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TITLE:

Tidal Creek Ecosystems: Sentinels for assessing the consequences of rapid development on Southeastern coasts

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ABSTRACT

Meandering shallow tidal creeks are a dominant feature of Southeastern estuaries and provide nursery grounds for many fish and crustaceans. The shores of these creeks are also preferred sites for human development. Previous research of over 40 headwater tidal creeks in South Carolina has found linkages between surrounding watershed land use (e.g., impervious cover) and the ecological condition (i.e., physical-chemical and biological conditions) of headwater tidal creeks. When the watershed reached approximately 10-20% impervious cover, physical-chemical conditions in creeks were adversely altered. When the amount of impervious cover exceeded approximately 20-30%, biological resources were degraded. This research has shown that these headwater creeks have the potential to serve as sentinel habitats for assessing the impact of watershed development on ecosystem and public health; however, most estuarine monitoring programs do not sample these habitats. Monitoring programs have generally focused their efforts on the deeper, main body of estuaries, ignoring these critical shallow water habitats. Because the larger, deeper water bodies receive pollution loadings from a mix of land use types (forested, suburban, urban) and point sources it is almost impossible to attribute specific changes to specific land use categories. Therefore, in 2005 the entire length (i.e., upper intertidal to the subtidal zone) of tidal creeks with varying land use in the South Carolina were sampled for physical, chemical, and biological indicators. The major finding of this research was headwater tidal creeks are the appropriate scale for obtaining early warning of the impacts of land use change on estuarine ecosystems.

KEYWORDS

Sentinel habitats, tidal creeks, land use, ecosystem condition

INTRODUCTION

The U.S. coastal natural resources are abundant and annually contribute hundreds of billions of dollars to the US economy as well as provide many free ecological services, including waste processing, clean air and water, and scenic vistas worth untold billions of dollars (Colgan, 2003; Constanza et al., 1997). Approximately 25% of the US land area and >50% of the population are located along the US coasts (Culliton, 1998). Coastal ocean-based tourism is the fastest growing component of the coastal economy, with hundreds of millions of Americans and international guests visiting our coasts annually (Colgan, 2003). Not surprisingly, coastal population densities are 2-5 times higher than in the rest of the nation (Beach, 2002). Along our coasts, land is being consumed for urban development 3-6 times as fast as the rate of population growth (Beach, 2002), resulting in major and permanent alterations to coastal ecosystems. These trends appear to be accelerating, with potentially serious impacts on the long term health of coastal ecosystems and the people who live, work and recreate there (Cohen et al., 1997; Vitousek et al., 1997).

Recent reports on the condition of the nation's coastal natural resources have noted measurably diminished resources (Pew, 2003; NMFS, 2002; USEPA, 2001). Major sources of impairment across all regions and habitats included chemical and microbial contamination, increased "flashiness" in freshwater inflows, nutrient over-enrichment and hypoxia, increased frequency of harmful algal blooms, habitat modification and degradation, wetland loss, increased abundance of non-native species, over-harvesting of fisheries, and impaired biological communities. Most of these reports conclude that the major environmental threats to coastal resources are from diffuse or non-point sources of pollution. In addition, the cumulative effects of multiple stressors, including the interactions among them, have been identified as the major contributor to diminished resources.

Existing monitoring programs for assessing the condition of coastal resources are insensitive to many stressors and do not provide early warning of ensuing harm to the ecosystems or the humans that rely upon them. The goal of most monitoring programs is to evaluate the health of the dominant habitat in a system which results in a focus on common habitats that encompass large areas. For example, the USEPA Environmental Monitoring and Assessment Program (EMAP) has focused its efforts on evaluating a suite of indicators in large tidal rivers and deep estuarine areas to make statements about the overall quality of the estuarine ecosystem. This information is important but does not provide early warnings of impairment, particularly the impacts of coastal development and the resulting nonpoint pollution.

Another approach is to evaluate specific habitats that are sensitive and exist in the appropriate location. One of the earliest symptoms of ensuing broad scale aquatic ecosystem impairment has been declines in the amount and ecological condition of habitats, sometimes called sentinel habitats, that are sensitive to major environmental stressors of interest. Some examples include sea grass beds, shellfish beds, kelp forests, coral reefs, and wetlands. These sentinel habitats or first responders generally decline years to decades before system wide impairment is documented by routine environmental quality monitoring activities (Bayley et al. 1978; Dustan and Halas 1987; Holland et al. 2004). Examples of system-wide impairment include broad scale hypoxia and dead zones, harmful algae blooms, and declining fisheries productivity. For example, the extent of sea grass beds in the Chesapeake Bay exhibited coverage declines as early as 1960s with the greatest declines occurring in the headwaters of major tributaries of the Bay. Shellfishing grounds have also generally been closed to harvesting because of microbial contamination well before other water quality indicators suggested problems. Unfortunately, the ecological knowledge to understand and interpret the warning signals provided by sentinel habitats has only recently become available (Kemp et al. 1983, Hoegh-Guldberg, 1999; Porter and Tougas, 2001; Turgeon, et al., 2002).

In southeastern estuarine environments salt marshes are important habitats for a number of processes including nursery habitats, buffers, and filters. Salt marshes also serve as the interface between the upland landscape and estuaries where freshwater from the land mixes with saline water, resulting in dynamic environments that are renowned for their ecological complexity, biological productivity and seafood production (Kneib, 1997, Holland et al., 2004, Mallin et al., 2000, Lerberg et al., 2000, Sanger et al., 1999a, b). Salt marshes are bisected by tidal creeks which facilitate water moving into and out of the system. In the Southeastern USA, the watersheds associated with tidal creeks and salt marshes are among the most rapidly developing in the nation. Recent information suggests that the headwater regions of these creeks and their associated salt marshes are a repository for much of the pollution released into the environment (e.g., Holland et al. 2004, Sanger et al., 1999a, b). The integrity and productivity of headwater portions of tidal creek environments are impaired by land use changes and the related non-point source pollution years to decades in advance of similar signals occurring in deeper open estuarine waters, suggesting these habitats are valuable sentinels of ensuing harm, including a myriad of potential public health threats. The goal of this paper is to document the importance of headwater tidal creeks as a sentinel habitat for evaluating early warnings of coastal development.

METHODS

A series of studies (Sanger et al. 1999a, 1999b, Lerberg et al. 2000, Gawle 2002, Smith 2003, Holland et al. 2004, Filipowicz 2004, Gillett et al. 2006) have been conducted in headwater tidal creeks starting in 1994 and continuing through the present with the Oceans and Human Health Initiative Hollings Marine Laboratory's Monitoring, Assessment and Prediction (MAP) Project. To date, over 50 headwater tidal creeks, representing a range of development levels, have been sampled in the southeast, primarily in South Carolina. The primary goal has been to evaluate the impacts of coastal development on first order, or headwater, tidal creek ecosystems with the recent addition of evaluating the continuum from the headwaters to the larger estuarine waterbodies. This has included assessing the water, sediment, and biological quality, watershed attributes (e.g., human population density, land cover, impervious cover), loadings, and benthic productivity. This paper will present select indicator data from twelve South Carolina tidal creek ecosystems sampled in the summer (June – August) of 2005 (Figure 1).

In order to characterize within creek variability the entire creek length was sampled, and a classification framework analogous to the freshwater stream ordering system (Horton 1945, Strahler 1957) was applied. The first order or headwaters of each creek directly drained coastal uplands and was predominately intertidal habitat (average depth at low tide=x m). The second order of each creek was formed by the confluence of two or more Order 1 creeks (average depth at low tide=x m). The third order of each creek was formed by the confluence of two or more Order 2 creeks (average depth at low tide=x m). Second and third order creeks were subtidally dominated habitats. Not every tidal creek had all orders and not every order could be sampled in each creek for this study. Tidal creeks in South Carolina have a 1-3 m tidal range, depending on latitude, with semi-diurnal tides. Surrounding salt marshes are dominated by *Spartina alterniflora* and *Juncus roemarianus*.

Watersheds and sub-watersheds were delineated for each creek based on the elevation contours defined by 1:24,000 United States Geological Survey (USGS) topographic maps. The outline of each sub-watershed was then digitized into ArcGIS 9. Watersheds ranged in size from approximately 100 to 5000 ha. Impervious cover data were determined for each creek (watershed) and each creek order (sub-watershed) (Figure 2). The impervious cover within each watershed was calculated by removing salt marsh and estuarine habitats and then clipping National Land Cover Database (NLCD) data (Homer et al. 2004) by the sub-watersheds. A conversion equation developed for this project (White et al., in prep) was then applied to correct the NLCD impervious cover values based on data presented in Holland et al. (2004).

The environmental quality measurements were collected throughout the length of each tidal creek order by dividing into three equidistant reaches using ArcGIS 9, and stations (number depending on parameter) were randomly located within each reach of each creek order for sample collection. Creeks were sampled on the ebb tide, approximately 2-3 hours prior to low tide in order to capture the upland influence on water quality. The first order was sampled by wading into the creek and the second and third orders were sampled by boat. Sampling was conducted in an upstream direction to ensure no resuspension of pollutants from the sediment occurred. A suite of parameters were sampled for and processed using standard methods and protocols (DiDonato et al., Holland et al., 2004, Lerberg et al., 2000). The parameters measured include: basic semi-continuous water quality (i.e., DO, salinity, temperature, pH, depth); macrobenthos; nekton; water column nutrients (i.e., total phosphorus, total dissolved phosphorus, phosphate, nitrate/nitrite, ammonia, total dissolved nitrogen, total nitrogen), chlorophyll *a*, total suspended solids; sediment contaminants, total organic carbon, and grain size; and water pathogens (i.e., fecal coliforms, Enterococci, F+ coliphage, F- coliphage). Evaluating the patterns throughout the tidal creek system (first to third order) of three parameters will be the focus of this paper including nitrate/nitrite (NOx) – measure of water quality, sediment contamination (ERMQ) – measure of sediment quality, and fecal coliforms – measure of public health risk.

Data were log10 (x+1) transformed prior to analysis to obtain normality and homoscedasticity, if necessary. All analyses were performed using SAS (version 9.1). Regression analysis was used to evaluate the relationship between impervious cover and the abundance of each indicator for each creek order. The regression analysis evaluated whether this relationship was consistent across the longitudinal gradient (i.e., in Orders 1 through 3).

RESULTS AND DISCUSSION

Sentinel Habitats

Lerberg et al. (2000) and Holland et al. (2004) observed a series of relationships between the amount of impervious cover and the environmental quality in first order tidal creeks. Some of the relationships were positive (e.g., sediment contaminants, stress tolerant macrobenthic species, fecal coliforms, and salinity range) and some were negative (e.g., stress sensitive macrobenthic species, penaeid shrimp, and silt/clay). Through this work we recognized the importance of these habitats for providing early warning; however, it was unclear if the relationships would also be apparent in larger tidal creeks (e.g., second and third order).

The fecal coliform concentrations, nitrate/nitrite concentrations, and sediment contaminant concentrations observed in the MAP project exhibit similar relationships in the first order creeks with increasing concentrations as the amount of impervious cover increases in the watershed (Figure 3). Some second and third order relationships were also apparent but they were always weaker than what was observed in the first order creeks and not statistically significant. Similar relationships have also been observed for a number of other water column nutrient and pathogen indicators (DiDonato et al. in prep; Riekerk et al., in prep). A number of the other relationships previously observed are still being analyzed to determine their differences and similarities, particularly the biological community parameters.

These data also demonstrate the value of subdividing the creek network into orders. The preliminary creek classification revealed a consistent and significant spatial pattern for various indicators as well as the impact of urbanization at the sub-watershed scale. Current OHHI MAP research is exploring the utility of formalizing a classification scheme for tidal creeks. The picture emerging from OHH tidal creek research in the Southeast suggests that for most environmental quality and public health indicators evaluated, the signal of land use effects on tidal creek ecosystems and human risk is strongest in shallow first order creeks. The degree of impact and risk decreases in second and third orders (e.g., Figures 2). Preliminary results also suggest that this response pattern applies to other Southeastern coastal areas (Georgia and North Carolina) with different tidal regimes from about 1-4 m. A similar pattern for pathogen indicators was also observed by Reeves et al. (39) in Southern California, USA. The inland areas in these studies represent the closest association with the upland and development. Therefore, the spatial scale at which research and monitoring activities occur and proximity to pollution sources are very important for identifying the impacts of land use changes on ecosystems.

A sentinel is defined in the medical profession as "an individual or part of a population potentially susceptible to an infection or infestation that is being monitored for the appearance or recurrence of the causative pathogen or parasite" *(*Merriam-Webster, Inc., 2002). Therefore, monitoring a sentinel habitat will provide an early warning of the ensuing harm to the larger ecosystem. There are several principal attributes of sentinel habitats. They should be key structural components of ecosystems that have important roles in sustaining overall ecosystem function (e.g., nursery habitat, feeding grounds, mineral cycling, biological productivity). The amount and complexity of the sentinel habitat has a major influence on the condition of the ecosystems in which it exists or are adjacent to it. This complexity and the impacts on the habitat are at least partially understood by scientists and appreciated by the public. They generally receive high exposure to stressors (e.g., frequently located in shallow water in environments with limited capacity to dilute pollutants or modulate environmental change) and are sensitive to changes in environmental conditions, particularly multiple stressors. Sentinel habitats should also be easily observed to ensure changes can be measured. Close proximity to land and shallow depth are some useful attributes.

One example of a sentinel habitat is coral reefs. Tropical coral reefs exist within narrow ranges of environmental condition and tolerate limited fluctuation in these conditions. As an important part of the global carbon budget, coral reefs are a crucial life support system of the biosphere and are one of the first major ecosystems to show significant impacts including loss of diversity, increased incidence of disease, reduced growth, reduced reproduction, and mass mortality (Richmond, 1993; Hoegh-Guldberg, 1999; Nystrom et al., 2000; Knowlton, 2001; Porter and Tougas, 2001; Patterson et al., 2002; Turgeon, et al., 2002) from global climate change and anthropogenic stresses. These habitats are experiencing rapid declines from deteriorating environmental conditions across the globe (Dustan and Halas, 1987; Bryant and Burke, 1998; Dustan 1999, Hoegh-Guldberg 1999; Wilkinson 1999). Recent reports indicate that 58–70% of coral reefs worldwide are directly threatened by human-associated activities, while over 80% of the Caribbean reefs have disappeared in the last 30 years (Bryant and Burke, 1998; Wilkinson 1999, Hoegh-Guldberg 1999; Goreau et al., 2000). Throughout the geologic record, reef ecosystems typically have been most impacted by global climate change. As human activities have elevated anthropogenic stresses to a global scale, changes in reef ecosystems can provide a sensitive indicator of not only global ecosystem health, but also near coastal environmental health; both of which influence human health. Clearly, global climatic changes have been linked to such disease outbreaks as *Vibrio cholera* and *V. parahemolyticus* (see excerpts from Monsoons to Microbes and Colwell 1996) while the increased use of chemicals (e.g., herbicides and pesticides, domestic and industrial sewage) provide an obvious avenue for long-term negative effects involving development and reproduction through endocrine disruption as well as life threatening pathologies (i.e. cancer) and chronic diseases (i.e. asthma and various allergies).

Significant opportunities for advancement with sentinel habitats and marine biological models include the following:

- Integrate the sentinel habitat approaches with data from environmental observations and human epidemiological studies to understand, predict, mitigate and prevent health risks to humans from ocean-borne pathogens, toxins and chemical contaminants, including both well-known and emerging threats and cumulative impacts of multiple stressors.
- Increase research and monitoring to understand the sources, fates, effects, and human health threats of contaminants, pathogens, and toxins in sentinel habitats, including possible roles as reservoirs of such threats; effects on ecosystem productivity, function and resilience; and the potential for use of sentinel habitats within the Integrated Ocean Observing System.
- Develop conceptual models that can then be used for developing forecasting capabilities.

Conceptual Model

As noted above, tidal creek networks are the primary hydrologic link between estuaries and land based activities. As the first zone of impact for non-point source pollution runoff, the potential for the microbial and chemical contamination in tidal creek habitats is great. Developing a conceptual model is a critical step to identifying and evaluating monitoring and management strategies including what parameters to measure and when and where measurements should be taken (NRC 1990). Holland et al. (2004) developed a conceptual model to provide a written or graphical description of the source-receptor links between the origin of an environmental problem (e.g., human activity, extreme natural event, linkages between ocean processes) and anticipated impacts on ecosystems. This is an essential first step in understanding a problem (Barnthouse and Brown 1994, Salia 1979). The model was mirrored after the EPA Ecological Risk Assessment model with stressors leading to changes in the physical-chemical environment (i.e., exposures) which result in a biological response.

The original conceptual model for tidal creeks proposed by Holland et al. (2004) did not include a number of new indicators or the relationship the environment has on the health and welfare of humans. Historically, scientists have only looked at human impacts on the environment but are starting to recognize the how those environmental changes then impact humans. Based on the data collected by Holland et al. (2004) and the Oceans and Human Health program at HML, the conceptual source-receptor model presented in Figure 4 was developed. This model provides an overview of the linkages between coastal development and associated human activities, "key" changes in the physical-chemical environment, and anticipated responses of tidal creek ecosystems and human systems. This model continues to be updated and revised as new information presents itself. For this case study, the model has been limited to key parameters related to microbial and chemical contamination and the related impacts. The elements of the model are being validated in South Carolina, North Carolina, and Georgia and have been useful for communication of results to general and technical audiences.

The tidal creek conceptual model identified adverse changes in the physical and chemical environment (e.g., water quality indicators such as indicator bacteria for sewage pollution or sediment chemical contamination) generally occurred when impervious cover levels in the watershed reach 10-20%. Ecological processes responded and were generally impaired when impervious cover levels exceeded 20-30% in suburban and urban watersheds (Figure 4). There is an emerging consensus that patterns of coastal development are associated with evidence of increasing fecal pollution in tidal creeks, estuaries, and bathing beaches (Mallin et al. 2000b, Karn and Harada 2001, Holland et al. 2004, Mallin 2006). From a human health perspective, the accumulation of pathogens in the water, sediments, and organisms may render seafood products unsafe to eat and water unsafe for body contact recreation. Flooding vulnerability, public health risk, and the economic impacts are also being considered. Estimates of impervious surface levels defining where human uses are impaired are currently being determined, but it generally appears that shellfish beds closures and the flooding vulnerability of headwater regions become a concern when impervious cover values exceed 20-30%.

The tidal creek conceptual model also provides a framework for defining system feedback loops and identifying which level of government is responsible for ensuring appropriate actions are taken to remediate and restore impaired systems (Figure 4). County and municipal governments are responsible for regulating land use activities and making most zoning decisions and are the agencies controlling impervious cover levels. State and federal governments mainly influence physical-chemical exposures (water and sediment quality) and ecosystem condition.

Forecasting

The relationship between watershed development and the ecological condition of the headwater reaches of tidal creeks in SC is fairly well-understood (Sanger et al. 1999a, 1999b, Lerberg et al. 2000, Holland et al. 2004), but spatial and temporal variability and patterns in ecological condition along tidal creek networks are poorly characterized. Effective monitoring, assessment, and prediction of the effects of coastal urbanization on tidal creeks and estuaries require that this variability be understood. Stratification of tidal creek networks into units that represent relatively homogenous environments or creek classes is one tool for characterizing and understanding the variability within tidal creek networks. This stratification is crucial for understanding at what scale land use impacts can be observed. Classifying watersheds that drain into specific creek networks based on the degree and type of development that has occurred is a tool and requirement for understanding variability among creek networks and forecasting the impacts of development.

In addition to reducing the variability within a creek using a classification system, other metrics must also be added to provide forecasting ability. One particularly important component is modeling the volume and rate of runoff leaving the upland. Smith (2003) found runoff leaving developed creeks occurred over hours immediately following the rain event compared to a reference creek with runoff occurring more slowly over a period of a day. However, measuring the volume and rate of runoff entering into tidal creeks is an expensive and time consuming activity. Therefore, other opportunities such as modeling the volume and rate need to be explored to determine the potential impact of the volume and rate of water entering into tidal creek ecosystems. Existing models such as Soil Conservation Service TR-55, can be modified for the southeastern US region to estimate the volume and runoff for a variety of rainfall events and under different development scenarios (i.e., change the impervious cover).

Most importantly, the tidal creek study and conceptual model, provides a framework for predicting the effects changes in watershed attributes and impervious cover associated with coastal development (Figure 5a) have on hydrographic characteristics of creeks (Figure 5b) and ultimately on indicators of water quality and ecosystem condition such as bacterial indicators (Figure 5c). Based on these relationships it is possible to use simple linear relationships to forecast the likely effects increases in impervious cover may have on critical indicators of ecosystem and public health (Figure 5d). The forecast models can be used by planners, developers, and managers to understand the potential impacts of a development before building instead of years after.

CONCLUSIONS

In the Southeastern U.S., the coastal uplands adjacent to tidal creeks and salt marshes are increasingly popular targets for building new homes, resorts, retirement destinations, and recreational facilities. These tidal creek networks are also critical feeding grounds, spawning areas, and nursery habitats for many species of fish, shellfish, birds, and mammals. Tidal creeks also form the primary hydrologic link between estuaries and land-based activities and, as such, reflect the impacts of coastal development earlier than larger coastal waterbodies (Holland et al. 2004). Nonpoint source pollution (e.g., stormwater runoff) carries sediments, chemicals, bacteria, viruses, and other pollutants into tidal creeks and salt marshes and degrades water quality.

The picture emerging from OHH tidal creek research in the Southeast suggests that for most environmental quality and public health indicators evaluated, the signal of land use effects on tidal creek ecosystems and human risk is strongest in shallow, Order 1 creeks. The degree of impact and risk decreases in Orders 2 and 3 creeks (e.g., Figures 2).

The scale of our tidal creek study watersheds (100s to 1000s ha) is also the spatial scale at which coastal land use decisions and remediation actions typically occur. Land use decisions are made at the local scale which requires information to be provided at the right scale. If creeks draining watersheds this size, especially the headwater portions of those watersheds, are valuable indicators of impacts from land use activities and urbanization, managers or land use planners are afforded a valuable tool to predict the impacts of developments on pathogen indicator concentrations in nearby tidal creeks and thereby inform the decision-making process.

The next two logical questions are: (1) how much is too much, and (2) what do to mitigate the impacts of coastal development. The carrying capacity is a difficult question to answer. The mitigation question is already being tested with the use of Best Management Practices (BMPs), such as stormwater ponds and low impact development (LID) practices. Current research indicates that the BMPs commonly in use today (e.g., stormwater ponds) are not providing the necessary benefits that was once hoped for.

First order tidal creeks are sentinel habitats for the following reasons: (1) important nursery habitats, (2) the direct connection with the upland, (3) impacts of development can be observed at this scale providing early warning, and (3) similar in watershed size as compared to the size of most developments in the southeast. Therefore, these tidal creeks, particularly the headwaters, have the potential to serve as sentinel habitats for early warning of the impacts of coastal development on the estuarine system with the potential for providing a forecasting tool.

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LITERATURE CITED

To be added

LIST OF ABBREVIATIONS

To be added

FIGURES

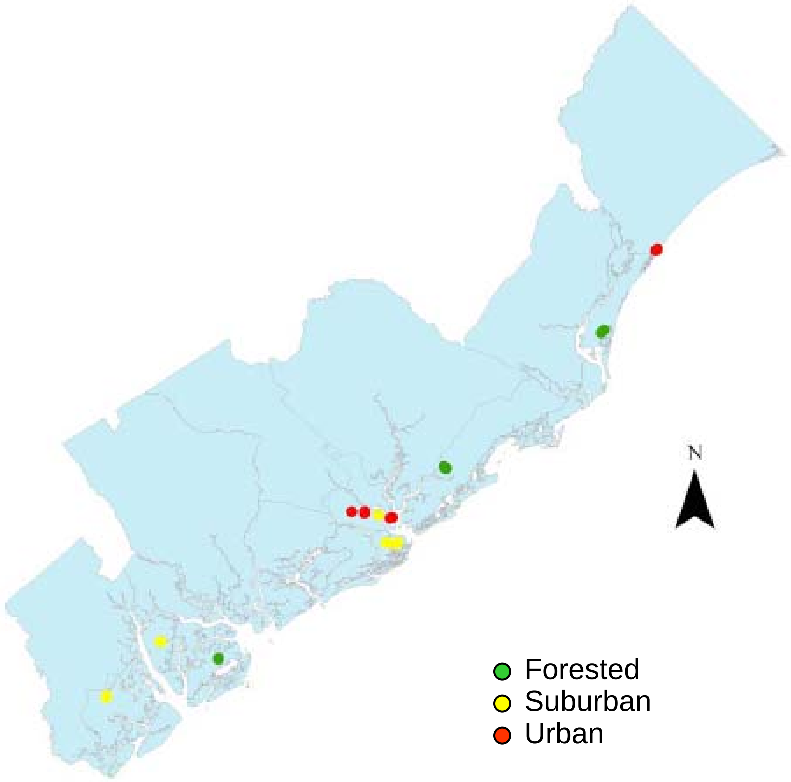

Figure 1. The South Carolina (U.S.A) coastal region and the locations of creeks sampled in 2005. Symbols indicate land use type in the surrounding watershed (green, forested; yellow, suburban; red, urban).

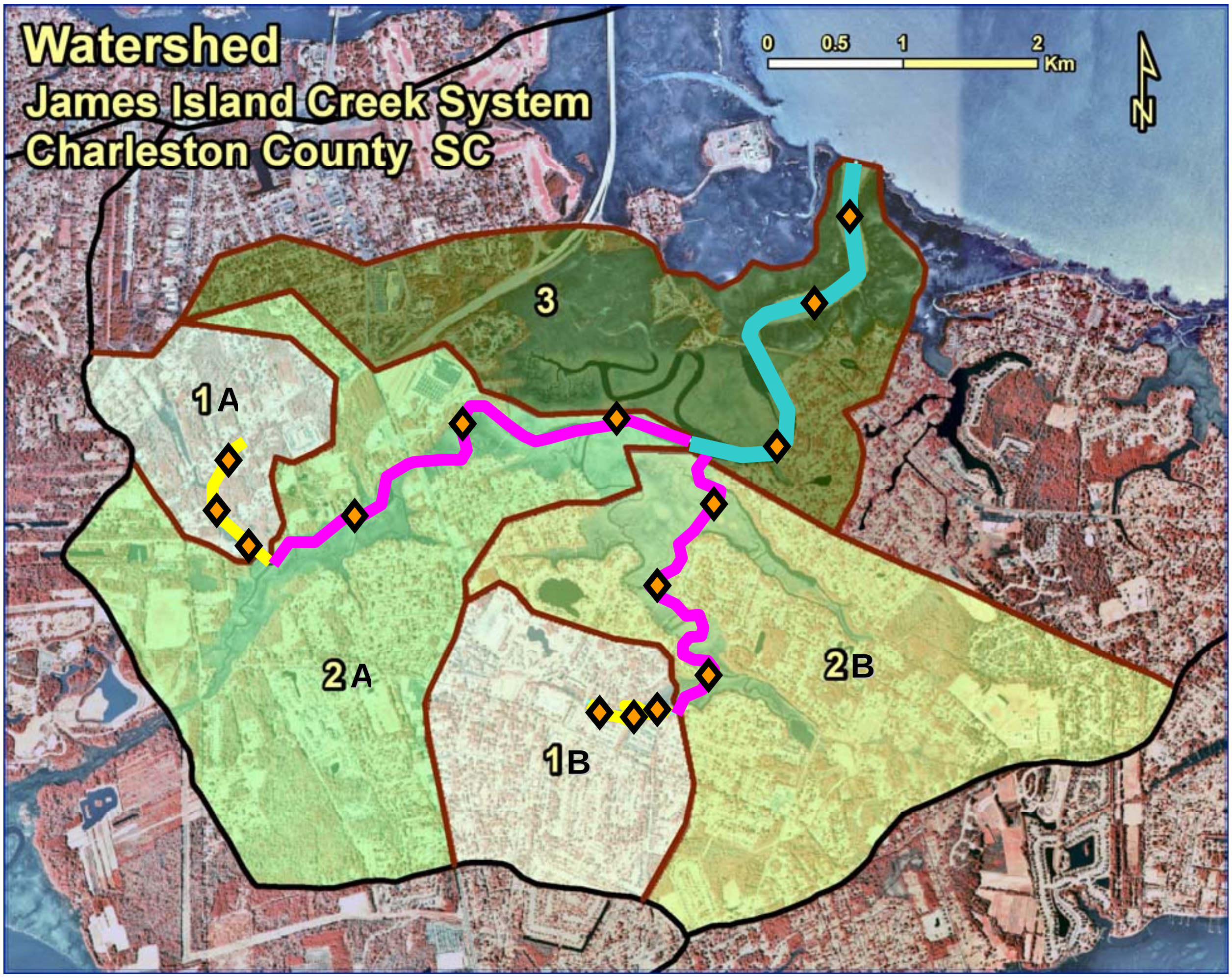

Figure 2. An example of the sample design for James Island Creek, Charleston, South Carolina, U.S.A. The diagram identifies the classification scheme (yellow, order 1; pink, order 2; teal, order 3), watershed boundaries for each system sampled (white, order 1; yellow-green, order 2; green, order 3), and sampling points (identified as orange triangles). In this example, two first and second order creeks and one third order creek was sampled. The underlying aerial is a 1994 digital ortho-quarter quad compliments of the SC Department of Natural Resources.

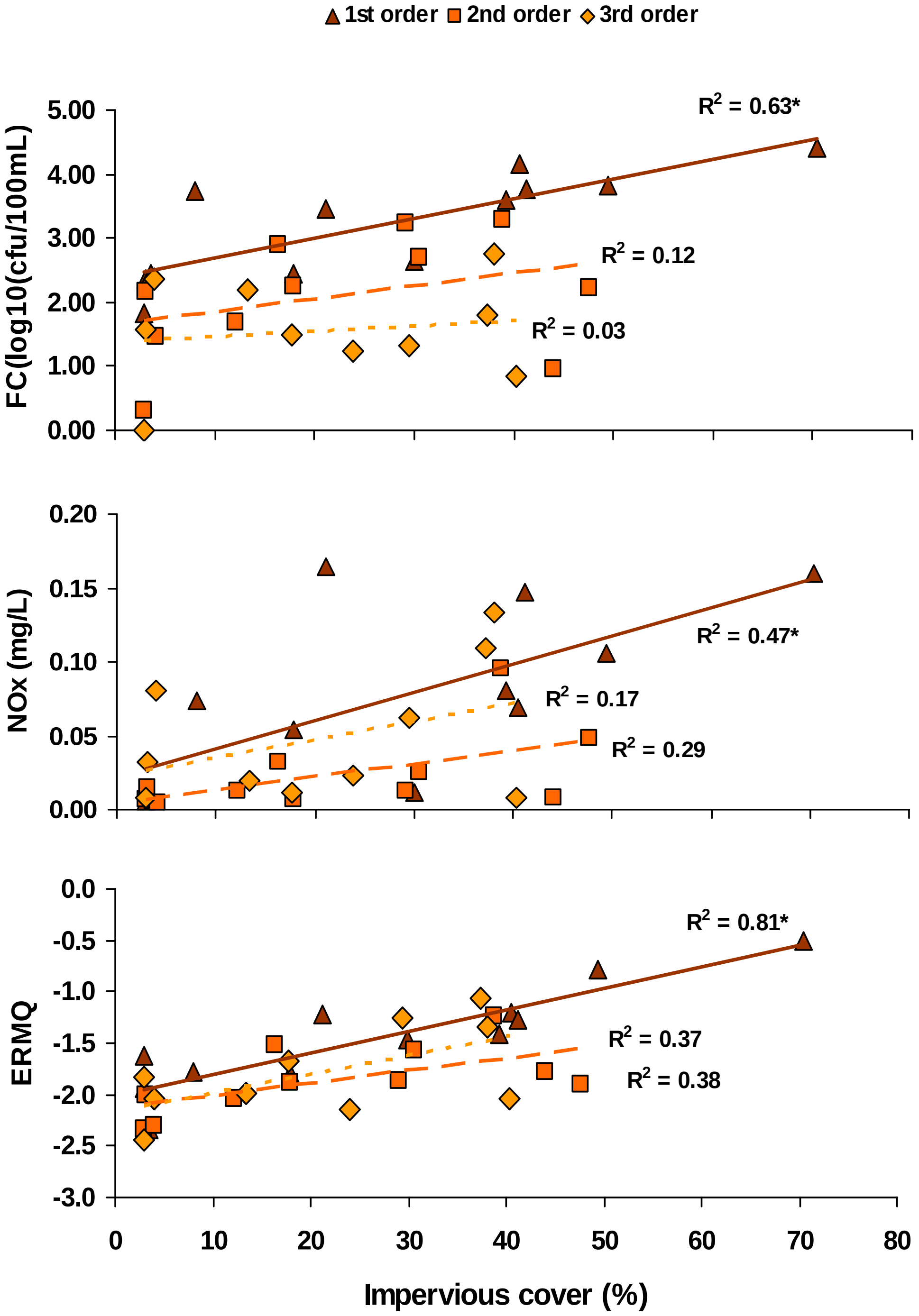

Figure 3. Results for sampled fecal coliforms (FC), nitrate/nitrite (NOx), and effects range median quotient (ERMQ) for each order. R^2 and p-values are provided for significant regressions ($\alpha = 0.05$).

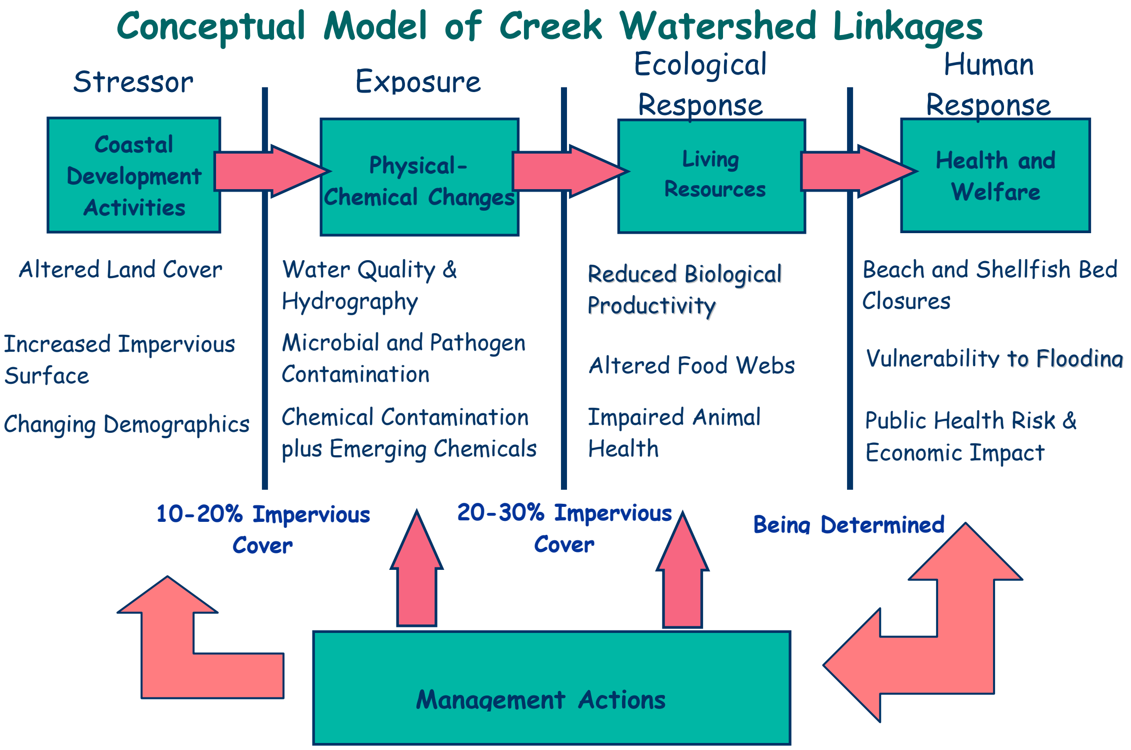

Figure 4. Tidal creeks conceptual model linking coastal development to environmental quality, ecological and human responses.

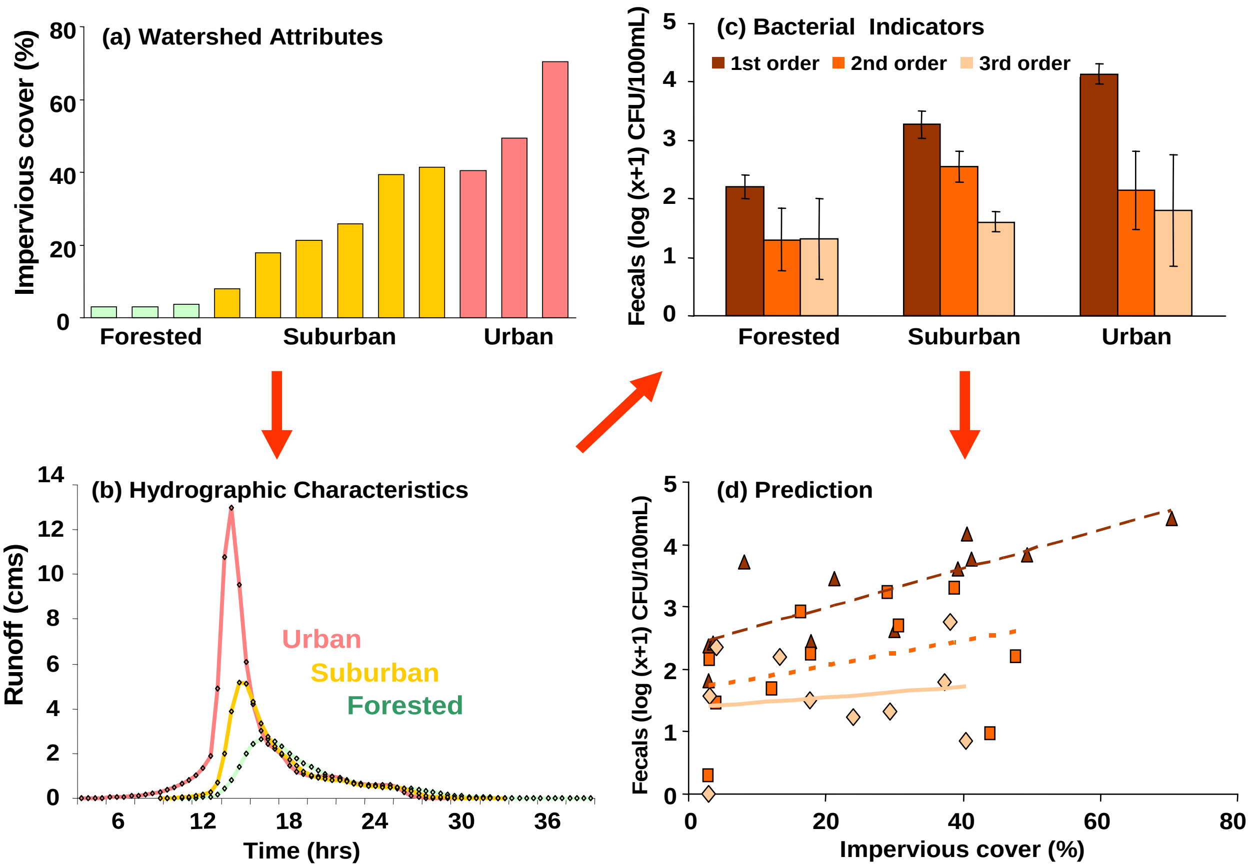

Figure 5. Potential tidal creek forecasting approach using fecals coliforms as an example parameter.