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SeaWiFS Helps Assess Hurricane Impact on Phytoplankton in Caribbean Sea

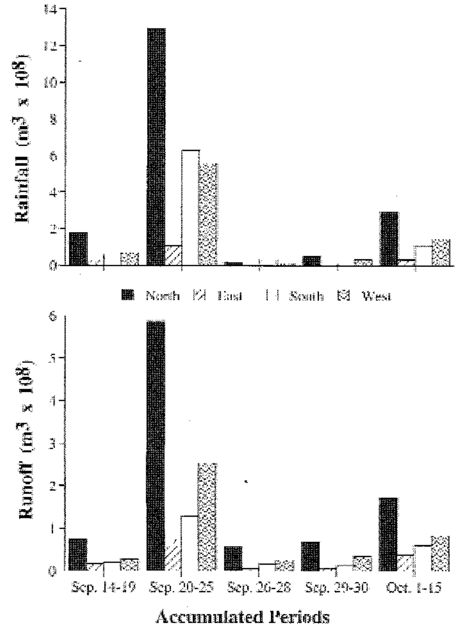


Fig. 1. Rainfall and runoff are estimated for the four geographic regions of Puerto Rico from September 19 to October 15, 1998. Hurricane Georges made landfall on the island on September 21, 1998.

Hurricanes can change the biogeochemistry and productivity of coastal regions due to their large impact on river discharge, land runoff, water circulation, and morphological conditions. Such changes are very dramatic, but they can only last from days to a few weeks. The brief span of these events makes a rapid and low-cost assessment of their regional impact very difficult. Remote sensing of ocean color is a promising tool for assessing the impact of hurricane disturbances in coastal areas at relatively low cost.

We recently evaluated the impact of Hurricane Georges in the Caribbean region by using a time series of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) images collected at the University of Puerto Rico at Mayagüez and at the University of South Florida using ground satellite antennas. Hydrological data from Puerto Rico were used to evaluate the effects of runoff on ocean color patterns around Puerto Rico. Rivers and aquifers around the island delivered approximately one thousand metric tons of nitrate in the form of nitrogen to coastal waters of Puerto Rico during and immediately after the storm. SeaWiFS imagery clearly shows that the flooding of rivers associated with the hurricane led to major changes in ocean color patterns, which are associated with phytoplankton distribution, in coastal and oceanic waters around Puerto Rico and Hispañiola.

Hurricane Georges

During the 1998 hurricane season, 14 tropical storms formed within the Atlantic Ocean and the Gulf of Mexico. Ten of these storms became hurricanes. The eighth storm of the season, Georges, became the second-strongest and second-deadliest hurricane of the 1998 season. Reaching hurricane intensity on September 17, Georges made seven landfalls in its transit from the northeastern Caribbean to the coast of Mississippi, leaving at least 602 fatalities in its track, primarily in the Dominican Republic and Haiti (see http://www.nhc.noaa.gov/1998georges.html).

The eye of Hurricane Georges made landfall on the eastern coast of Puerto Rico at 7:00 P.M. on Monday, September 21, 1998. At that time, this storm was classified as a category 3 hurricane on the Saffir-Simpson scale with sustained winds of 185 km per hour and gusts of 241 km per hour. Within the mountainous interior of Puerto Rico, over 50 cm of rain were measured over a 2-day period at several locations [*U.S. Geological Survey*, 1999]. The eye of Hurricane Georges left the island through the western coast by 1:00 A.M. the next day. Georges then intensified over Mona Passage, reaching the eastern coast of Hispañiola the morning of September 22. It continued to produce extensive flash floods and landslides before leaving that island on September 23.

A previous article [*Stone et al.*, 1999] presented the impact of Hurricane Georges and the morphological changes, like beach erosion and sediment deposition, along the northern coast of the Gulf of Mexico. Here we describe its impact on the Caribbean region by using hydrological and satellite ocean color data.

Hydrological Data

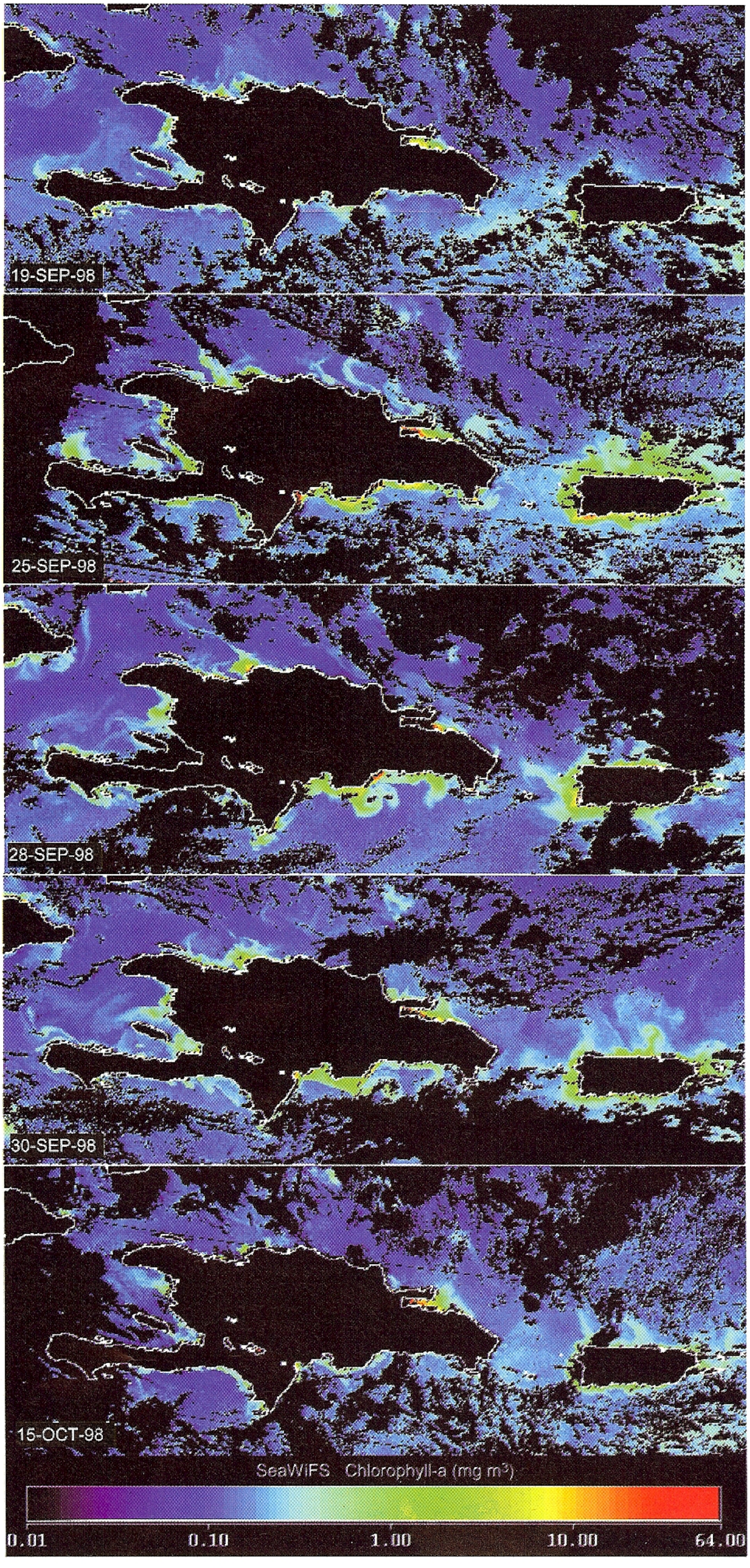
The riverine sediment and nutrient load associated with Hurricane Georges had a significant but transitory effect on the water quality of the coastal waters of Puerto Rico. To better understand the origin and dispersion of colored waters documented in the SeaWiFS imagery, we must establish how much water was discharged to the coastal regions of Puerto Rico for the periods preceding each image acquisition. Typically, only a portion of the rain falling on a watershed will discharge directly to the coastal waters as streamflow. A significant amount of rainfall returns to the atmosphere through evapotranspiration, it is withdrawn or diverted for agricultural or urban use, or infiltrates through the soils to recharge aquifers. Groundwater may take weeks or months before reaching and mixing with coastal waters. The remaining water is transported out of the watershed into the ocean as river runoff. In Puerto Rico, the percentage of rainfall that becomes runoff is highest in the steep, humid watersheds draining toward the eastern coast and lowest in the arid basins draining to the southern coast. However, the total runoff volume draining to the southern coast is greater than that draining to the eastern coast because the total area of southern coast drainage basins is almost four times the drainage area of east coast basins.

The coastal ocean around Puerto Rico was divided into four regions for hydrologic analysis: north, east, west, and south. The runoff to these coastal regions from September 14 through October 15, 1998, was estimated from spatial patterns of rainfall and river discharge measurements using data compiled and analyzed within a Geographic Information System (GIS). Coastal discharge was estimated from discharge stations operated in the uplands because tidal effects prevent routine measurements of discharge at the river mouths.

Measurements of precipitation at 55 rainfall stations operated by the National Weather Service and surface water discharge at six steam flow-gaging stations operated by the U.S. Geological Survey were analyzed for five periods: September 14–19, September 20–25 (passage of Hurricane Georges), September 26–28, September 29–30, and October 1–15 (Figure 1). Each of these periods includes the acquisition of relatively cloud-free SeaWiFS imagery in the northeastern Caribbean Sea.

The total precipitation recorded at each of the 55 rainfall stations was used to draw approximate rainfall isopleths (isohyets) over the island for the five analysis periods. Each isohyet map was converted into a smoothly varying grid of cumulative rainfall amounts. Grid cells were 100 m on a side.

The entire mainland of Puerto Rico was divided into 15 drainage basins; six were gaged and nine were ungaged. The basins were converted into grid zones co-registered with



the rainfall grids. The six gaged stations were selected because they survived the storm, they had a long period of record, and they drained to different coastal areas. The total area for the 15 basins equals 8,710.1 km², the area of the entire mainland of Puerto Rico, excluding the offshore islands of Culebra, Vieques, and Mona. The area of basins draining to the north, east, south, and west coasts was calculated to be 4,634.8 km², 539.6 km², 1,970.0 km², and 1,565.7 km², respectively. The mean rainfall within each basin for each period was estimated using zonal statistics calculated by the Global Information System (GIS). The percentage of cumulative rainfall relative to discharge (as cumulative runoff from each of the gaged basins) was calculated for each period and used to estimate runoff for the ungaged basins. Cumulative rainfall and discharge data starting on September 14 were used to estimate average runoff to rainfall ratios for the periods between image acquisitions. This method minimized the effect of temporal differences between rainfall and the corresponding runoff. Calculations of runoff for individual periods will depend greatly on rainfall that occurred in previous periods and can result in runoff to rainfall ratios that exceed 100%.

Even though cumulative data were used, discharge measurements at two stations appeared to exceed the amount of rain falling on the basins during the hurricane period. One station received significant discharge from an adjacent karst area; the other had significant deposition of sediments, thereby requiring a recalibration of the stage-discharge relationship for the site. Therefore, these stations were not used to estimate rainfall runoff ratios for the rest of the island. Using the remaining gaged basins, the percentage of rainfall that was measured as runoff over the entire period from September 14 through October 15 was calculated to be approximately 25% for the south coast, 50% for the north and west coasts, and 65% for the east coast. With the exception of the south coast station, these values are almost 10–20% higher than the long-term average values. It is possible that significant quantities of the rain falling on the south coast soaked into the ground to be discharged diffusely to coastal waters in the days and weeks following the storm. Therefore, the calculated runoff for the south coast could be an underestimation. Apparently, this is the case as shown later in the satellite imagery.

As Hurricane Georges passed over the island of Puerto Rico during September 21–22, more than 50 cm of rain fell over much of the island's mountainous interior and between 10 and 30 cm fell over coastal areas. The results of the GIS analysis show that the north, east, south, and west coast basins received 14%, 6%, 22%, and 17% of their annual averages of 189 cm,

Fig. 2. Chlorophyll-a as estimated using the SeaWiFS satellite sensor before and after Hurricane Georges crossed over the Caribbean region.

248 cm, 150 cm, and 189 cm of precipitation, respectively. The north and west coast basins were again hit hard by lesser but still intense rainstorms during September 29–30. Hurricane Georges generated runoff from the north coast basins that averaged more than 1,100 $m^3 s^{-1}$ during the days preceding September 25. This runoff returned to an average value of 130 $m^3 s^{-1}$ during October 1–15. The east, south, and west coasts basins had average discharges of 110 $m^3 s^{-1}$, 250 $m^3 s^{-1}$, and 490 $m^3 s^{-1}$ during September 20–25 and dropped back to 29 $m^3 s^{-1}$, 47 $m^3 s^{-1}$, and 65 $m^3 s^{-1}$ during October 1–15.

The mean concentration of nitrate (as nitrogen) for 294 surface water samples collected around Puerto Rico from 1958 to 1999 is 0.79 mg/L (standard deviation = 0.56; see http://water.usgs.gov/PR/nwis). During dry periods, microbial decay of organic debris increases the amount of re-mineralized nutrients available in the soil. Nutrient concentrations in surface waters commonly increase above their long-term means during heavy rains as the nutrients are flushed from the soils into the streams. Using a conservative estimate of 1 mg l^{-1} for average nitrate concentration (as nitrogen), more than 1 thousand metric tons of nitrate were delivered to the coastal waters of Puerto Rico during September 20–25. This pulse of nutrients to the coastal waters significantly increased phytoplankton concentrations and was discernible in the SeaWiFS imagery.

SeaWiFS Imagery

The impact of Hurricane Georges on the waters of Puerto Rico was assessed with SeaWiFS imagery from September 19, 25, 28, and 30, and October 15, 1998 (Figure 2). Standard SeaWiFS algorithms [*O'Reilly et al.*, 1998] were used to derive phytoplankton Chlorophyll-*a* (Chl-*a*) concentrations. However, it is likely that the signal detected by SeaWiFS during the large runoff of this event was contaminated with other colored constituents like sediments and dissolved organic matter. In particular, the relatively high concentrations of Chl-*a* indicated for the area off of the southwest coast of Puerto Rico in the image acquired on September 25 probably reflects the flushing of significant quantities of humic acids from the mangrove forests that fringe that coast. Besides the possible contamination, we use the term Chl-*a* in our discussion because for reasons already explained, a large component of the signal is phytoplankton.

Our work demonstrates that SeaWiFS is a good tool for rapid and low-cost assessment of the changes in colored constituents, including phytoplankton. Chl-*a* concentrations were relatively low in waters around Puerto Rico on September 19, before Hurricane Georges reached the island (Figure 2). Much higher Chl-*a* concentrations were seen on September 25, 3 days after the hurricane crossed the island. The highest concentrations occurred along the northern coast, where the highest runoff was also registered (Figure 1). High Chl-*a* concentrations persisted for a few days, and two well-defined filaments were observed extending off the western coast on September 28. Two other filaments of high Chl-*a* were observed spreading off the north coast of the island on September 30 after intense rainstorms during September 29–30. Concentrations returned to typical summer values after about two and a half weeks, as documented in the image of October 15. Similar Chl-*a* patterns, including an increase in concentrations and coastal filaments, were observed around Hispañiola (Figure 2). Although we have no information on rainfall and runoff for Hispañiola, we expect that the perturbations in Chl-*a* were also related to the same processes that occurred in Puerto Rico, which we ascribe to increased rainfall and nutrient-laden terrestrial runoff.

This study marked the first time that ocean color data were used to assess hurricane impacts on coastal water quality in this region, and SeaWiFS imagery proved the utility of rapid regional and local-scale assessments. The launch of new ocean color sensors—like the Moderate Resolution Imaging Spectrometer (MODIS)—as part of NASA's Earth Observing System will help in this effort. The satellite data capture facilities for both SeaWiFS and MODIS in the University of Puerto Rico at Mayagüez and the University of South Florida provide a regional capability for real-time, routine, and quasi-operational assessment of the impact of hurricanes and other episodic events on the water quality of the Caribbean Sea and adjacent areas. More details about efforts to use remote sensing in coastal and oceanic studies of the Caribbean Sea can be found in http//cacique.uprm.edu/biol.

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References

O'Reilly, J. E., S. Maritorena, B. G. Mitchell, D. A. Siegel, K. L. Carder, S. A. Garver, M. Kahru, and C. McClain, Ocean color chlorophyll algorithms for SeaWiFS, *J. Geophys. Res., 103*, 24,937–24,953, 1998.

Stone, G. W., P. Wang, D. A. Peper, J. M. Grymes III, H. H. Roberts, X. Zhang, S. A. Hsu, and O. K. Huh, Studying the importance of hurricanes to the northern Gulf of Mexico coast, *Eos, Trans. AGU, 80*, 301, 305, 1999.

U. S. Geological Survey, *U. S. Geological Survey Fact Sheet 040-99*, 4 pp., Puerto Rico, 1999.