

# Incorporating geomorphic zonation in nutrient models for coastal-estuarine environments: coupling GIS and aquatic ecosystem modeling

**E.M. Bruce**<sup>a</sup>, **L.C. Bruce**<sup>b</sup> and **P.J. Cowell**<sup>a</sup>

<sup>a</sup> *Geocoastal Research Group, School of Geosciences, Faculty of Science, University of Sydney, NSW, 2006, Australia*

<sup>b</sup> *School of Earth and Environment, The University of Western Australia, Crawley WA 6009, Australia.*

*Email: [eleonor.bruce@sydney.edu.au](mailto:eleonor.bruce@sydney.edu.au)*

**Abstract:** Estuaries provide an important role in filtering and transforming nutrients transported from catchment areas into marine environments. The dynamic interactions between biophysical processes operating within these systems will influence the vulnerability of an estuary to human induced change. Process-based aquatic ecosystem models have been applied to coastal estuaries to understand how these systems respond to anthropogenic nutrient enrichment. These models account for system-level responses that are specific to estuarine environments including the sensitivity of benthic sediments and associated biota to eutrophication and the role of substratum condition in altering nutrient flux. However, there is a need to explicitly recognise the spatial heterogeneity of benthic sediments associated with the underlying geomorphology in these models. The intent of this paper is to determine how the incorporation of estuarine geomorphic zonation within an aquatic ecosystem model affects estimates of nutrient flux associated with spatial variation in depositional environment. GIS is coupled with a simple aquatic ecosystem model for a tide-dominated drowned river estuary to examine the influence of geomorphic setting.

**Keywords:** *estuarine geomorphology, Geographical Information Systems (GIS), Aquatic Ecosystem Models (AEM), sediment flux, nutrient cycling, coastal management*

## 1. INTRODUCTION

Quantifying the transformation, cycling, transport and ultimate fate of nutrients in estuarine environments is of paramount importance to coastal management due to the role that nutrients play in the bottom-up control of estuarine ecosystems. Estuarine nutrient loads act as a source for primary producers and limit the potential rate of net primary production (Howarth, 1988). In the context of estuarine management this potential can be viewed as either positive in relation to harvestable yield of secondary producers in estuaries (Grelowski *et al.*, 2000) or negative in that excessive nutrient loads can lead to eutrophication, associated toxic algal blooms and ecosystem deterioration (Duarte *et al.*, 2009). Either way quantification of estuarine nutrient loads is necessary for effective coastal management given the wide-spread economic impacts for both the fishery and recreational industries. To this extent Aquatic Ecosystem Models (AEMs) are frequently applied to aid decision making on nutrient load management to estuarine environments (Robson *et al.*, 2008; Webster and Harris 2004; Soetaert and Herman 1995). As the level of nutrient flux between benthic sediments and the water column is a key variable of many AEMs it is important to understand how levels of substrate nutrient stores may vary within an estuary. Based on the assumption that benthic nutrient flux is influenced by depositional environment, the intent of this paper is to investigate how the incorporation of estuarine geomorphic zonation within an aquatic ecosystem model affects estimates of benthic nutrient flux.

Based on an evolutionary estuarine facies model Roy *et al.* (2001) identify four geomorphic zones within south-east Australian estuaries: (1) marine flood-tidal delta; (2) central mud basin; (3) fluvial delta; and (4) riverine channel and alluvial plain. Each geomorphic zone has characteristic substratum conditions, hydrological regimes and nutrient cycling behaviours. The aerial extent of these zones will reflect the evolutionary stage or level of sedimentary infilling of the estuary (Roy *et al.*, 2001). Estuary evolution and associated changes to geomorphic zones has important implications for understanding patterns of nutrient cycling. There is a need to account for evolutionary stage of an estuary in modeling nutrient flux as (1) infilling trends influence water volume, estuary shape (relevant to tidal induced mixing and current movements) and turbidity levels and; (2) benthic substrate nutrient stores vary between geomorphic zones. This paper focuses on the second point to examine the role of geomorphic zonation in providing improved estimates of sediment nutrient flux.

Rates of nutrient cycling within the water column and flux across the sediment-water interface have been linked to benthic hydrodynamics (Oldham and Lavery, 1999), sediment type (Reay *et al.*, 1995) and water clarity (Wang *et al.*, 1999). For example, the central mud basin and inter-distributary embayments in fluvial deltas are major repositories of nutrients within estuaries due to the dominance of finer grained sediments and limited disturbance by wave and current movement (Roy *et al.*, 2001). In the current study nutrient cycling domains are based on geomorphic zonation and photic zone depth is used in estimating primary productivity.

The model is applied to the Berowra Creek estuary, a cut-off embayment in the Hawkesbury River, a tide-dominated, drowned river estuary. The Berowra Creek estuary has been formed by the seaward progradation of the fluvial delta front associated with non-uniform rates of infilling in the Hawkesbury. Cut-off embayments trap organic material and act as nutrient factories (Roy *et al.*, 2001). The main depositional environments within Berowra Creek estuary are classified into (1) fluvial delta (2) estuarine mud basin (3) fluvial delta/mud basin and, (4) intertidal zones (Figure 1). These zones were mapped based on surficial sediment sample data and bathymetry, the smaller fluvial deltas were defined by abrupt changes in bathymetry and occurrence of sandy sediments (Coastal and Marine Geosciences, 1998).

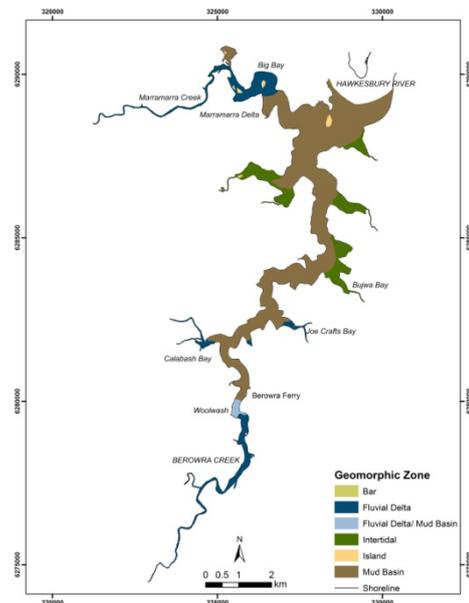


Figure 1. Berowra Creek estuary geomorphic zones.

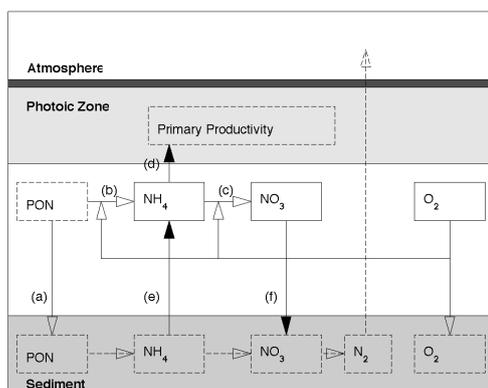
## 2. METHODS

### 2.1 Model configurations

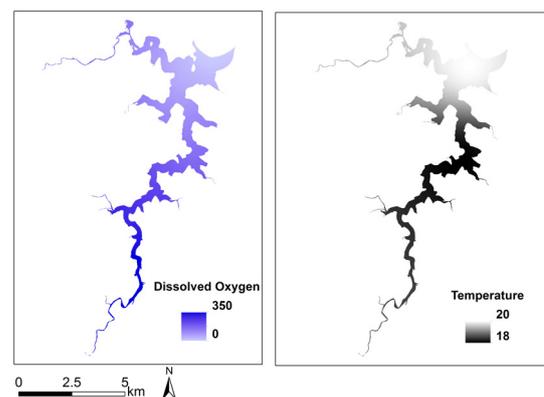
Spatial variability in benthic sediment nutrient cycling rates across an estuary is examined by incorporating aquatic ecosystem modeling principles within a GIS environment. Nitrogen flux across the sediment water interface is estimated under three model configurations with the same input conditions to examine the influence of benthic sediment heterogeneity. Configuration 1 assumes homogeneity in benthic sediment and depositional environment across the estuary and assigns a constant value for sediment ammonium concentration and surface sediment porosity. Configuration 2 uses a continuous surface for sediment ammonium concentration derived from interpolated sediment sample data and a constant surface sediment porosity value. In configuration 3, both ammonium concentration and sediment porosity are determined by estuarine geomorphic zonation. Model outputs of net nitrogen flux are then used to estimate primary productivity potential across the estuary.

### 2.2 Estimating benthic sediment flux

The flux of ammonium from the sediments to the water column is assumed to depend on the overlying oxygen concentration and diffusive properties of the sediment according to Fick's First Law (Figure 2). Although base assumptions have been made in the derivation of this function it has proved to be a sufficient first estimate under favorable estuarine conditions (Lavery *et al.*, 2001). Estimation of the rate of nitrate flux into the sediments is dependent on overlying water column oxygen concentrations and used as a proxy to determine rates of estuarine nitrogen assimilation via sediment denitrification.



**Figure 2.** Conceptual model of equations used to derive model results. Solid lines represent flux explicit to the model and dashed lines represent processes implicit to the model. Processes: (a) PON settling; (b) PON mineralisation; (c) nitrification; (d) uptake by primary producers; (e) NH4 sediment flux; (f) NO3 sediment flux



**Figure 3.** Simulated benthic oxygen and temperature ( $^{\circ}\text{C}$ ) profile for Berowra Creek estuary.

The flux of ammonium across the sediment water interface was estimated using equation 1 (adapted from Bruce and Imberger, 2008).

$$f_{sed}^{NH_4} = F_{max}^{NH_4} \frac{K_{sed}^{NH_4}}{K_{sed}^{NH_4} + O_2} (\theta_{sed}^{NH_4})^{T-20} \quad (1)$$

Where,  $O_2$ , is the concentration of oxygen in the benthic layer ( $\text{mmolO}/\text{m}^3$ ),  $K_{sed}^{NH_4}$ , is the half saturation constant for oxygen dependence of sediment ammonium flux (estimated at  $40 \text{ mmol}/\text{m}^3$ ),  $\theta_{sed}^{NH_4}$  is an Arrhenius temperature multiplier (set to 1.08) and  $F_{max}^{NH_4}$ , the maximum flux of ammonium is defined based on Lavery *et al.*'s (2001) numerical approximation of Flick's Law,

$$F_{max}^{NH_4} = \phi D_{NH_4} \frac{\Delta C_{NH_4}}{\Delta z} \quad (2)$$

Where,  $\varphi$  is the sediment porosity ( $\text{m}^3$  porewater /  $\text{m}^3$  bulk sediment) dependent on sediment type,  $D_{NH_4}$  is the diffusion coefficient for ammonium ( $1.4 \times 10^{-9} \text{ m}^2/\text{s}$ ),  $C_{NH_4}$  is the concentration of ammonium in the sediments ( $\text{mmol N}/\text{m}^3$ ) and  $\Delta z$  is the depth of sediment (assumed for the purpose of this study to be constant at 1mm).

The flux of nitrate across the sediment water interface was estimated using equation 3

$$f_{sed}^{NO_3} = F_{max}^{NO_3} \frac{O_2}{K_{sed}^{NO_3} + O_2} (\theta_{sed}^{NO_3})^{T-20} \quad (3)$$

Where,  $K_{sed}^{NO_3}$ , is the half saturation constant for oxygen dependence of sediment nitrate flux (estimated at 100  $\text{mmol}/\text{m}^3$ )  $\theta_{sed}^{NO_3}$  is an Arrhenius temperature multiplier (set to 1.08).

The rate of ammonium and nitrate flux was then used to estimate net nitrogen flux as a measure of nitrogen assimilation efficiency using equation 4.

$$f_{sed}^{N_{Net}} = f_{sed}^{NH_4} - f_{sed}^{NO_3} \quad (4)$$

### 2.3 Primary Productivity Potential

Assuming primary productivity to be nitrogen limited in the estuary (Howarth, 1988), primary productivity potential has been defined in this study as the potential increase/reduction in primary productivity due to net nitrogen sediment flux. Assuming that all nitrogen flux is available for primary production in the photic zone (defined here as the top 2m of the water column), potential is estimated for the estuary using equation 5.

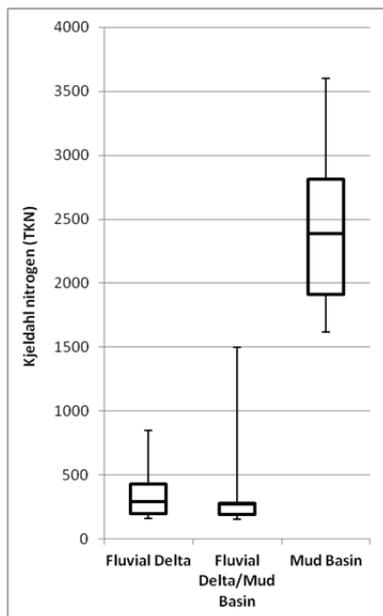
$$PP_{potential} = Y_{C:N} f_{sed}^{N_{Net}} \frac{h_{photic}}{h_{wc}} \quad (5)$$

Where  $Y_{C:N}$  is the Redfield molecular ratio of carbon to nitrogen (106:16) consumed in photosynthesis.

### 2.4 GIS application

The aquatic ecosystem model (Figure 2) was developed in ESRI ArcGIS 10 Model Builder using Spatial Analyst map algebra functions.

The dissolved oxygen raster surface was derived using cost distance analysis to account for increased concentration with distance from the estuary mouth associated with the oxygen saturation gradient from marine to freshwater dominated sections of the estuary. Water temperature is recorded at water monitoring probes within Berowra Creek estuary. These data were interpolated to derive a continuous water temperature surface for input into the model using the ArcGIS Inverse Distance Weighted (IDW) with barriers function to allow for discontinuities associated with supra-tidal areas (Figure 3).

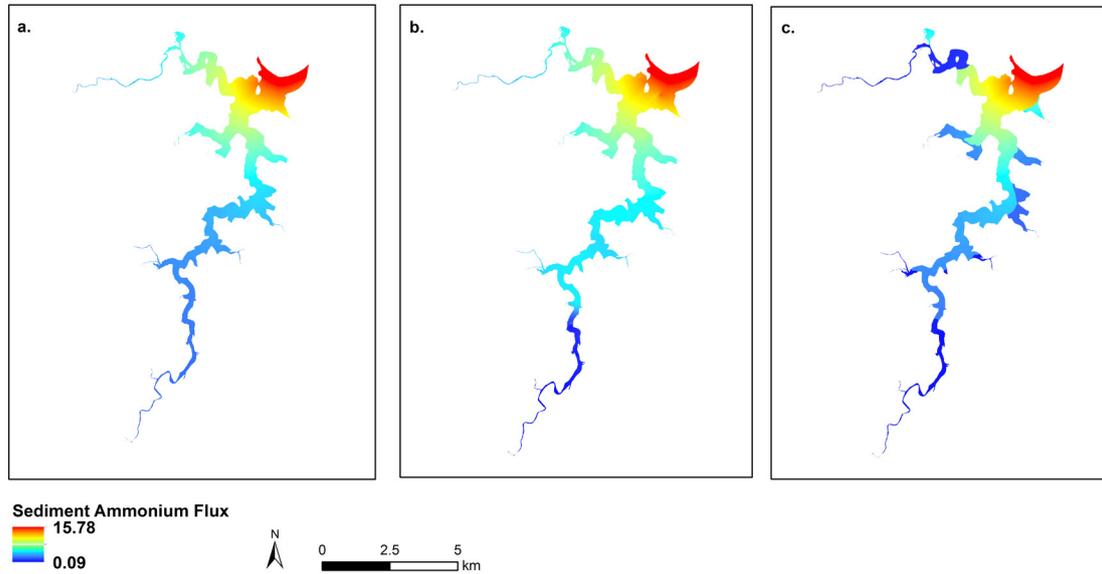


**Figure 4.** Distribution of Kjeldahl nitrogen (TKN) data sampled within the Berowra Creek estuary (Hornsby City Council, 1997)

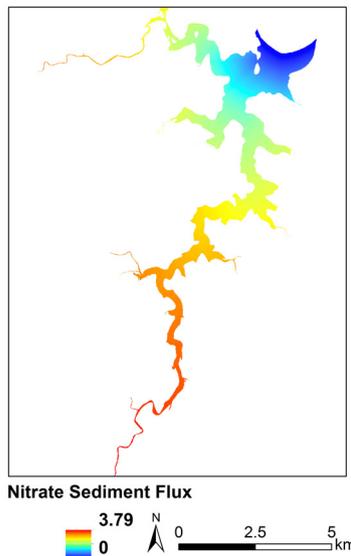
The raster layer for concentration of ammonium in the benthic sediments was generated for configuration 2 of the model through linear interpolation and for configuration 3 based on estuarine geomorphic zonation. A total of 44 surface sediment grab samples in which total Kjeldahl nitrogen (TKN) was recorded were used as a measure of ammonium concentration (Figure 4). Average concentrations of sediment ammonium were assigned to each zone based on geomorphic zonation literature (Roy *et al.*, 2001 and Rochford, 1951) and sample averages.

### 3. RESULTS AND DISCUSSION

Common to each model configuration is a clear pattern in the gradient of ammonium sediment flux, increasing from riverine to bay waters (Figure 5). When sediment properties are accounted for in configuration 2, using a linear interpolation increased fluxes were simulated in the nutrient rich central basin (Figure 5b). With consideration of geomorphology (configuration 3) spatial variability in ammonium sediment flux based on distinct patterns of zonation is evident (Figure 5c). Although the fluvial delta/mud basin transition is evident in Figure 5b lower levels of nutrient enrichment potentially occurring in the smaller fluvial deltas is not represented in model configurations 1 and 2.



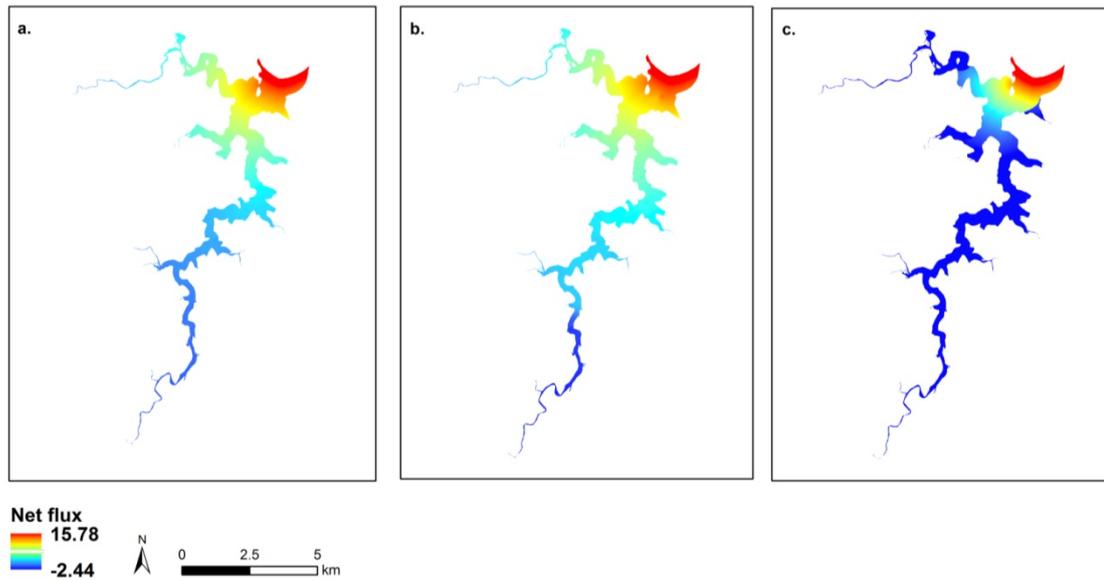
**Figure 5.** Sediment ammonium flux for Berowra Creek Estuary estimated for (a.) Model configuration 1 assuming homogeneous sediment condition, (b) Model configuration 2 based on interpolated sediment nutrient sample points and (3) Model configuration 3 based on geomorphic zonation.



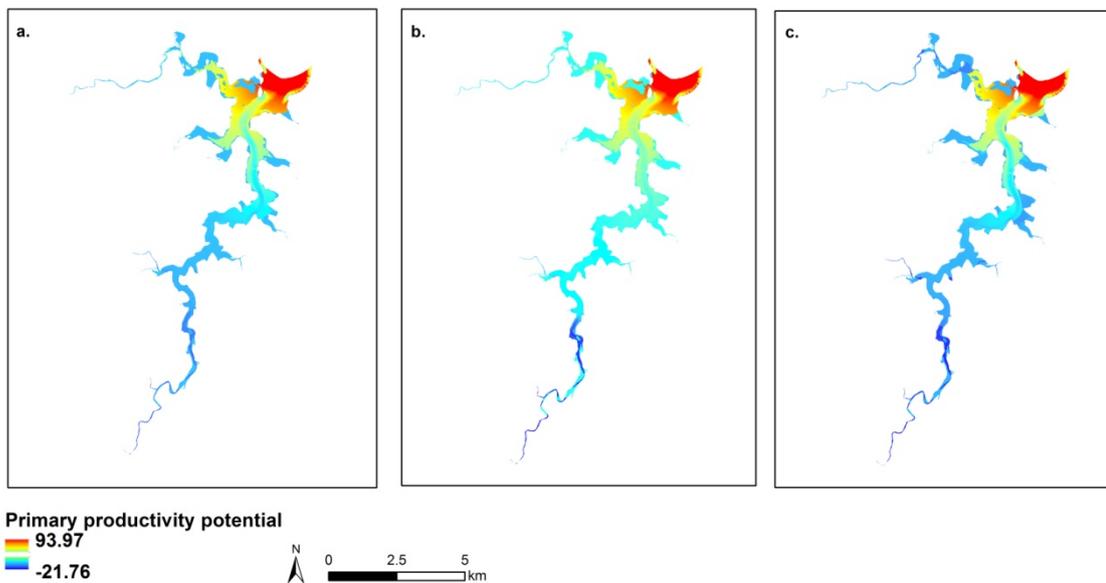
Simulated flux of nitrate into the sediment (Figure 6) has been parameterized as a function of oxygen concentration and shows a direct comparison to the oxygen profile (Figure 3). Highest rates of sediment denitrification occur in the upper reaches of the estuary in the highly oxic riverine waters and lowest at the strongly stratified downstream confluence with the Hawkesbury.

The simulated balance between sediment demand and release of nitrogen is dependent on both water column and sediment properties and show clear differences between sediment model configurations selected (Figure 7). Highest rates were simulated in muddy sediment environments with low oxygen and are lowest in high oxygen sandy sediment environments. Primary productivity estimates simulated in model configuration 3 (Figure 8c) provide a more appropriate relative estimate for intertidal mudflat environments and upstream fluvial deltas.

**Figure 6.** Sediment nitrate flux for Berowra Creek estuary.



**Figure 7.** Net sediment nitrogen flux ( $\text{mmol/N/m}^2/\text{day}$ ) for Berowra Creek Estuary estimated for each model configuration.



**Figure 8.** Primary productivity potential ( $\text{mmol/C/m}^2/\text{day}$ ) for Berowra Creek Estuary estimated for each model.

Geomorphic zones have characteristic substratum conditions, hydrological regimes and nutrient cycling behaviours and correspond to units that can be mapped using high resolution remotely sensed imagery, bathymetry and sediment records (Roy *et al.*, 2001). In the absence of finely sampled substrate sediment data geomorphic zonation provides a basis for establishing patterns of spatial variability in benthic nutrient flux. Nutrient enrichment levels are linked to depositional environments within an estuary with nutrient sinks associated with mud basin deposits. Knowledge of underlying geomorphology and estuarine evolutionary stage can also provide a framework for improving benthic sediment sampling design in the collection of empirical data used in aquatic ecosystem models.

This study presents a preliminary investigation and further research is required to refine interpolation techniques, establish model validation methods and examine general pattern over a range of estuary types. Estuaries are irregularly shaped non-convex regions presenting a challenge for the interpolation of point samples and Euclidean distance may not be an appropriate distance metric (Rathbun, 1998, Little *et al.*, 1997). Geostatistical techniques that account for barriers should be considered (Olaf *et al.*, 2006). Estimates

of nutrient flux across the sediment-water interface simulated in the current model should be incorporated into a comprehensive AEM to establish actual primary productivity to allow validation of this approach at a fine temporal scale. The principle of estuarine geomorphic zonation is based on an evolutionary facies model (Roy *et al.*, 2001) and comparative analysis through application of the model to estuaries of differing type (wave dominated, barrier and intermittent estuaries) and evolutionary stage is required.

#### 4. CONCLUSIONS

This paper presents a method for incorporating geomorphic zonation when estimating nutrient flux across the sediment-water interface in process-based biogeochemical models for coastal estuarine environments. Differences in the estimates for net nutrient flux and primary productivity potential obtained from the three model configurations demonstrates the importance of considering spatial variability in sediment condition and the possible limitations associated with reliance on interpolated benthic sample data. The translation of estuarine evolutionary principles within aquatic ecosystem models has the potential to improve estimates of sediment nutrient flux. Consideration of geomorphically governed spatial variability in benthic nutrient cycling has important implications for estuarine management. Although sediment nutrient flux is one component within complex aquatic ecosystem models, these simulations are used in assessing the consequences of coastal management practices and poor estimates may result in inappropriate policy decisions.

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