Briefing Document

Estuarine Processes and Integrated Flood Mitigation

Executive Summary

This briefing synthesizes the **core principles of estuarine processes** and demonstrates their application in an integrated flood mitigation and ecosystem restoration project in Linden, New Jersey.

Estuarine hydrodynamics are fundamentally governed by the interaction between:

- **Freshwater inflow** from terrestrial sources, and
- **Saline water exchange** driven by ocean tides.

These forces regulate salinity gradients, vertical stratification, sediment transport, and overall hydraulic behavior.

Process quantification ranges from:

- Direct field measurement (Velocity–Area Method),
- Empirical formulas (Manning's Equation),
- To advanced numerical modeling tools.

A case study at **Marshes Creek in Linden, NJ** illustrates a multi-faceted response to chronic residential flooding. The project, led by Rutgers University in partnership with the City of Linden, integrates:

1. **Green Infrastructure (GI)** for stormwater control
2. **Hydraulic conveyance improvements** to a tidally restricted creek

Advanced hydrologic and hydraulic modeling using EPA-SWMM and HEC-RAS was essential for evaluating system response.

A central finding is the **non-linear relationship between tidal restoration and upstream flood risk**:

- During dry or low-rainfall conditions, removing tidal restrictions can *increase* upstream water levels.
- During major storm events (25-year to 100-year rainfall), improved conveyance *reduces* peak flood elevations.

This demonstrates the necessity of **integrated rainfall–tide modeling** for resilient coastal and estuarine infrastructure design.

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1. Core Principles of Estuarine Processes

Estuaries are dynamic transition zones governed by freshwater–saltwater interaction. Understanding these processes is essential for flood mitigation, ecosystem restoration, and climate adaptation.

1.1 Freshwater Inflow

Freshwater inflow is the primary terrestrial driver of estuarine behavior.

Sources of Inflow

- **Surface Streams:** River and watershed runoff (dominant source)
- **Groundwater Seepage:** Coastal aquifer discharge

Groundwater inflow can be estimated using **Darcy's Law**:

$$q_x = -K \frac{dh}{dx}$$

Where:

- K= hydraulic conductivity
- dh/dx= hydraulic gradient

Importance of Freshwater Inflow

Freshwater inflow:

- Controls salinity distribution and vertical stratification
- Influences sediment transport and deposition
- Delivers nutrients and pollutants
- Governs overall estuarine circulation dynamics

Quantification of Streamflow

Fundamental Discharge Relationship

$$Q = A \times V$$

Where:

- Q= discharge
- A= cross-sectional area
- V= mean velocity

Gauged Streams

1. Velocity–Area Method

- Cross-section divided into subsections
- Depth and velocity measured
- Total discharge summed

2. Stage–Discharge Rating Curve

$$Q = f(h)$$

This relationship is typically non-linear, with discharge increasing at an accelerating rate as stage rises.

Ungauged Streams

Manning's Equation

SI Units:

$$Q = \frac{1}{n} A R_h^{2/3} S^{1/2}$$

US Units:

$$Q = \frac{1.486}{n} A R_h^{2/3} S^{1/2}$$

Where:

- n= Manning's roughness coefficient
- A= flow area

- R_h= hydraulic radius
- S= channel slope

Typical Manning's n Values

Channel Description	Typical n
Concrete (trowel finish)	0.013
Concrete (unfinished)	0.017
Earth, straight/uniform	0.022
Natural stream, clean/straight	0.030
Natural stream, sluggish/weedy	0.070
Major streams (>100 ft width)	< 0.030

Hydrologic Modeling

Watershed-scale rainfall–runoff modeling is conducted using:

- HEC-HMS
- EPA-SWMM

These models generate inflow hydrographs for both gauged and ungauged basins.

1.2 Saline Water Exchange and Tides

Tides drive cyclical saline exchange with the ocean.

Tidal Phases

- **Flood Tide:** Incoming (landward) flow
- **Ebb Tide:** Outgoing (seaward) flow

Typical semidiurnal period ≈ 12.42 hours.

Tidal Prism

Definition:
The volume of water entering an estuary during a flood tide.

$$P_{flood} = \frac{2}{\pi} A_f T_f$$

Where:

- A_f= peak flood discharge
- T_f= flood duration

Example:
If $A_f = 1800\ m^3/s$and $T_f = 6.21$hours (22,356 s),
then tidal prism ≈ 25.6 million m³.

1.3 Estuary Classification and Dynamics

Simons Ratio

$$\text{Simons Ratio} = \frac{\text{Freshwater Volume}}{\text{Tidal Prism}}$$

Interpretation:

- 1 → Stratified estuary
- < 0.1 → Fully mixed estuary

Tidal Propagation

Without Friction:

$$c = \sqrt{gh}$$

Velocity in phase with elevation

- Reflection at closed ends → standing waves

With Friction:

- Tidal amplitude decays landward
- Velocity lags elevation

Tidal Flushing

Classical flushing time:

$$T_f = \frac{\text{Estuary Volume}}{\text{Tidal Prism + Freshwater Volume per Cycle}}$$

The “new ocean water” concept recognizes that only a portion of floodwater represents newly introduced ocean water.

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2. Numerical Modeling in Estuarine Management

Numerical models are essential for simulating rainfall–tide interactions and evaluating management interventions.

HEC-RAS

Developed by the U.S. Army Corps of Engineers.

Capabilities:

- 1D/2D steady and unsteady flow
- Sediment transport
- Mobile bed simulation
- Temperature and water quality
- Floodplain mapping (RAS Mapper)

EPA-WASP

Developed by the U.S. Environmental Protection Agency.

Functions:

- Water quality prediction
- Dynamic compartment modeling
- Linkage with hydrodynamic models
- Widely used in TMDL development

3. Case Study: Flood Mitigation and Ecosystem Restoration in Linden, NJ

3.1 Project Overview

The project focuses on the **Tremley residential community** at the head of Marshes Creek in Linden.

Problem Drivers

- Increased runoff from impervious surfaces
- Flow-restrictive culverts
- Sediment accumulation
- Tidal backwater effects

Partners

- Rutgers University
- City of Linden
- National Fish and Wildlife Foundation
- Phillips 66

3.2 Project Components

Component 1: Green Infrastructure

- Rain barrels
- Rain gardens
- Bioswales
- Porous pavement parking lot

Objective: Reduce runoff at the source.

Component 2: Hydraulic Capacity Recovery

- Culvert clearing
- Culvert enlargement
- Potential sluice gate installation

Objective: Improve tidal conveyance and reduce upstream backwater.

3.3 Modeling and Key Findings

Integrated modeling approach:

- Watershed runoff → EPA-SWMM
- Creek hydraulics → HEC-RAS

Model calibration demonstrated strong agreement with measured:

- Rainfall
- Runoff
- Water surface elevation
- Velocity

Modeled Peak Water Surface Elevations (WSEL)

Scenario	Description	Existing (m)	Proposed (m)	Change (m)
1	Tide Only	0.87	1.12	+0.24
2	Tide + 10-yr Rain	1.25	1.29	+0.04
3	Tide + 25-yr Rain	1.39	1.36	-0.02
4	Tide + 50-yr Rain	1.50	1.42	-0.08
5	Tide + 100-yr Rain	1.63	1.50	-0.12

Key Insights

Dry Weather:
Removing restrictions increases upstream tidal penetration (+0.24 m).

Wet Weather:
Beyond ~25-year rainfall threshold (~1.35 m WSEL), improved conveyance reduces peak flooding.

Extreme Event (100-year):
Peak flood level reduced by 0.12 m.

This non-linear system response underscores the importance of **coupled rainfall–tide simulation**.

3.4 Strategic Perspective

Local interventions align with broader resilience efforts:

- Blue Acres floodplain restoration
- Regional flood barrier proposals
- Surge protection at New York Harbor

Guiding philosophy:

In adapting to rising sea levels, infrastructure challenges must address both structural deterioration and environmental change. The optimal strategy is to retrofit aging systems into resilient ones—preferably through mobile and green approaches.

Concluding Perspective

The Linden case study demonstrates that:

- Estuarine systems require integrated freshwater–tidal analysis.
- Flood mitigation cannot be separated from ecosystem restoration.
- Numerical modeling is indispensable for evaluating non-linear hydrodynamic behavior.
- Green infrastructure and hydraulic retrofits must be designed together.

This integrated, science-based framework provides a replicable approach for coastal and estuarine communities facing intensified rainfall, tidal influence, and sea-level rise.