Briefing Document: Tides, Coastal Processes, and Restoration Case Studies

Executive Summary

This document synthesizes key principles of tidal phenomena and their real-world implications for coastal engineering and ecosystem restoration, drawing on two distinct case studies in New Jersey. Tides, while primarily driven by the gravitational and centrifugal forces within the Earth-Moon-Sun system, are highly complex. Their predictable astronomical patterns are significantly modified by local factors including coastal topography, basin resonance, the Earth's rotation (Coriolis effect), and meteorological events, which can produce dangerous storm surges.

Human infrastructure frequently alters natural tidal flows. Flow-restrictive structures like levees and undersized culverts, often built for flood protection or transportation, can degrade upstream wetland habitats by limiting saline water exchange, leading to sedimentation and the proliferation of invasive species. Addressing these restrictions presents opportunities for ecological restoration but requires careful analysis to balance ecosystem benefits with flood risk management.

Two case studies illustrate these challenges and potential solutions:

1. **Greenwich, NJ:** Three earthen levees on the Delaware Bay restrict tidal flow, degrading 226 hectares of wetlands. A study proposes installing mobile gates to restore natural tidal exchange. This solution is shown to be cost-effective, with a benefit-cost ratio near 1.0, offering the dual benefits of enhancing ecosystem value (estimated at over $2 million annually) and improving long-term flood resilience.
2. **Linden, NJ:** In a heavily urbanized and industrialized setting, a flow-restrictive culvert on Marshes Creek causes upstream sedimentation and alters flood dynamics. A hydraulic model reveals a complex relationship between tidal restoration and flood risk. While restoring full flow would increase water levels during dry weather or minor rainfall, it would *decrease* peak water levels and reduce flood risk during major rainfall events. This highlights that the impact of restoration on flooding is site-specific and depends critically on the interaction between tides, rainfall intensity, and local land elevation.

Together, these analyses demonstrate that while the principles of tides are universal, their application in coastal management demands nuanced, data-driven solutions tailored to the unique hydrological and ecological context of each location.

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1. The Science of Tides and Coastal Water Levels

1.1 Components of Total Water Level

The total water level at any given coastline is a composite of several factors. The baseline is the **astronomical tide**, the predictable rise and fall of sea level due to gravitational forces. During storms, this level is augmented by **storm surge**, which is an abnormal rise in water generated by a storm, over and above the predicted tides.

The components contributing to the total water level, particularly during a storm event, are:

- **Mean Sea Level (Astronomical Tide):** The base water level predicted by the positions of the Moon and Sun.
- **Pressure Setup:** A rise in sea level caused by low atmospheric pressure during a storm.
- **Wind Setup:** The piling up of water against the coast by strong onshore winds.
- **Wave Setup:** An increase in the mean water level near the shoreline caused by the energy of breaking waves.
- **Wave Crest (Total Water Level):** The peak height of the water, including all the above components.
- **Wave Runup:** The maximum vertical extent of wave up-rush on a beach or structure above the still water level.

A **storm tide** is the combination of the storm surge and the astronomical tide. For example, a 2-foot normal high tide combined with a 15-foot storm surge results in a 17-foot storm tide, which can cause significant coastal flooding.

1.2 Primary Drivers of Tides

The fundamental forces generating tides are a combination of gravitational attraction and centrifugal force within the Earth-Moon-Sun system.

- **Gravitational and Centrifugal Forces:** The Moon's gravitational pull (Fg) is strongest on the side of the Earth facing it, pulling the ocean's water toward it. Simultaneously, the Earth revolves around the common center of mass of the Earth-Moon system (the barycenter), creating a centrifugal force (Fc) that pushes water away from the center of revolution.
    - On the side of the Earth **facing the Moon**, the gravitational force is greater than the centrifugal force (Fg > Fc), creating a tidal bulge.
    - On the side of the Earth **opposite the Moon**, the centrifugal force is greater than the gravitational force (Fc > Fg), creating a second tidal bulge.
    - This dynamic results in two high tides on Earth at any given time.
- **The Earth-Moon-Sun System and Tidal Cycles:** The Sun also exerts a gravitational force, though it is less than half as powerful as the Moon's due to its greater distance. The alignment of these three bodies dictates the monthly tidal cycles.
    - **Spring Tides:** Occur during the New Moon and Full Moon, when the Earth, Moon, and Sun are aligned (syzygy). Their gravitational forces combine, producing the largest tidal range (the highest high tides and lowest low tides).
    - **Neap Tides:** Occur during the First and Third Quarter Moons, when the Moon and Sun are at a right angle relative to the Earth (quadrature). Their gravitational forces partially cancel each other out, resulting in the smallest tidal range.

1.3 Factors Modifying Tidal Patterns

While astronomical forces are the primary driver, actual tidal patterns observed at coastlines are highly variable due to a combination of geographic, oceanographic, and meteorological factors.

- **Tidal Patterns:** Globally, three main tidal patterns are observed:
  - **Semidiurnal Tides:** Two high tides and two low tides of approximately equal height each day (e.g., East Coast of the US).
  - **Diurnal Tides:** One high tide and one low tide each day (e.g., parts of the Gulf of Mexico).
  - **Mixed Semidiurnal Tides:** Two high tides and two low tides of unequal height each day (e.g., West Coast of the US).
- **Modifying Influences:**
  - **Lunar Day:** Because the Moon orbits the Earth in the same direction that the Earth rotates, it takes approximately **24 hours and 50 minutes** (a lunar day) for a point on Earth to pass directly under the Moon again. This is why the timing of high and low tides shifts by about 50 minutes each day.
  - **Tidal Constituents:** Tides are the sum of many different wave components (constituents), each with its own period (e.g., M2 from the Moon ≈ 12.42h, S2 from the Sun = 12.00h). The combination of these constituents creates complex local patterns.
  - **Basin Geometry and Resonance:** The shape, width, and depth of ocean basins, bays, and estuaries cause water to "slosh" (resonate). If the forcing period of a tidal constituent is close to a basin's natural period, that tide can be significantly amplified.
  - **Coriolis Effect:** The Earth's rotation deflects moving water. This creates **amphidromic systems**, where the tidal wave rotates around a central node of zero tidal range. The rotation is counter-clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere.
  - **Friction and Nonlinearity:** Friction from the seafloor can dampen tides and shift their timing. Nonlinear effects can create overtides (e.g., M4), which alter the interval between high and low water.
  - **Weather:** Atmospheric pressure and wind can superimpose effects on astronomical tides, leading to unpredictable water levels.

1.4 Tidal Datums and Engineering Applications

Consistent reference points, or tidal datums, are essential for coastal engineering, navigation, and habitat mapping. These are typically calculated as averages over a 19-year period to account for long-term astronomical cycles.

Datum	Full Name	Description
MSL	Mean Sea Level	The average height of the sea surface for all stages of the tide over a 19-year period.
MHW	Mean High Water	The average of all the high water heights over a 19-year period.

MHHW	Mean Higher High Water	The average of the higher of the two daily high waters in a mixed tide regime.
MLW	Mean Low Water	The average of all the low water heights over a 19-year period.
MLLW	Mean Lower Low Water	The average of the lower of the two daily low waters in a mixed tide regime. This is commonly used as the **Chart Datum (CD)** for depths on nautical charts.
MHWS	Mean High Water Springs	The average height of the high waters occurring at the time of spring tides.

These datums are critical for defining elevations of coastal features, such as the zones of tidal wetlands (Tidal Flat, Low Marsh, High Marsh) which are delineated by their relationship to specific water levels like MHW and Spring High Water.

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2. Case Study: Flood Protection and Wetland Restoration in Greenwich, NJ

2.1 Context and Problem

Greenwich, New Jersey, located on the Delaware Bay, is the site of three earthen levees (Levees 48, 50, and 51) that were constructed for flood protection. These structures, however, severely restrict the natural tidal flow into upstream tidal creeks (Pine Mount Creek, Mill Creek, and Mounce Creek).

This restriction has led to the significant degradation of upstream wetland ecosystems. The lack of regular tidal exchange has favored the dominance of the invasive common reed, *Phragmites australis*, over native salt marsh grasses like *Spartina spp*. Observations at Levee 48 on Bacons Neck Road during a spring high tide on October 7, 2017 (predicted high of 6.27 ft), showed water levels reaching the road surface and leaking through the corroded sheet pile walls.

2.2 Proposed Solution and Analysis

A study by Weinstein, Guo, and Santasieri evaluated a solution that aims to both restore the ecosystem and maintain flood protection. The core proposal is to reestablish unrestricted tidal flow by incorporating **mobile gate systems**, such as vertical lift gates, into the existing levees.

This modification would allow for natural tidal cycles to be restored to the degraded upstream areas, promoting the recovery of native salt marsh habitat. The study estimated that this action could potentially restore up to **226 hectares** of tidal salt marsh.

2.3 Economic and Ecological Outcomes

The study conducted a benefit-cost analysis to determine the viability of the project over a 50-year period.

- **Ecological Benefit:** The estimated total economic value (TEV) of the goods and services provided by the restored 226 hectares of wetlands ranges from **$2,058,182 to $2,390,854 per year**.
- **Engineering Cost:** The associated annual engineering cost to install and maintain a mobile gate system is approximately **$1,925,614 per year**.
- **Conclusion:** This results in a **benefit-cost ratio of 0.98–1.14**. This analysis indicates that the project is cost-effective and provides a dual benefit: it improves long-term flood resilience for the community while simultaneously preserving and enhancing valuable ecosystem functions.

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3. Case Study: Tidal Restriction and Flood Risk in Linden, NJ

3.1 Context and Problem

In the heavily industrialized and residential area of Linden, New Jersey, Marshes Creek suffers from an anthropogenically flow-restricted waterway. A specific culvert acts as a bottleneck, impairing the natural tidal exchange. This restriction causes two primary problems:

1. **Water Backup:** Water backs up upstream of the culvert during certain tidal and rainfall conditions.
2. **Sedimentation:** The reduced flow velocity upstream of the culvert causes sediment to drop out of the water column, leading to significant accumulation that further impedes flow and degrades the channel.

3.2 Hydrological/Hydraulic Analysis

A study by Byrne and Guo used a hydrological/hydraulic model to investigate the impact of removing this restriction on upstream flooding risk in the adjacent community of Tremley. The model simulated peak water surface elevations (WSELs) under both the existing restricted flow conditions and a fully unrestricted flow scenario, considering the combined influence of tides and various rainfall events.

3.3 Key Findings on Flood Risk

The research revealed that restoring tidal flow has a complex, non-linear effect on flood risk, which is highly dependent on the magnitude of rainfall.

- **Dry Weather and Minor Rainfall:** Under conditions with no or low rainfall, a fully unrestricted conveyance option results in a **higher** peak WSEL compared to the existing restricted culvert. The tidal range is restored by 0.25 meters.
- **Major Rainfall Events:** As rainfall intensity increases, the peak WSEL under the unrestricted scenario rises more slowly than under the restricted scenario. For rainfall events exceeding a **threshold depth of approximately 150-154 mm**, the unrestricted flow scenario results in a **lower** peak WSEL, thereby reducing flood risk.
- **The Threshold Concept:** The key determinant of flood risk is the relationship between the peak WSEL and the adjacent **minimum grade elevation** (1.35 m in the model).
    - If tidal restoration generates a common peak water level that is **lower** than this grade elevation, it reduces flooding risks.
    - However, if the simulated common water level is **higher** than the grade elevation, full tidal restoration will increase flooding risk.

The study concludes that full restoration in this specific urban context can reduce flooding during major storms but may increase nuisance flooding during smaller events. This underscores the need for careful engineering solutions, such as enlarged culverts paired with sluice gates, to actively manage flow and balance the goals of ecosystem restoration and flood protection.