvector loadings with absolute values > 0.3 for each Principle Component are in bold.

Prin. Comp.:	1	2	3	4	5
Eigenvalues:	2.60	2.10	1.99	1.71	1.32
Parameter	Eigenvectors				
LSal	0.232	**0.461**	0.094	-0.023	0.023
pH	0.136	**0.370**	0.123	-0.183	**0.505**
DO	**-0.517**	**0.336**	0.078	0.025	0.031
LTurb	0.128	0.121	**0.424**	0.082	**-0.489**
LChla	**0.370**	0.128	0.032	0.040	0.223
LTSS	0.283	**0.371**	**0.355**	0.012	-0.289
LTP	-0.119	-0.167	**0.357**	**-0.329**	**0.369**
LTN	-0.094	-0.264	**0.412**	-0.287	0.143
LFecal	-0.103	-0.194	**0.327**	0.210	-0.050
Temp	**0.457**	-0.134	0.073	-0.085	0.215
L24HR	-0.002	-0.085	0.232	**0.570**	0.246
LSilicate	-0.078	-0.190	**0.382**	-0.239	-0.189
%Sat	**-0.422**	**0.407**	0.119	-0.001	0.127
L3DR	-0.013	-0.083	0.200	**0.577**	0.230

Table 3. Results of Principal Components Analysis of monitoring data from SBWSA 201 Area, transformed as in Table 1: significant ($p<0.05$) pairwise positive and negative correlations between Fecal Coliforms (LFec) and other parameters.

Dependent Variable	Independent Variable	Correlation
Fecal Coliforms (LFec)	Salinity (LSal)	-0.197
	Turbidity (LTurb)	+0.169
	Total Phosphate (LTP)	+0.135
	Total Nitrogen	+0.143
	24-hour Rainfall (L24HR)	+0.235
	Silicate (LSi)	+0.207
	3-Day Rainfall (L3DR)	+0.199