Briefing Document: Estuarine Processes and Integrated Flood Mitigation

Executive Summary

This document synthesizes key principles of estuarine processes and details their application in a flood mitigation and ecosystem restoration project in Linden, New Jersey. The analysis highlights that freshwater inflow and saline water exchange are the foundational drivers of estuarine hydrodynamics, controlling salinity, stratification, and sediment transport. Quantification of these processes relies on methods ranging from direct measurement (Velocity-Area Method) and empirical formulas (Manning's Equation) to sophisticated numerical modeling.

The case study of Marshes Creek in Linden, NJ, demonstrates a multi-faceted approach to addressing recurrent flooding in a residential community. The project, a collaboration led by Rutgers University, integrates two primary components: green infrastructure for stormwater management (e.g., rain gardens, porous pavement) and hydraulic capacity improvements to a tidally restricted creek. Advanced hydrologic and hydraulic modeling (using EPA-SWMM and HEC-RAS) was crucial for evaluating the interventions.

A central finding from the case study is the complex, non-linear relationship between restoring tidal flow and upstream flood risk. Model results indicate that while unrestricted flow can raise water levels during dry weather or low-rainfall conditions, it significantly reduces peak water surface elevations and lowers flood risk during major storm events (e.g., 25-year to 100-year rainfall). This underscores the necessity of detailed, integrated modeling to design resilient infrastructure that accounts for the combined influence of tides and rainfall.

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1. Core Principles of Estuarine Processes

Estuaries are dynamic systems governed by the interaction of freshwater from terrestrial sources and saline water from the ocean. Understanding these fundamental processes is critical for effective management.

1.1 Freshwater Inflow

Freshwater inflow is the primary source of fresh water to estuaries and plays a pivotal role in their physical and ecological characteristics.

- **Sources of Inflow:**
    - **Surface Streams:** Runoff from rivers and streams is the most significant source.

- **Groundwater Seepage:** Direct seepage from coastal aquifers contributes to freshwater input. This flow can be quantified using **Darcy's Law**, which states that the specific flow (`qx`) is linearly proportional to the hydraulic conductivity (`K`) and the hydraulic gradient (`dh/dx`).

- **Importance of Inflow:**
    - Controls salinity distribution and vertical stratification.
    - Affects sediment transport and deposition patterns.
    - Delivers essential nutrients as well as pollutants.
    - Serves as a key driver for overall estuarine hydrodynamics.
- **Quantification of Streamflow:**
    - **Fundamental Concept:** Discharge (`Q`) is the product of the cross-sectional area (`A`) and the mean velocity (`V`), expressed as `Q = A × V`.
    - **Gauged Streams:**
        - **Velocity-Area Method:** The stream's cross-section is divided into subsections where depth and velocity are measured to calculate total discharge.
        - **Stage-Discharge Rating Curve:** A continuous record of water level (stage) is used to determine a continuous flow record based on an established relationship, `Q = f(h)`. The relationship is typically non-linear, with discharge increasing at an accelerating rate as stage rises.
    - **Ungauged Streams:**
        - **Manning's Equation:** This formula for open channel flow calculates discharge based on channel geometry and material.
        - **SI Units:** `Q = (1/n) * A * R_h^(2/3) * S^(1/2)`
        - **US Units:** `Q = (1.486/n) * A * R_h^(2/3) * S^(1/2)`
        - Where `n` is Manning's roughness coefficient, `A` is flow area, `R_h` is the hydraulic radius, and `S` is the channel slope.
        - **Manning's Roughness Coefficient (n):** This empirical value depends on the channel material and condition. The table below provides illustrative values.

Channel/Stream Description	Typical `n` Value
Concrete, trowel finish	0.013
Concrete, unfinished	0.017
Earth, straight and uniform	0.022
Natural Streams, clean, straight	0.030
Natural Streams, sluggish, weedy	0.070
Major Streams (top width > 100 ft)	< 0.030

- **Hydrological Modeling:** Rainfall-runoff models like HEC-HMS and SWMM are used to generate inflow time series for entire catchments, which is especially useful for ungauged areas or analyzing specific storm events.

1.2 Saline Water Exchange and Tides

The exchange of saline water with the ocean is primarily driven by tides, which create cyclical patterns of water movement.

- **Tidal Dynamics:** The tidal cycle consists of two primary phases:
  - **Flood Tide:** The period of incoming or rising tide, where flow rate is negative (landward).
  - **Ebb Tide:** The period of outgoing or falling tide, where flow rate is positive (seaward).
  - A full tidal period is typically around 12.42 hours.
- **Tidal Prism:**
  - **Definition:** The volume of water that enters an estuary during the flood tide. It is a key parameter for classifying estuaries and assessing flushing.
  - **Calculation:** The tidal prism (`P_flood`) can be calculated from the tidal flow rate using the formula `P_flood = (2/π) * A_f * T_f`, where `A_f` is the peak flood flow and `T_f` is the flood duration.
  - **Example Calculation:** For a peak flood flow (`A_f`) of 1800 m^3/s and a semidiurnal flood duration (`T_f`) of 6.21 hours (22,356 s), the tidal prism is approximately 25.6 million m^3.

1.3 Estuary Classification and Dynamics

- **Classification by Salinity Structure:** The **Simons Ratio** classifies estuaries based on the relative strength of freshwater inflow versus tidal mixing.
  - **Formula:** `Simons Ratio = Volume of Freshwater Inflow / Tidal Prism`
  - **Interpretation:**
    - **Ratio > 1:** Indicates a **Stratified Estuary**, where freshwater flows over denser saltwater with limited mixing.
    - **Ratio < 0.1:** Indicates a **Fully Mixed Estuary**, where tidal forces are strong enough to mix the water column completely.
- **Tidal Propagation:** The behavior of the tidal wave changes as it moves up an estuary.
  - **Without Friction:** Celerity (wave speed) is given by `c = sqrt(gh)`. Tidal velocity is in phase with elevation. In a closed-end estuary, reflection causes standing waves with node-antinode patterns.
  - **With Friction:** Tidal amplitude decays as it moves landward, and velocity begins to lag behind elevation changes.
- **Tidal Flushing:** This describes the time required to replace the existing water in an estuary.
  - **Classical Concept:** Flushing time is calculated as the total volume of the estuary divided by the sum of the tidal prism and freshwater input per tidal cycle.
  - **"New" Ocean Water Concept:** This refined concept recognizes that only a portion of the water entering on a flood tide is "new" ocean water that has not recently been in the estuary.

2. Numerical Modeling in Estuarine Management

Numerical models are essential tools for simulating complex estuarine processes and predicting the effects of management actions or environmental changes.

- **HEC-RAS (River Analysis System):** Developed by the U.S. Army Corps of Engineers, this software is used for:
    - One- and two-dimensional steady and unsteady flow calculations.
    - Sediment transport and mobile bed computations.
    - Water temperature and water quality modeling.
    - Its graphical user interface includes tools like RAS Mapper for floodplain mapping and inundation analysis.
- **EPA-WASP (Water Quality Analysis Simulation Program):** Developed by the U.S. Environmental Protection Agency, this model:
    - Predicts water quality responses to natural phenomena and man-made pollution.
    - Is a dynamic compartment-modeling program for aquatic systems, including the water column and benthos.
    - Can be linked with hydrodynamic models to provide inputs like flows, depths, velocities, and temperature.
    - Has been widely applied in the development of Total Maximum Daily Loads (TMDLs).

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

A demonstration project in the City of Linden, New Jersey, applies the principles of estuarine science and numerical modeling to address chronic flooding and restore local ecosystems.

3.1 Project Overview

- **Context and Location:** The project focuses on the residential Tremley community at the head of Marshes Creek, an area characterized by both residential housing and heavy industry. The community experiences flooding during rainfall events.
- **Problem Statement:** Flooding is exacerbated by stormwater runoff from impervious surfaces and by flow-restrictive culverts along the creek, which cause water to back up upstream and promote sedimentation.
- **Partners and Funding:** The project is a collaboration between **Rutgers University** and the **City of Linden**. It is funded by the **U.S. Department of the Interior** via the **National Fish and Wildlife Foundation**, with additional support from **Phillips 66**.

3.2 Project Components and Interventions

The project employs a two-pronged strategy to mitigate flooding.

- **Component 1: Green Infrastructure for Stormwater Management:**
    - Measures are designed to reduce stormwater runoff at its source by capturing and infiltrating rainwater.

    - Implementations include rain barrels at residences, rain gardens and bio-swales along public parking lots, and the installation of a porous pavement parking lot at a local baseball field.
- **Component 2: Hydraulic/Drainage Capacity Recovery:**
    - This component focuses on improving the conveyance of Marshes Creek by addressing structural bottlenecks.
    - Actions include unclogging existing culverts and proposing the enlargement of flow-restrictive culverts, potentially to be equipped with sluice gates for flow management.

3.3 Modeling, Analysis, and Key Findings

A combined hydrologic-hydraulic model was developed to simulate watershed runoff (using EPA-SWMM) and tidal creek flow (using HEC-RAS). The model was calibrated and validated against measured data for rainfall, runoff, water surface elevation, and velocity, showing a strong correspondence between simulated and observed conditions.

The validated model was used to simulate peak water surface elevations (WSELs) upstream under existing (restricted flow) and proposed (unrestricted flow) conditions for various combined tide and rainfall scenarios.

Table: Modeled Peak WSELs (m) at Location 4 - Existing vs. Proposed Conveyance

Scenario #	Tide & Rainfall Description	Existing Peak WSEL (m)	Proposed Peak WSEL (m)	Proposed WSEL Change (m)
1	Tide Only	0.87	1.12	0.24
2	Tide + NRCS 10 YR Rainfall	1.25	1.29	0.04
3	Tide + NRCS 25 YR Rainfall	1.39	1.36	-0.02
4	Tide + NRCS 50 YR Rainfall	1.50	1.42	-0.08
5	Tide + 100 YR Rainfall	1.63	1.50	-0.12

Key Findings:

- **Dry Weather Impact:** With tide only, removing the flow restriction increases the peak WSEL by 0.24 meters, as more tidal water can propagate upstream.
- **Wet Weather Impact:** As rainfall intensity increases, the effect reverses. For storms exceeding a "threshold rainfall depth" (approximately a 25-year event, where WSEL is ~1.35 m), the proposed unrestricted conveyance results in a *lower* peak WSEL.
- **Flood Risk Reduction:** For a 100-year rainfall event, the proposed changes reduce the peak flood level by 0.12 meters, demonstrating a significant flood mitigation benefit during extreme weather.

- **Publication:** These findings were published in the ASCE *Journal of Hydrologic Engineering* in 2021 by Byrne and Guo, detailing a methodology for evaluating the flood risk of restoring tidal flow to restricted waterways.

3.4 Related Initiatives and Strategic Perspectives

The local interventions are part of a broader context of coastal resilience planning.

- **Blue Acres Restoration:** In adjacent areas, the project includes floodplain and ecosystem restoration through the creation of wetlands and rain gardens.
- **Regional Proposals:** The area is also subject to large-scale proposals by the U.S. Army Corps of Engineers, including a regional flood wall along the Arthur Kill River and a massive surge barrier across the entrance to New York Harbor.
- **Strategic Vision:** A guest column in the *Star-Ledger* articulated the guiding philosophy: *"In New Jersey's effort to adapt to rising sea levels, we are facing infrastructure challenges on two fronts – structural deterioration and environmental change. This is the time for us to tackle both fronts together by replacing or retrofitting the aged infrastructure into a resilient one, preferably through mobile and green means."*