Extreme Events and Ecological Forecasting

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Abstract

Almost all extreme events lasting less than several weeks that significantly impact ecosystems are weather related. This review examines the response of estuarine systems to intense short-term perturbations caused by major weather events such as hurricanes. Current knowledge concerning these effects is limited to relatively few studies where hurricanes and storms impacted estuaries with established environmental monitoring programs.

Freshwater inputs associated with these storms were found to initially result in increased primary productivity. When hydrographic conditions are favorable, bacterial consumption of organic matter produced by the phytoplankton blooms and deposited during the initial runoff event can contribute to significant oxygen deficits during subsequent warmer periods. Salinity stress and habitat destruction associated with freshwater inputs, as well as anoxia, adversely affect benthic populations and fish. In contrast, mobile invertebrate species such as shrimp, which have a short life cycle and the ability to migrate during the runoff event, initially benefit from the increased primary productivity and decreased abundance of fish predators.

Events studied so far indicate that estuaries rebound in one to three years following major short-term perturbations. However, repeated storm events without sufficient recovery time may cause a fundamental shift in ecosystem structure (Scavia et al. *2002). This is a scenario consistent with the predicted increase in hurricanes for the east coast of the United States.*

More work on the response of individual species to these stresses is needed so management of commercial resources can be adjusted to allow sufficient recovery time for affected populations.

Introduction

Short-term natural events (days to weeks) causing significant stress to estuarine environments are primarily weather related: hurricanes, tropical storms or northeasters. These powerful weather systems damage habitats through direct wind or wave action and alter habitats by loading freshwater, nutrients, and pollutants into the estuary. On a global time scale, periodic disturbances by these weather systems are highly predictable along the Gulf of Mexico and the eastern coast of the United States. Precisely predicting when and where they will occur on shorter time scales (year-to-year), however, is highly unpredictable.

This high degree of variation makes detailed studies of the short and long-term effects of storms on estuarine environments and populations difficult. Most of the objective knowledge concerning the effects of these perturbations comes from ongoing long-term studies that coincided with a hurricane passing through the study area. The notable studies are the effect of Hurricane Agnes on the Chesapeake Bay in 1972, and Hurricanes Fran (1996) and Floyd (1999) on North Carolina estuaries (Figure 1).

As a result of the limited number of long-term studies, separating the effects of these storms from normal environmental variation can only be estimated from current studies of less extreme runoff and wind events. These smaller events generally occur much more frequently and hence are easier to study because the effects of a larger than normal spring runoff or a major wind event often mimic, to a lesser degree, the stress and excess nutrient loading that accompanies a tropical storm or hurricane.

The remainder of this paper briefly reviews what can

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accurately be predicted about the effects of major storm events on estuarine systems, what information managers will need to adequately respond to these storms, and what research is needed before there can be accurate forecasting of these effects.

To understand the effects of short-term, intense perturbations such as hurricanes on estuarine systems, it is important to consider three specific aspects of each storm: the amount of storm runoff, the time of year the storm occurs, and the amount of direct physical damage caused by the storm. The amount of rainfall and subsequent runoff varies tremendously between storms and directly determines the salinity stress. In addition, it directly affects the overall amounts of nutrients, sediments, and toxicants introduced into the estuary. Secondly, the time of year the storm occurs is critical because the total oxygen consumption by an estuary is directly related to ambient temperatures. The warmer the water, the more rapidly nutrients are taken up by phytoplankton and converted to carbon sources that promote bacterial growth and respiration. Given that warm water holds relatively little oxygen, this increased bacterial respiration often leads to hypoxia or anoxia. Lastly, storms vary greatly in the amount of direct physical damage they inflict through wind and wave action. This damage is of particular concern when it destroys environmentally sensitive areas such as breeding habitats of endangered species.

Case Study

There are no current models that adequately address how these intense short-term events will impact estuaries. Most of the available data on the response of estuaries to short-term, large scale perturbations comes from Hurricane Agnes's strike on Chesapeake Bay in 1972, and Hurricanes Fran and Floyd, which made landfall in North Carolina in 1996 and 1999 (Tester *et al.* 2003), respectively. Therefore, the following case study represents a conceptual model based on current knowledge of how various components of estuarine ecosystems are thought to respond to short-term, large-scale weather-related events.

Salinity Stress – The freshwater input during and after major storms, particularly hurricanes, determines the mortality among sessile organisms as well as displacement and mortality of mobile species (Jury *et al.* 1995). The mesohaline region of the estuary is generally the most impacted by runoff during these events. When runoff reduces the salinity in this region to less than 10 psu for more than a week, extensive mortality occurs among benthic organisms such as sponges, tunicates, bryozoans, coelenterates and mollusks (Andrews 1973, Smock *et al.* 1994). Some species may be eliminated.

Although species with pelagic larvae and fast growth rates generally repopulate the region within three months, repopulation may take years for species with limited dispersal capacity. Furthermore, if the salinity stress coincides with the breeding season of a particular organism, fecundity and survival will be affected. This must be taken into account when anticipating the effects of hurricanes and tropical storms on an estuary (Livingston *et al.* 1999). The closer the storm occurs to the peak breeding season, the greater the chances of severe population impacts.

The consequences of acute or prolonged salinity stress on fish stocks are less understood. Preliminary studies indicate that runoff causes extensive mortalities of estuarine fish populations (Dorf and Powell 1997, Paerl *et al.* 1998). The long-term effects on each population are now beginning to be rigorously quantified (Crowder, personal communication). Considerable work remains to adequately quantify losses and determine how mortalities affect future reproduction and recruitment. These studies should also include a rigorous examination of how food web disruption caused by runoff affects the recovery of various fish species, particularly mesohaline bottom feeders.

Little is known about how changes in the lower trophic levels caused by increased runoff impact fish populations. This information is critical to accurately understand how fish stocks will be affected by runoff events. Stressed fish are more susceptible to disease and parasites (Noga 2000, Paerl *et al.* 2001). Therefore, fish mortality due to these causes should also be investigated immediately following the initial stress event and in subsequent years when lowered food abundance and anoxic events may again stress these populations. Ideally, once the general effects of runoff-induced mortality and stress are known, local fisheries managers could adjust catch limits to enable the recovery of fish populations.

Since prolonged salinity stress will severely affect an estuarine ecosystem, one critical need is to accurately predict runoff in a watershed under different conditions. While it provides information for implementing more accurate evacuation plans, having a precise estimate of the potential runoff also will help sewage treatment facilities and farm operations reduce unintended discharges. Large releases of waste material adversely affect estuarine water quality for weeks. They also pose a public health threat (Mallin *et al*. 1999). The NOAA weather service, academic scientists and the USGS have made great strides in developing runoff prediction models (Pietrafesa *et al*. 1997). However, much work remains to improve these models, as was shown from the unexpectedly severe flooding in North Carolina during Hurricane Floyd.

Nutrient Loading – Besides reducing the overall salinity regime, runoff adds inorganic nutrients, dissolved organic nutrients, and sediments to the estuary (Paerl *et al*. 1998). More than 50 percent of the annual nutrient loading can occur during a single, large runoff event (Hahl 1981).

Of all nutrients in the runoff, nitrogen and to a lesser extent, phosphorous, play a direct role in stimulating phytoplankton growth (Howarth 1988). In addition, most hurricanes and tropical storms occur in the warmer months when the phytoplankton are actively growing. Under these conditions, phytoplankton take up the inorganic N and P and grow rapidly. These same results occur during smaller storm events that also contribute nutrients into the estuary.

The biomass increase generally occurs within a week following nutrient input and lasts from a few weeks to three months, depending on the extent of loading (Loftus *et al*. 1972, Flint 1985, Bennett *et al*. 1986). In estuaries where flushing rates are high, excess nutrients and cells may be transported out of the system, resulting in a smaller bloom than found in the lagoonal systems that efficiently trap nutrients.

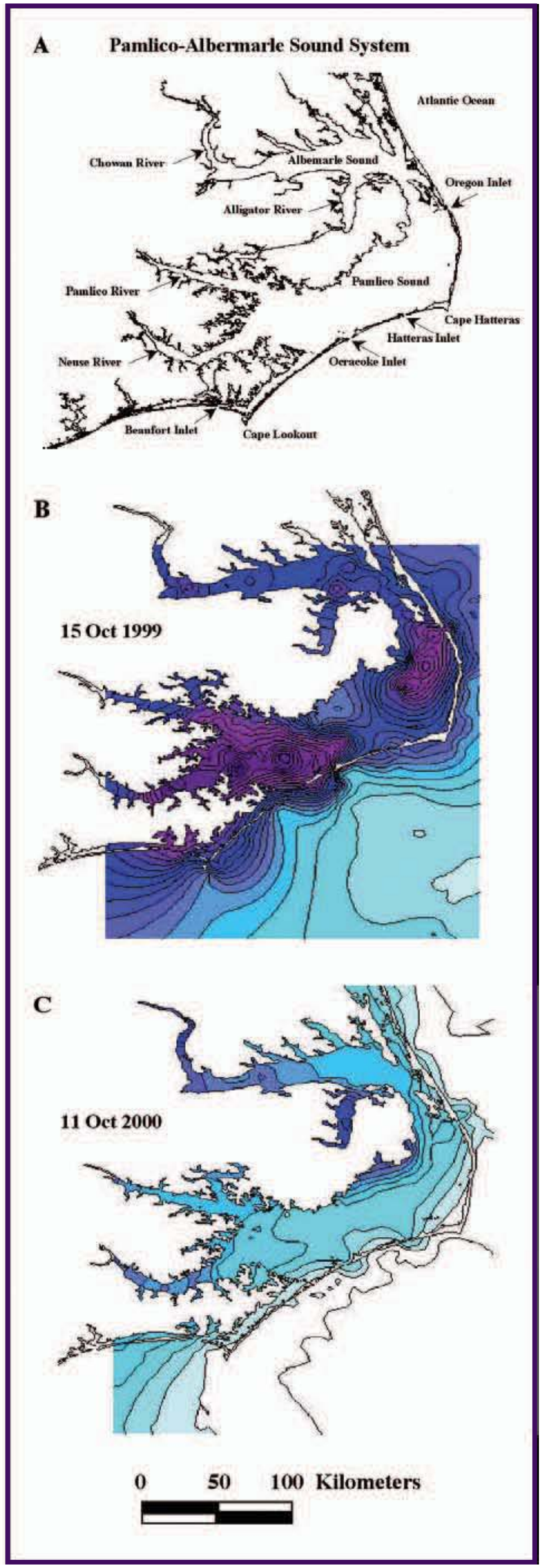

***Figure 1**. A) Record rainfall and extensive flooding in the Pamlico-Albemarle Sound system (PAS) accompanied hurricanes Dennis, Floyd, and Irene, which made landfall in coastal North Carolina in September-October 1999. The physical and chemical changes following this massive freshwater influx served as a large-scale natural experiment. In a matter of weeks, half of the annual supply of nutrients was delivered to the PAS as freshwater runoff. The relative abundance and distribution of colored dissolved organic matter (CDOM) in the PAS system are shown during the flooding events (B, 15 October 1999) and under a normal flow regime 1 year after the hurricanes (C, 11 Oct 2000). Light blue indicates relatively low CDOM, whereas dark purple indicates very high levels of CDOM in the system. The CDOM inputs into the PAS originate from the surrounding pine forests and swamp. Hence, CDOM serves as a visual proxy for both the amount of runoff from the surrounding coastal regions and overall nutrient inputs. The CDOM data were gathered during a series of over flights of the PAS using a NOAA observation plane equipped with NASA's airborne oceanographic light detection and ranging instrument (AOL3). Laser induced fluorescence (LIF) at 355 nm served as a measure of CDOM (Tester* et al. *2003).*

Phytoplankton blooms contain a large quantity of carbon, the base of the food chain. Zooplankton grazing communities would generally be major consumers of this increased productivity. However, zooplankton biomass is often significantly decreased following major runoff events (Shaheen and Steimle 1995). This further favors the development of phytoplankton blooms and subsequent bacterial use of newly-produced carbon that would otherwise have been consumed by the zooplankton community.

As phytoplankton cells in the bloom die and sink out of the water column, bacteria remineralize the phytoplankton. During warmer months, the complete remineralization of N and P is often complete within a few hours to several days (Nixon 1981). This efficient recycling mechanism amplifies the productivity stimulated by the initial nutrient input. Frequently, macrophytic algae also respond to the increased nutrient load and become so abundant they also contribute to severe anoxic events (Sfriso *et al*. 1987, Barranguet and Alliot 1995).

If runoff-induced phytoplankton blooms occur in stratified salt wedge estuaries, the cells will settle into a high-salinity wedge. This wedge does not mix effectively with the upper layer. Studies of salt wedge estuaries that have experienced a runoff event and bloom during warmer months indicate that if both the carbon supply from sinking phytoplankton and temperatures are sufficiently high, extensive bacterial respiration will cause the lower salt wedge to become hypoxic or anoxic (Taft *et al*. 1980, Bennett *et al*. 1986).

Transient hypoxic or anoxic events similarly occur in shallow estuaries when the primary production (phytoplankton or macrophytes) is sufficiently high so the biological oxygen demand (BOD) consumes all or most of the oxygen in the water column (Barranguet and Alliot 1995, Conley *et al*. 2000). Sometimes these hypoxic or anoxic zones can be quite large and lead to additional fish kills or the decimation of the benthic microfauna (Bianchi *et al*. 2000). Though anoxia tends to slow down remineralization of organic compounds in the benthos, significant amounts of ammonium and phosphate can be released (De Casabianca *et al*. 1997). If nutrients released below the pycnocline are transferred to the upper layers of the estuary via wind, tidal, or shear mixing forces, additional phytoplankton/macrophyte growth will occur, which will subsequently increase the BOD (Malone *et al*. 1986). This cycle accounts for the increasing number of anoxic events with increased nutrient loading in estuaries.

Accurate models are needed to address the link between hydrography, nutrients, phytoplankton biomass, and the potential for anoxia events. The latest generation of Doppler radar current meters, buoyed meter arrays, and real-time satellite uplinks make gathering these data much more practical and should lead to ever improving circulation models. Improved models and real-time monitoring will give environmental managers better information relating to potential anoxic events and their potential to affect environmental and public health. In addition to determining the effects of hurricanes, these models would also help predict the potential effects of increased nutrient loading from aquaculture, waste treatment plants, and agricultural runoff.

Sediment Loading – Runoff from tropical storms and hurricanes can load more than a year's worth of sediment into an estuary within several weeks (Gross *et al*. 1978). Sedimentation affects the benthic community directly by burying many benthic organisms so they cannot feed effectively. Indirectly, the sediments represent a large source of organic carbon, exacerbating the BOD problem during the warmer months (Paerl *et al*. 1998). The initial anoxic or hypoxic conditions produced by storm runoff are often not the result of bacterial action on increased algal production, but rather the immediate metabolism of organic material in the sediment. Over the next three to five years, additional nutrients will be released as this organic matter continues to be remineralized by benthic bacteria. The particulate organic matter therefore functions as a 'time-release fertilizer,' increasing productivity and resulting in more frequent and severe anoxia events in subsequent years (Paerl *et al*. 2001).

The increased productivity following runoff events can have both positive and negative effects. On the positive side, the increased productivity can result in a rapid increase in the abundance of certain invertebrates. For example, a general phenomenon is that shrimp harvests increase substantially the year after hurricanes or tropical storms cause large runoff events (Flint 1985). Presumably the shrimp, either directly or indirectly, take advantage of the increased primary productivity and the disruption of predatory fish populations. On the negative side, certain parts of an estuary, with fairly low flushing rates and high recycling rates, may experience nuisance algal blooms when there is little wind. These blooms greatly reduce the recreational value of the estuary and can supply enough carbon for the bacterial community to create anoxia and related fish kills.

Toxic Chemicals – The extent to which hurricanes load toxicants into estuaries depends largely on upstream sources. Large amounts of water coming into the system often dilute dissolved toxic compounds below levels of detection. Given sufficient outflow from the estuary during the event, they can be largely eliminated from the estuary. In that respect, the runoff can cleanse the estuary.

When the toxic substances are bound to sediment particles, the impact is less clear. If the upstream sediment is contaminated with heavy metals, pesticides, or other harmful chemicals, these substances can be retained in the system. After reaching the benthos, they either remain inertly attached to the particle or are mobilized to enter the food chain. If the sedimentation rate is sufficiently high, some of the labile material will be buried and effectively sequestered unless released by bioturbation. The amount of bioturbation following the sedimentation event is, therefore, an important component determining how rapidly toxic compounds enter the food chain.

In cases where bioturbation is important, the remineralization process may be delayed for months after the runoff event until the benthic community is reestablished. Similarly, physical resuspension of already contaminated sediments by wind and wave action can contribute to the renewed cycling of once sequestered toxic compounds (Tisue *et al*. 1992). To adequately understand how runoff will affect the distribution and cycling of toxic compounds in estuarine systems, more research is needed to estimate potential toxic loads in upstream watersheds and understand how certain toxins are transformed and transferred at different salinity regimes within the estuary.

Much is known regarding the migration and transformation of heavy metals, pesticides, and other organic compounds; however, accurate loading estimates are often lacking. To obtain a realistic picture of the potential threat to an estuary, toxic compounds will require frequent monitoring, particularly during runoff events. Estuaries receiving significant inputs of industrial waste or pesticides should be given priority monitoring to identify any significant deterioration in environmental quality. Given the limited resources available to environmental managers, the toxicants measured should also be carefully selected so the focus is on those most likely to cause adverse effects on human or animal health. Reviews should be made periodically to determine if other critical toxins should be measured or if more appropriate and economical detection methods have been developed.

Wind and Wave Damage – Hurricanes, tropical storms, and particularly northeasters are also notable for the physical damage they cause to estuarine environments. Much of this damage may persist for years. In the broadest ecological terms, these physical disturbances can all be viewed as a means to open niche space. No matter how severe the disruption, the same or different species will eventually exploit the newly-created habitat.

Vascular plant communities surrounding estuaries are most visibly affected by major storms. Mortality and damage occurs from uprooting, stripping leaves and limbs, and salt spray damage. The periodic damage inflicted by hurricanes, therefore, plays a crucial role in the structure of these plant communities.

A good example is the mangrove community (Wanless *et al*. 1996). Hurricanes open space in mangroves by destroying trees, removing peat deposits, and by bringing poisonous anoxic sulfide rich sediments to the surface. Once the peat is gone, subsidence occurs; the sulfide released from the mud kills weakened trees and saplings. Despite this damage, the mangrove and other plant communities gradually respond with increased productivity after the storm and generally recover until the next storm produces similar damage.

The immediate effect of these storms, however, is to degrade the habitat for many vertebrate and invertebrate species. Storm surges also frequently disrupt littoral sand communities and deposit large amounts of sand onto existing marshes further inland (Courtemanche *et al*. 1999), causing significant habitat destruction. Many species are forced to disperse to find food and shelter, accounting for the increase in reported hornet and wasp stings and snakebites following hurricanes (Valiela *et al*. 1998).

The physical disturbances caused by major storms cannot be altered and is primarily of concern when there are endangered species within the affected habitat. In this case, strategies should be sought to encourage establishing as many spatially-dispersed habitats as possible to ensure the best chances for survival.

The timing of the physical disturbance must also be considered when determining its specific impact on various estuarine species. Juvenile oysters, for example, sometimes benefit from the reduction in predators and open surfaces created by the physical disturbance during storms. However, if the storm event occurs during maximal recruitment or significantly affects the ability of the adult population to produce larvae, the effects on the population will be negative (Livingston *et al*. 1999). Similar effects on different life cycle stages would apply to hundreds of different organisms. Given the limited knowedge about many estuarine organisms, it will be difficult to incorporate timing issues into models that will accurately predict the effect of hurricanes, tropical storms and northeasters on estuarine environments and populations.

Conclusions/Next Steps

There is a broad understanding of how major storms affect estuarine environments, both positively and negatively. Better models of rainfall, runoff and estuarine circulation are needed to improve predictive capabilities. Without robust basic hydrographic models, it will not be possible to understand and predict the effects of a storm on an estuary. Once these models are available, then realistic model inputs for nutrients, toxicants and other factors can be incorporated and first order predictions made. Once these predictions are available, monitoring real time storm events is needed to test the models' predictions.

A particularly important model parameter to evaluate will be nutrient loading. Having accurate loading information is crucial in determining whether nutrient loading is increasing through time, either through increased hurricane activity or anthropogenic inputs. If eutrophication is allowed to proceed, there will be adverse long-term biogeochemical and trophic changes in estuarine and coastal habitats (Paerl *et al*. 2001). Only by carefully monitoring nutrient inputs and using sophisticated modeling will it be possible to predict those changes and justify the political support for modifying land use, agricultural, and waste treatment policies sufficiently to avoid an unalterable degradation in estuarine environments.

The next steps will be to integrate long-term monitoring projects with intensive acute response monitoring to determine how large, short-term perturbations such as hurricanes affect estuarine ecosystems. This is particularly important given the greater eutrophication stress being placed on estuaries and predictions for increased hurricane activity (Goldenberg *et al*. 2001).

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