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Impacts of Tropical Cyclone Isabel on Shallow Water Quality of the York River Estuary

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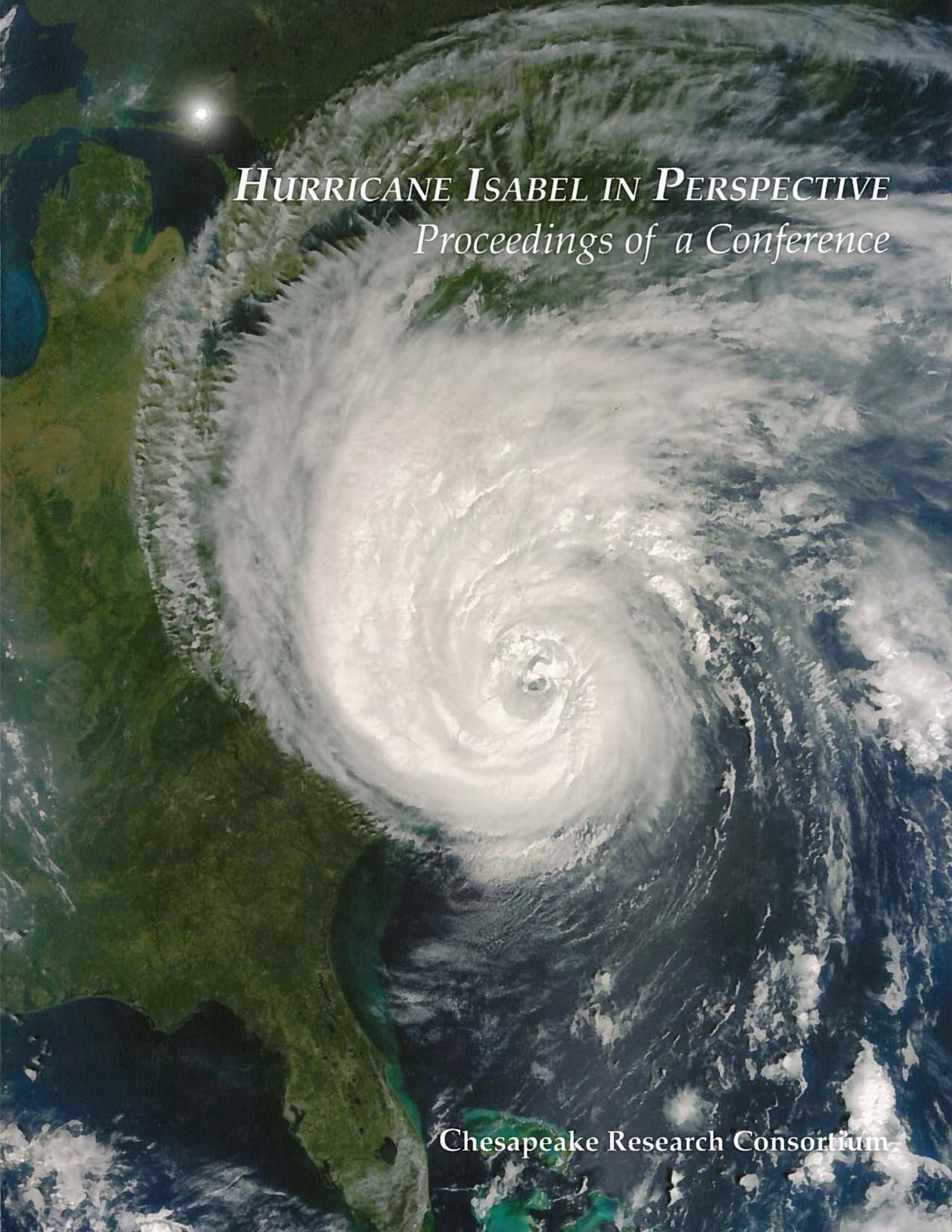
HURRICANE ISABEL IN PERSPECTIVE

Proceedings of a Conference



Chesapeake Research Consortium

Hurricane Isabel in Perspective

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Proceedings of a Conference

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IMPACTS OF TROPICAL CYCLONE ISABEL ON SHALLOW WATER QUALITY OF THE YORK RIVER ESTUARY

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ABSTRACT

Water quality impacts from Tropical Cyclone Isabel on the York River estuary were assessed based on long-term, near-continuous, shallow-water monitoring stations along the York River proper (poly- and mesohaline regimes) and its two tidal tributaries—the Mattaponi and Pamunkey rivers (oligohaline and tidal freshwater regimes). Regional rainfall from 18 to 19 September 2003 ranged from 5.8 to 11.7 cm. Peak mean daily stream flow occurred on 21 September 2003 and represented a 20- and 30-fold increase over pre-storm conditions on the Mattaponi and Pamunkey rivers, respectively. Isabel produced a storm surge of 1.7 m near the mouth of the estuary and 2.0 m in the upper tidal freshwater regions. The tidal surge resulted in a short-term (12- to 36-hour) pulse of high salinity water (approximately 10 ppt greater than pre-storm conditions) within the oligohaline portion of the estuary. In comparison, salinity levels within the upper tidal fresh water and down-river poly-and mesohaline regions remained relatively unchanged. Following the storm surge, salinity levels within lower portions of the estuary declined 1.5 to 4.5 ppt for an extended period in response to freshwater runoff. Elevated turbidity—in some cases extreme—was in direct response to the storm surge and waves associated with Tropical Cyclone Isabel. With the exception of a single station, maximum storm-associated turbidity levels varied between 192 and >1000 NTUs (nephelometric turbidity units). Turbidity levels returned to pre-storm conditions within a 24- to 30-hour period at most stations. Perhaps the most significant environmental impact associated with the passage of Isabel was the persistent low dissolved oxygen (DO) levels (3–4 $mg{\cdot}L^{-1}$) that occurred at the tidal freshwater stations. Low DO at these stations coincided with increased freshwater inflow to the Mattaponi and Pamunkey rivers, suggesting augmented loadings of readily degradable organic material from the watershed. Mean daily DO levels took approximately two weeks to return to pre-storm levels at these sites. Dissolved oxygen levels at the poly- and mesohaline stations within the York River proper remained at or above 5 $mg{\cdot}L^{-1}$ prior to, during, and after the storm's passage.

INTRODUCTION

Large-scale tropical cyclones, such as tropical storms and hurricanes, can generate both short- and long-term disturbances in estuarine systems. These disturbances occur in response to the high winds, storm surges, and rainfall generally associated with such storms. Isabel brought hurricane conditions to portions of eastern North Carolina and southeast Virginia and is considered to be one of the most significant storms to have affected the Chesapeake Bay region. It has been compared to the Category 3 Chesapeake-Potomac Hurricane of 23 August 1933, described as the storm of the century for Chesapeake Bay. Effects caused by large storm surges and surface waves include extensive flooding of low-lying areas, shoreline erosion, sediment resuspension and associated pollutant availability, vertical water column mixing, and increased upstream salinities [1]. The consequences of excessive rainfall include elevated freshwater input and associated downstream salinity depression [2, 3], along with elevated sediment [1], carbon

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[3, 4, 5], and nutrient [4, 5] loadings from stormwater runoff. Just as each storm has distinct characteristics and hydrologic responses by the impacted watershed and water body, the types and severity of biological responses can also vary. Reported observations have included elevated phytoplankton biomass and changes in community composition stimulated by newly available nutrients [2], depressed oxygen levels and severe hypoxic events [2, 4, 5, 6], and damage to submersed aquatic vegetation [7, 8], wetlands, and coastal upland forest communities [9].

On 18 September 2003, at approximately 01:00 PM (EDT), Hurricane Isabel made landfall near Drum Inlet, North Carolina, approximately 240 km south of the entrance to Chesapeake Bay. Upon landfall, Hurricane Isabel was a Category 2 storm with hurricane force winds extending 185 km from the storm's center and tropical-storm-force winds extending out to 555 km [10]. Rainfall was on the order of 10 to 20 cm. Following landfall, Isabel tracked northwest at a speed of near 30 $km \cdot hr^{-1}$ and began to rapidly weaken. Hurricane Isabel was downgraded to a tropical storm over southern Virginia; at 23:00 (EDT) the storm's center was just west of Richmond, Virginia. Given Isabel's track, the Chesapeake Bay was predominantly impacted by the northeast quadrant of the storm, a region characterized by the maximum effects of wind, surge, and rain.

The main objective of this paper is to describe the temporal and spatial patterns of water quality within the nearshore, shallow water regions of the York River estuary in response to Tropical Cyclone Isabel. Near-continuous data collected prior to, during, and after the passage of the storm are used to assess the response.

STUDY SITE AND METHODS

This study was conducted in the York River estuary, the Chesapeake Bay's fifth-largest tributary in terms of flow and watershed area (6900 km^2). The York River basin is located within Virginia's Coastal Plain and Piedmont physiographic provinces, and includes all of the land draining into the Mattaponi, Pamunkey, and York rivers (Figure 1). Tidal influence occurs as far as 97 km upriver on the Mattaponi and as far as 60 km upriver on the Pamunkey. Mean tidal range near the mouth of the York River is 0.7 m and increases to 0.9 and 1.2 m in the upper tidal freshwater regions of the Mattaponi and Pamunkey rivers, respectively [11]. The York River basin is predominantly rural with forest cover accounting for 61% of the basin's cover, agricultural land for 19%, urban land for 4%, mixed-open land for 14%, and water for the remaining 2%.

The York River estuary continuous water quality monitoring network is operated by the Chesapeake Bay National Estuarine Research Reserve (CBNERR) and supports the NOAA/NERR System-Wide Monitoring Program and Chesapeake Bay Shallow Water Monitoring Program. A total of nine fixed water quality stations are located within the polyhaline (GI, GP, and YT), mesohaline (CB and TC), oligohaline (MP and SH), and tidal freshwater (WH and WK) regions of the system (Figure 1). All stations except TC are located along the tributary proper or in a more open water setting (GI). The TC station is located in a tidal creek immediately adjacent to the York River; forests and tidal wetlands dominate the creek's watershed. Two stations, GI and YT, were damaged and inoperable during portions of the study. All stations were located within shallow water or shoal regions where mean water depths were about 2 m or less. Water quality stations were instrumented with YSI 6600 EDS data sondes that collect information from 25 to 50 cm off the bottom substrate on water depth, temperature, specific conductance, percent dissolved oxygen (DO) saturation, and turbidity. Salinity and DO concentrations are calculated parameters. Water depths were corrected for atmospheric pressure changes during the deployment period. Water quality stations were maintained on either a one- or two-week schedule, depending on salinity regime and season, to minimize biofilm effects.

Daily precipitation and wind speed information was obtained from meteorologic stations maintained by NOAA's National Weather

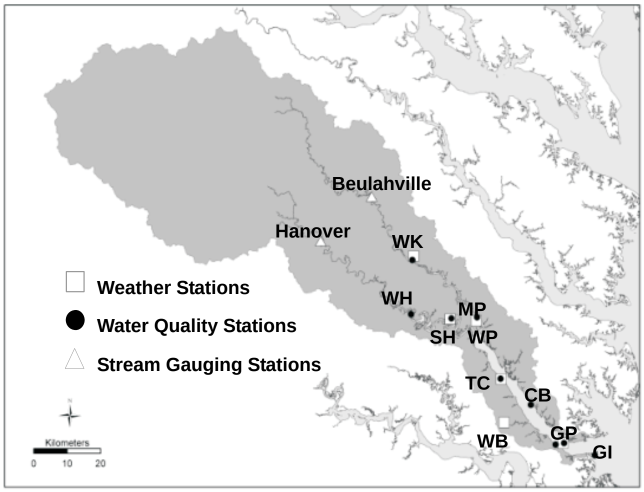

Figure 1. Location map of environmental data collection stations. Continuous water quality stations include: Goodwin Islands (GI), Gloucester Point (GP), and Yorktown (YT) in the polyhaline region; Clay Bank (CB) and Taskinas Creek (TC) in the mesohaline region; Sweet Hall (SH) and Muddy Point (MP) in the oligohaline region; and White House (WH) and Walkerton (WK) in the tidal freshwater region. Meteorologic stations include Gloucester Point (GP), Williamsburg (WB), Taskinas Creek NERR (TC), West Point (WP), Sweet Hall Marsh NERR (SH), and Walkerton (WK). Stream gauging stations were near Hanover and Beulahville, Virginia.

Service (NOAA/NWS; stations: WK, WP and WB), the CBNERR (stations: SH and TC), and the Virginia Institute of Marine Science (VIMS; station: GP) (Figure 1). River stage and calculated stream flow was measured continuously within the Pamunkey and Mattaponi rivers at the U.S. Geological Survey (USGS) gauging stations near Hanover (Station ID: 01673000) and Beulahville (Station ID: 01674500), Virginia, respectively. The Hanover station integrates discharge from 45% of the York River basin as compared to 25% for the Beulahville station.

RESULTS

Physical Conditions, Rainfall and River Flow

A minimum atmospheric barometric pressure of 990 mb was measured along the York River proper (TC) during the passage of Isabel. At Gloucester Point, near the mouth of the York River, strong winds (>20 $m\cdot sec^{-1}$) persisted for over six hours; maximum measured wind speed was 31.9 $m\cdot sec^{-1}$. Total rainfall amounts during Isabel's passage on 18 to 19 September 2003 ranged from 5.8 to 11.7 cm within the York River watershed (Figure 2). Peak mean daily stream flow occurred on 21 September 2003 and represented an approximate 20- to 30-fold increase over pre-storm (early September) conditions on the Pamunkey (317.1 vs. 10.5 $m^3\cdot sec^{-1}$) and Mattaponi (57.5 vs. 3.4 $m^3\cdot sec^{-1}$) rivers. River discharge exhibited a complex hydrograph thought to result from rainfall associated with post-Isabel storm activity. Figure 3 presents Pamunkey and Mattaponi river mean daily streamflow for water year (WY) 2002 (October 2001 to September 2002), WY 2003, and succeeding months. Results from an acoustic Doppler current profiler showed maximum wave heights of 2 meters and an up-estuary current of 1 $m\cdot sec^{-1}$ [12]. Isabel produced a storm surge, as determined by the difference between storm water levels and predicted tide levels, of 1.7 m near the mouth of the estuary (GP) and 2.0 m in the upper tidal freshwater regions (WH). Water levels remained elevated for the succeeding tide after the storm's passage and returned to near normal

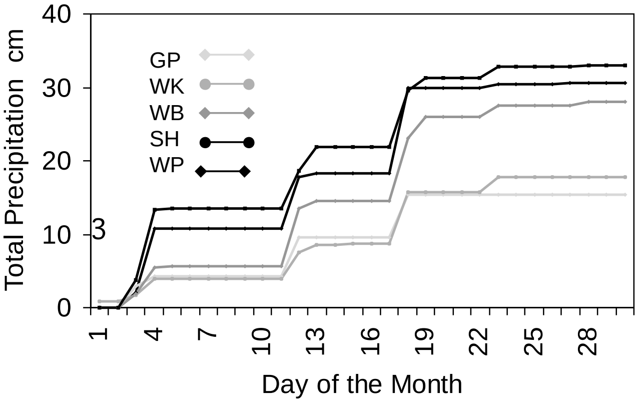

Figure 2. Cumulative total precipitation (cm) within the York River watershed for September 2003. Meteorologic stations include Gloucester Point (GP), Williamsburg (WB), West Point (WP), Sweet Hall Marsh NERR (SH), and Walkerton (WK). Average regional long-term September total precipitation, based on historical data from WK (1932 to 2004), WP (1954 to 2004) and WB (1941 to 2004), is 10.4 cm (denoted by 3).

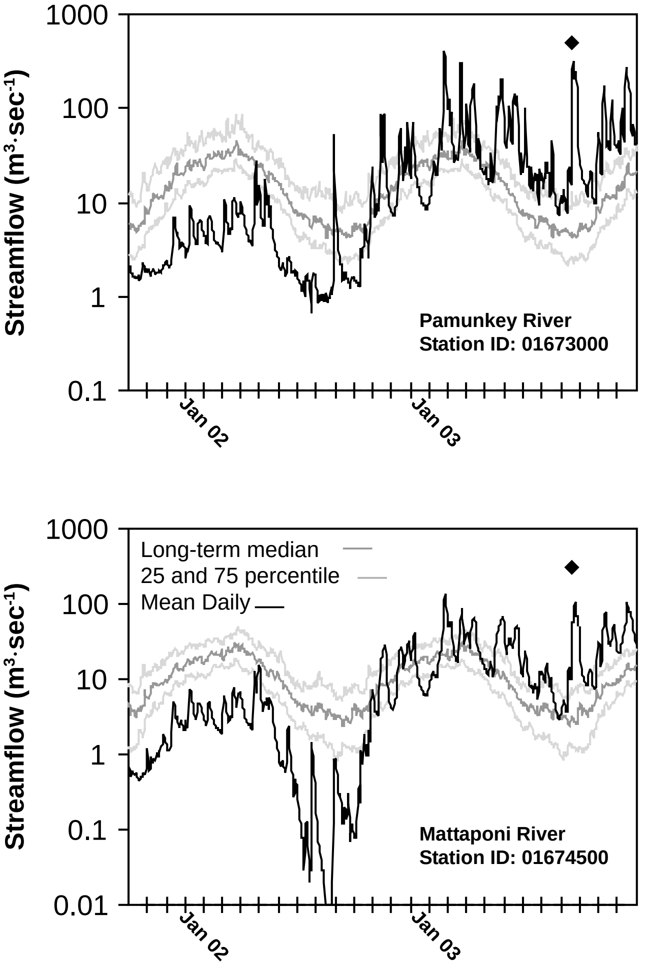

Figure 3. Pamunkey and Mattaponi rivers mean daily streamflow for WY 2002 (October 2001 to September 2002), WY 2003, and succeeding months. The 25th and 75th percentile values represent the normal range of streamflow over the record at USGS stations 01673000 and 01674500. The symbol (♦) represents 18 September 2003, the passage of Isabel.

conditions approximately 30 hours after peak storm tide levels (Figure 4).

Salinity, Turbidity and Dissolved Oxygen

In conjunction with water levels, salinity values within the shallow waters of the York River estuary from 14–22 September 2003 are presented in Figure 4. Little change in salinity was observed at the polyhaline (GI and GP) and mesohaline (CB and TC) stations during the storm tide. In contrast, significant increases in salinity were observed at the oligohaline stations (MP and SH). Peak salinity values were 15.0 ppt at MP and 11.7 ppt at SH,

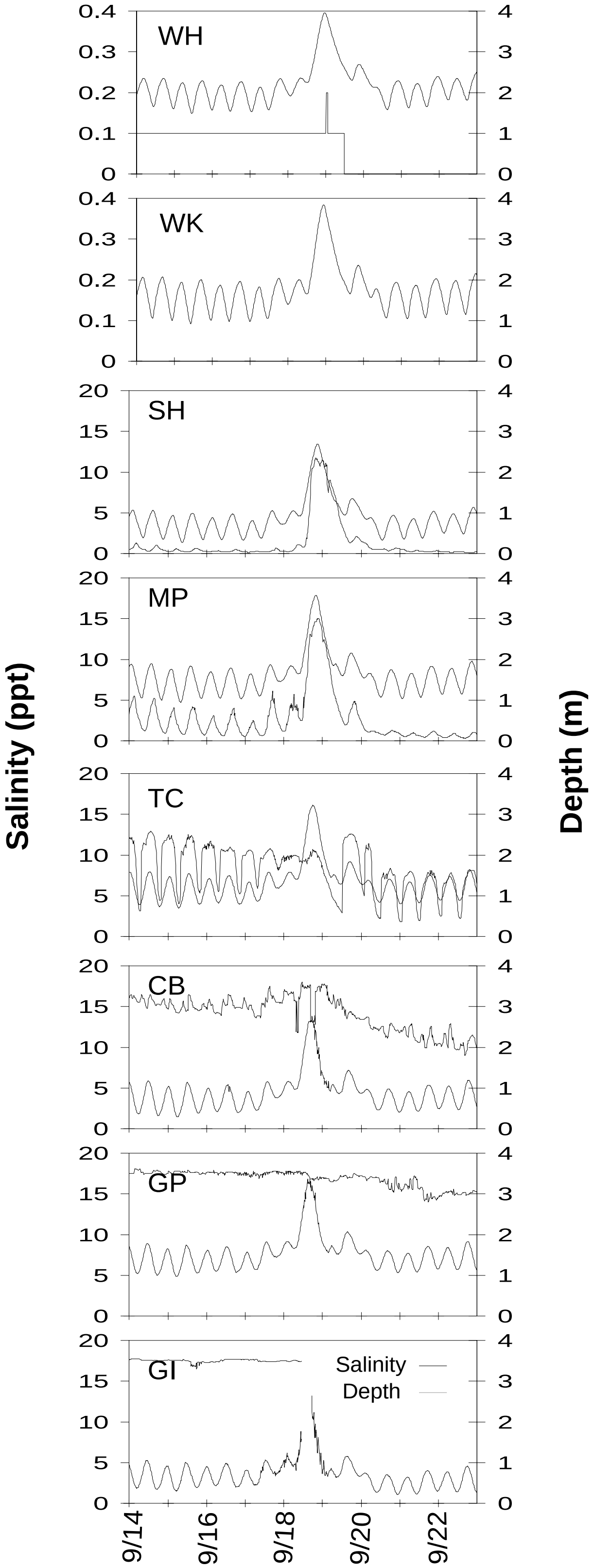

Figure 4. Water and salinity levels within the York River estuary from 14–22 September 2003. Note: Salinity values for WK were 0.0 ppt throughout the measurement period.

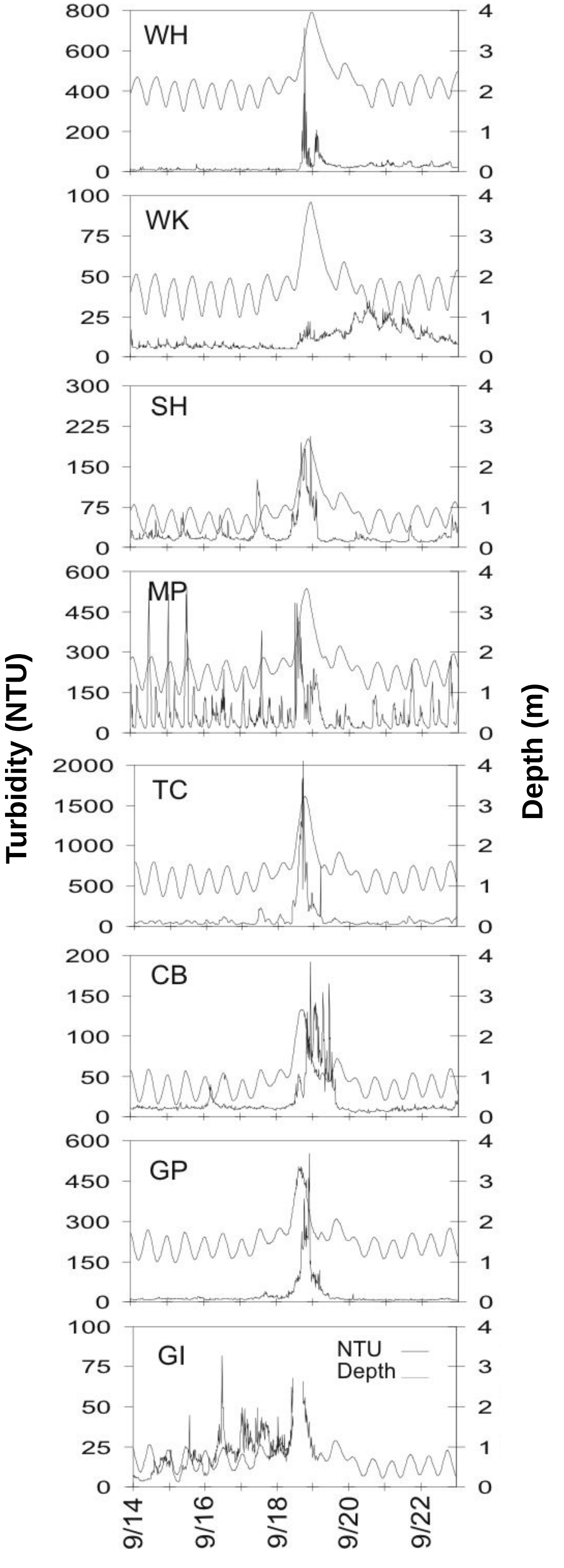

Figure 5. Water and turbidity levels within the York River estuary from 14–22 September 2003.

coinciding with peak storm tide water levels. Pre-storm salinities were 0.8 to 5.7 ppt at MP and <0.5 ppt at SH. The tidal freshwater stations (WH and WK) remained fresh throughout the passage of Isabel. Following the storm surge, freshwater runoff depressed salinities 1.5 to 4.5 ppt in the lower portions of the York River estuary.

Elevated water turbidity, in some cases extreme, occurred in direct response to Tropical Cyclone Isabel. With the exception of station WK, maximum storm surge-associated turbidity levels varied between 192 and >1000 NTUs (Figure 5). Mean daily pre-storm turbidity levels were approximately 10–15 NTUs at the tidal freshwater (WH, WK), polyhaline (GP, GI), CB and SH stations; they ranged from 50–100 NTUs at the TC and MP stations. Timing and patterns of water turbidity peaks varied between stations. Peak turbidity values occurred prior to peak storm water levels at WH, MP, and TC, and following peak storm water levels at SH, CB, and GP. Distinct twin turbidity peaks, occurring on either side of slack high water during the storm surge, were observed at the WH, MP, and SH stations. Turbidity levels at the oligohaline (MP and SH), mesohaline (CB and TC), and polyhaline (GI and GP) stations returned to pre-storm conditions within 24 to 30 hours. The tidal freshwater stations (WH and WK) exhibited moderately elevated turbidity levels (>20 NTUs) for several days following the storm's passage, a time that coincided with increased streamflow.

Figure 6 depicts DO levels from 14–22 September 2003. Prior to Isabel's arrival, DO levels were 60–80% of saturated levels at the tidal freshwater and oligohaline stations and 80–100% of saturation levels at the mesohaline and polyhaline stations. Tidal freshwater regions exhibited a rather dramatic decline in DO immediately following the peak storm tide.

Instantaneous low DO levels, as measured by 15-minute data for stations WH and WK were 2.33 and 3.57 mg·L^{-1}, respectively. From peak storm tide until recovery of pre-storm conditions—a time period of 16 to 20 days—70% of readings were below 5 mg·L^{-1} at WH as were 43% of the readings

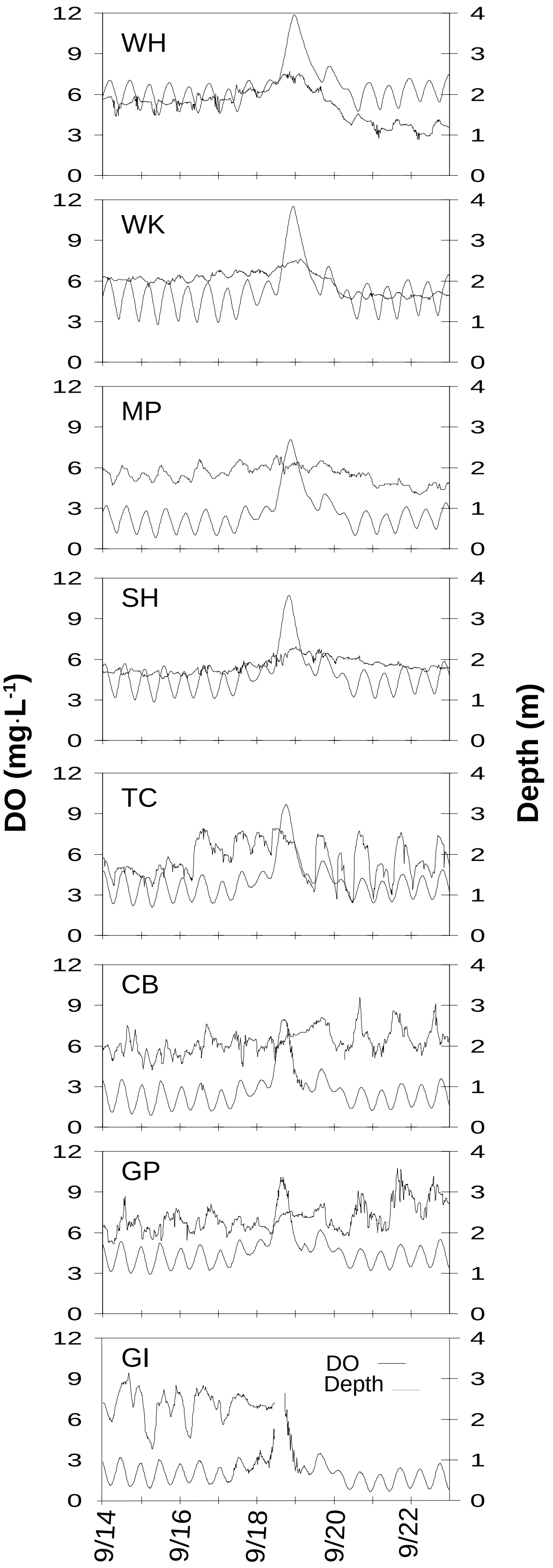

Figure 6. Water and dissolved oxygen levels in the York River estuary from 14 to 22 September 2003.

at WK. Oligohaline stations SH and MP exhibited a similar, but less pronounced pattern. Dissolved oxygen levels at the polyhaline and mesohaline stations within York River proper (GI, GP, and CB) remained above 5 mg·L^{-1} prior to, during, and after the storm's passage.

DISCUSSION

To more fully understand the consequences and potential implications of Tropical Cyclone Isabel on the Chesapeake Bay, and more specifically the York River estuary, it is necessary to describe conditions prior to the storm's arrival. Compared to long-term averages, the 2003 water year (WY) (October 2002 to September 2003) was relatively wet and followed an unusually dry water year. Total precipitation in WY 2003 was approximately 60% greater than the long-term average and 145% greater than WY 2002. Table 1 provides long-term averages for total precipitation and streamflow along with comparisons between WY 2002 and WY 2003. As expected, streamflow in the Pamunkey and the Mattaponi rivers, the principal tributaries of the York River estuary, reflected total precipitation within the watershed. Mean daily stream flows in WY 2003 were 35% and 65% greater in the Pamunkey and Mattaponi rivers, respectively, compared to the long-term average. These WY 2003 values were approximately an order of magnitude greater than those for WY 2002. Due to the wet conditions of 2003, salinity levels throughout the York River estuary were generally depressed compared to prior years. In the Chesapeake Bay system, freshwater inflow during the 2003 WY was 56% above the average, the second highest level since record keeping began in 1937. High freshwater inputs in the WY prior to Isabel caused increased loadings of nutrients and sediments and near-record low DO levels within the Bay [13].

Significant rainfall occurred throughout the York River watershed immediately prior to, during, and (in more isolated portions of the watershed) following the passage of Isabel. Rainfall associated with Isabel ranged from 5.8 to 11.7 cm. For

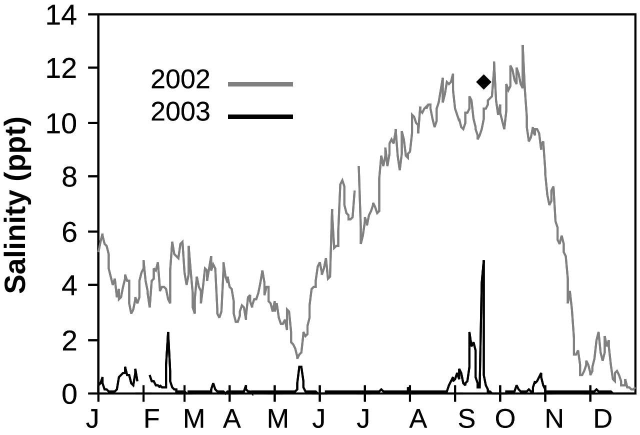

Figure 7. Daily mean salinity values at Sweet Hall Marsh (Station: SH) for CY 2002 and 2003. The symbol (♦) represents the maximum instantaneous salinity value observed during Isabel.

comparative purposes, rainfall amounts of previous tropical cyclones that affected the Bay region were 6.8 to 11.3 cm for Agnes (21–23 June 1972), 0.4 to 6.6 cm for Fran (5–8 September 1996), and 21.7 to 43.1 cm for Floyd (14–16 September 1999). While not excessive, the rainfall immediately prior to, during, and after Isabel did elevate freshwater inflow for several days following the storm's passage. Although daily discharge rates increased approximately 20- (Mattaponi River) to 30-fold (Pamunkey River) over pre-storm conditions, they did not represent the peak mean daily values of the 2003 WY.

The storm surge from Tropical Cyclone Isabel was significant; in some cases, its magnitude was unexpected within some portions of the Chesapeake Bay. Surge values of 1.7 m were observed at the mouth of the York River estuary and increased up to 2.0 m in the upper tidal freshwater regions. When combined with waves up to 2.0 m in height along with persistent high winds and upriver current velocities, the York River estuary experienced extensive shoreline erosion, sediment resuspension, and water and salt transport up the river. The tidal surge significantly increased salinity by about 10 ppt, within the oligohaline portion approximately 70 km upriver from the mouth of the York. In comparison, salinity in downriver poly- and mesohaline regions and upper tidal freshwater regions remained relatively unchanged. The pulse of high salinity water within the oligohaline reaches was short-lived with pre-storm levels restored within 12 (MP) to 36 (SH) hours. Following the storm surge, the effects of freshwater runoff were evident in the lower portions of the York River where salinities remained depressed for an extended period.

Short-term salinity pulses and longer-term seasonal trends in elevated salinity have biological consequences for marsh plant communities. Studies within the York River estuary suggest that plant communities at a lower tidal freshwater/upper oligohaline marsh (SH) are shifting to more salt-tolerant species due to increases in salinity associated with relative sea level rise [14]. More recent work within this marsh indicates that the vegetation community may be more highly variable from year to year, perhaps in response to short-term climatic effects.

To put Isabel's induced salinity pulse in perspective, Figure 7 shows the mean daily salinity pattern at Sweet Hall Marsh for CY 2002 and 2003. Isabel's storm tide resulted in peak instantaneous and mean daily salinity levels of 11.7 and 4.9 ppt, respectively, at this site. During the drought of 2002, salinity levels of 5 ppt or greater occurred during 70% of the growing season (April through October) and mean daily levels of 5 ppt or greater persisted from early June through October. Clearly this marsh system has been exposed to salinity levels observed during Isabel for extended periods, however, the exact impact of such exposure on inter-annual plant community variation is unknown and warrants further investigation.

Decreased water clarity, as measured by increased turbidity, was observed within the shallow-water regions of the York River estuary during and after Isabel's passage. Extensive shoreline erosion and sediment resuspension caused by waves and water currents are primary contributing factors that resulted in elevated and, in some cases extreme, turbidity levels during the storm surge. Several stations within the tidal freshwater and oligohaline portions of the estuary exhibited distinct turbidity peaks on either side of the storm's

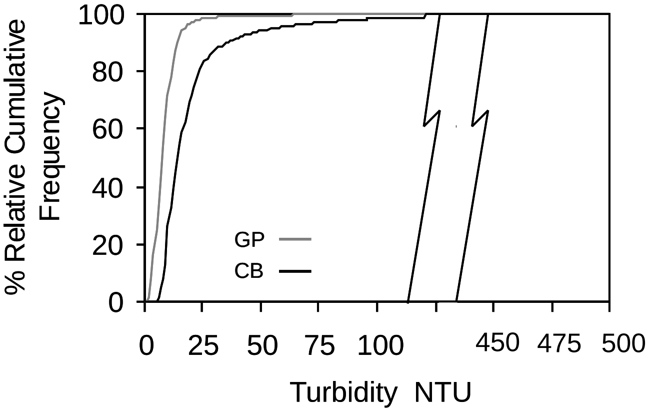

Figure 8. Relative cumulative frequency of turbidity measurements (NTUs) at the GP and CB stations during the 2003 SAV growing season.

peak water level, suggesting reduced sediment resuspension as current velocity decreased near slack high water. The duration of storm-induced, highly turbid water (≥200 NTUs) was relatively short-lived; turbidity levels returned to pre-storm or near pre-storm conditions within 24 to 30 hours at the oligo-, meso-, and polyhaline stations. Subaqueous substrate at several of these stations, particularly those in the York River proper (CB, GP, GI), was dominated by coarse-textured sediments; the rapid settling of such sediments promote quick recovery of water clarity. Moderately elevated turbidity levels persisted for several days following the storm at the tidal freshwater stations (WH and WK). Freshwater inflow, and associated storm runoff from Isabel and post-Isabel events, may have contributed to the turbidity.

Water clarity is a principal water quality criterion by which shallow water habitats, specifically submerged aquatic vegetation (SAV) beds, are assessed. Within the York River estuary, SAV is currently restricted to the lower 10 km (GP and GI); historical distribution of SAV extended approximately 40 km upriver (CB). For higher salinity southern Bay waters, the SAV water clarity criterion is 22% ambient light through water, which translates into turbidity levels of 7 NTUs for 1-m depths and 12 NTUs for .5-m depths. Mean daily average turbidity for the 2003 SAV growing season was 9.7 NTUs at GP (data availability: 28 May to 30 November) and 23.5 NTUs at CB (1 April to 30 October). Based on analysis of relative cumulative frequencies, peak turbidity levels at station GP (460–553 NTUs) during Isabel were representative of the upper 0.1% of turbidity values observed during the 2003 SAV polyhaline growing season (Figure 8). Peak turbidity levels at CB (147–192 NTUs) represented the upper <1% of observed values during the 2003 mesohaline growing season. While storm-induced elevated turbidity levels at both sites occurred with low frequency, levels on the scale of Isabel (both in terms of NTU values and time duration) occurred several times at CB during the 2003 growing season.

Prior to Isabel, DO levels and temporal patterns at the oligohaline and tidal freshwater stations differed from the higher salinity stations in the York River proper. Shallow-water DO levels generally varied from 5–6 mg·L^{-1} (60–80% saturation) at the tidal freshwater and oligohaline stations (WH, WK, SH, MP) and from 5–8 m·L^{-1} (60–100% saturation) at the meso- and polyhaline stations (TC, CB, GP, GI). A gradual increase in DO of 1–2 mg·L^{-1} was observed prior to and during the storm tide at oligohaline and tidal freshwater stations, likely in response to enhanced mixing and agitation from wind, waves, currents, and an influx of higher salinity water at the oligohaline stations. This pattern was not evident at the meso- and polyhaline stations, where daily maximum oxygen concentrations were at or near saturation. As the storm tide ebbed, DO levels returned to pre-storm conditions at the oligohaline stations but continued to recede at the tidal freshwater stations. While hypoxic conditions (<2 mg·L^{-1}) did not occur, relatively long-term recessions resulting in concentrations of 3 (WH) and 4 mg·L^{-1} (WK) were observed at the tidal freshwater stations (Figure 9). It took approximately two weeks for mean daily DO levels to return to pre-storm DO levels at these stations. While not as pronounced or as long in duration, oligohaline stations (SH and MP) exhibited a similar pattern. In contrast, shallow-water DO levels within the higher salinity York River (CB and GP) remained at or above 5 mg·L^{-1} prior to, during, and after the storm's passage. Varying between a low of 2–3 mg· L^{-1} (20–40%

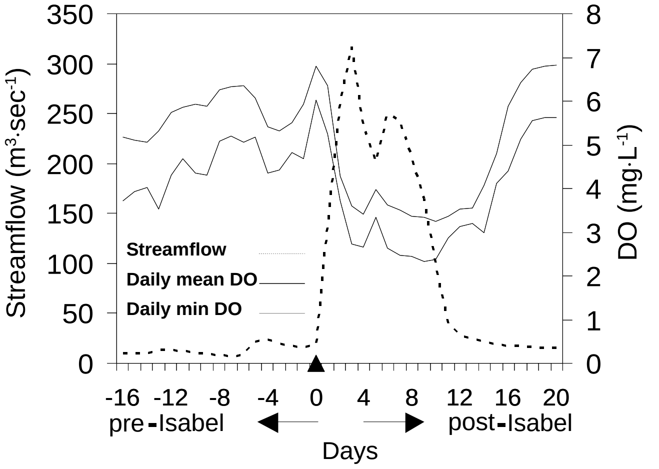

Figure 9. Daily mean and minimum dissolved oxygen concentrations at White House (Station: WH), and mean daily streamflow at Hanover, Virginia prior to, during (day 0 = 18 September 2003), and post-Isabel.

saturation) and a high of 7–8 mg·L^{-1} (100% saturation) on a daily basis, DO dynamics were more complex at the TC station compared to other stations. In addition to diel biological processes, oxygen levels at TC reflected high-salinity and high-DO water inputs at high tide with flushing of low-salinity, low-DO water draining forests and tidal wetlands during low tide.

Several possible explanations may account for the low DO levels at the tidal freshwater (WH and WK) stations following Isabel, including water column stratification from enhanced freshwater inflow, decreased light penetration due to increased turbidity and subsequent reduction in productivity, increased nutrient loading with consequent response by primary producers and decomposers, or increased availability of readily degradable *in situ* or watershed-derived organic material. Since these stations are in shallow, freshwater reaches with moderate tidal currents (0.3–0.8 m·sec^{-1}), stratification of the water column by enhanced freshwater inflow and subsequent oxygen consumption in bottom waters does not seem a satisfactory explanation. Vertical temperature, salinity, and DO profiles taken during instrument deployment and retrieval events support this premise. With respect to stimulation of primary productivity and decomposition by increased nutrient availability, one would anticipate an increase in the amplitude of the diel DO fluctuations. In contrast, a relatively steady decay of oxygen levels was observed, suggesting other dominant controlling factors. Given that post-Isabel low-DO levels at the tidal freshwater stations coincided with increased freshwater inflow to the Mattaponi and Pamunkey rivers (Figure 9), enhanced watershed material loadings (e.g., sediment and degradable organic matter) are implicated as plausible explanations. Organic material loadings from natural habitats (e.g., forests and wetlands), agriculture, and developed areas are a frequent and widespread consequence of large-scale storms within river and estuarine systems [5].

Near-continuous monitoring resulted in an unprecedented ability to measure water quality parameters prior to, during, and after the passage of Tropical Cyclone Isabel within shallow-water regions of the York River estuary. Both spatial and temporal responses to salinity, turbidity, and DO were observed, highlighting the dynamic nature of estuarine systems. Noteworthy changes in salinity caused by short-term saltwater intrusion occurred within oligohaline regions; freshwater inputs caused salinity depression for days in mesohaline areas. Increased turbidity, which decreases water clarity, occurred throughout the York River estuary. While turbidity was exceedingly high in some instances, the impact was short-lived with many sites returning to pre-storm condition within 24 to 30 hours. Perhaps the most significant environmental impact associated with Isabel was the low oxygen levels at selected stations. While hypoxic conditions were not observed, persistent low DO occurred in some tidal freshwater regions. Sustained, near-continuous monitoring of water quality and causative factors (e.g., waves, current, meteorologic variables, and streamflow) will provide greater insight into the system's response to event-based or chronic disturbances.

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