ChatGPT

Wave-Dominated Estuarine Depositional System: Procedural Generation Rule Set

Hierarchical Multiscale Structure of the Estuary

Estuary-Scale Morphology: A wave-dominated estuary typically consists of a semi-enclosed coastal water body (lagoon or bay) separated from the open ocean by a sandy barrier at its mouth [1]. The overall planform often appears elongated parallel to the coastline (especially if constrained by valley walls or a steep hinterland) and may be roughly rectangular or irregular in shape [2]. The seaward boundary is a **barrier island or spit** system, which shelters a **central basin** (lagoon) from direct ocean waves [3] [4]. Inland, the estuary tapers into a fluvial channel that delivers river water and sediment. This arrangement produces a clear *tripartite zonation* of facies: (1) a marine-influenced sand barrier and inlet complex at the mouth, (2) a central mud-dominated basin, and (3) a bay-head delta and fluvial channels at the estuary's landward end [4].

- **Barrier–Inlet Complex (Marine Sand Body):** The coastal barrier at the estuary mouth is composed of beach and dune sands shaped by wave-driven littoral drift [1]. Depending on wave climate and angle, this barrier may be a continuous island with **multiple inlets** or a long **sand spit** attached to one side. *If wave approach is only slightly oblique,* several tidal inlets may punctuate the barrier (as sand is moved from an updrift delta and distributed alongshore) [5]. *If wave approach is highly oblique,* strong littoral drift tends to form one long spit that nearly closes the estuary, leaving a single narrow inlet at the downdrift end [6]. The inlet channel(s) connect the ocean to the lagoon; their positions can shift or alternate through time with breaching events (see Time-Evolution Rules). **Ebb and flood tidal deltas** are associated with these inlets: sand carried by tidal currents deposits in a fan-shaped *flood-tidal delta* on the lagoon side and an *ebb-tidal delta* on the seaward side [7]. In wave-dominated estuaries (especially microtidal ones), the ebb delta is often small (waves rework its sand into the barrier or alongshore), while the flood delta can form distinctive shoals inside the basin [7]. The barrier itself is typically only a few meters above high tide (dune elevations on the order of 3–10 m) and can range from a few hundred meters to a few kilometers in width. It commonly has a low height-to-width ratio (width tens to hundreds of times the height) – a broad, flat barrier is more stable, whereas a narrow barrier is prone to overwash and breaching (see stability discussion below).

- **Central Basin (Lagoon and Mud Flats):** Immediately landward of the inlet/barrier is the central estuarine basin, often a lagoon or broad shallow bay. **Sedimentology:** This zone is typically mud-dominated – fine silts and clays settle out in the low-energy environment behind the wave shelter [8]. Water circulation here is limited; wave energy is minimal because the barrier dissipates ocean waves [3]. Tidal currents, if present, weaken with distance from the inlet, so much of the central basin serves as a settling area for suspended sediment. Over time, extensive **tidal flats** can develop on the basin margins, built by mud and fine sand accumulation during flood tides and settling during slack water [9] [10]. The finest sediments are deposited furthest from the inlet channels (in the upper reaches of flats or basin), where vegetation can colonize to form **salt marshes** [11] [12].

The central basin may be several kilometers across in larger systems, but depth is usually modest (a few meters) due to infilling; it often becomes shallower toward the landward end. **Internal structure:** Within the central basin, any tidal channels or sub-basins form a branching network. For example, one or more tidal channels may extend from the inlet's flood delta into the lagoon, meandering across the flats and delivering water to the far reaches. These channels and adjacent flats define distinct facies: channel thalwegs with sand or mixed sand-mud (from tidal scour) and overbank flats with laminated mud and bioturbation. Marsh fringes line the basin margins, where muds accumulate and plants trap sediments. Any **estuarine turbidity maximum** (ETM) – a zone of enhanced sediment trapping where river and marine waters meet – often occurs near the upper basin or bay-head, leading to especially muddy deposits there.

- **Bay-Head Delta and Fluvial Channel-Floodplain (Riverine Zone):** At the landward end of the estuary, where the river enters, a *bay-head delta* commonly forms [4]. This is a sandy or mixed sand-mud deltaic lobe built by the fluvial sediment load into the quiet waters of the lagoon. **Morphology:** The bay-head delta may consist of distributary channels, small mouth bars, and prodelta deposits interfingering with the lagoon muds. The main river channel typically transitions from a normal alluvial river into a tidal/fluvial channel as it meets the estuary head. It often meanders and bifurcates, depositing coarse sediment near the river mouth and creating levées or splays. If tidal influence is present, these bay-head channels experience some backwater effect (slowing of flow, possibly brackish water incursion). **Facies:** Bay-head delta sediments are usually fine-to-medium sand with some silt, showing current-generated structures (ripples, cross-beds) and low marine bioturbation, reflecting fluvial dominance [13] [14]. They grade seaward into finer central-basin muds. On either side of the channels, **floodplain and marsh** environments may exist where overbank deposition occurs. The bay-head delta deposits prograde over time, and they typically coarsen upward (becoming sandier upward) as the delta builds into the basin. This forms part of the tripartite estuarine stratigraphy: fluvial sand (bay-head delta) at the head, encroaching into central muds, which in turn transition to marine sand at the mouth [15].

- **Tidal Channels, Creeks, and Marshes:** Across the estuary, smaller-scale channel-facies occur. Tidal creeks may extend into marshes on the margins, draining the intertidal flats. These creeks often meander and can undercut marsh banks, causing lateral marsh erosion [12]. Channel facies (whether tidal channels in the flats or the main inlet channel) are typically sandy or firm due to higher velocities, whereas overbank and marsh facies are finer (mud, peat). A hierarchy of channels exists: the main inlet channel (deepest, up to tens of meters across, dominated by marine sand and shell), secondary tidal channels branching in the lagoon (shallower, mixed sediment), and tiny tidal creeks in marshes (muddy with some sand at bends). Each channel is flanked by levees or elevated rims of sand/silt that were deposited during floods. These channels and associated point bars create small-scale heterogeneity in the environment, but their layout is controlled by larger-scale patterns of tidal flow and topography.

Vertical Facies Succession: The spatial zones described also produce a characteristic vertical record. For instance, a core from the center might show an upward transition from basal fluvial sand (if the river valley was incised), to central-basin mud (as transgression flooded the valley), and capped by marine sand of the barrier as the estuary eventually infills or the barrier migrates over it. This *sand-mud-sand* vertical sequence is a diagnostic signature of a wave-dominated estuary filling over time [15]. Channels leave lenticular sand bodies within muds, marshes leave peat layers, and washover events from the barrier leave sand sheets over lagoon muds. These details ensure that any generated analog image reflects the multiscale complexity

– from the broad planform down to channels and facies distributions – of a real wave-dominated estuarine system.

Physical Drivers and Controls on Estuary Form

The morphology and evolution of a wave-dominated estuary arise from the interplay of several key physical drivers and boundary conditions [16] [17]:

- **Wave Energy:** High **wave action** at the coast is the defining influence for this estuary type. Ocean waves (especially storm waves) move sediment **alongshore (littoral drift)** and drive sand *onshore* into the estuary mouth [3]. This leads to the formation of sand bars, spits, and barrier islands that partially block the estuary. **Wave climate parameters** such as significant wave height, wave period, and dominant approach angle are critical. *Influence:* Strong wave energy and oblique wave incidence favor a long uninterrupted barrier (or spit) because continuous littoral drift pushes sand into a single accumulative feature [6]. More moderate or multi-directional wave climates might allow multiple stable inlets (the barrier is segmented) [6]. Waves also limit the number and size of inlet openings by tending to close small gaps with alongshore sand transport. Inside the estuary, wave action is greatly reduced due to the barrier's sheltering effect, which is why fine sediments can settle in the lagoon [3]. However, locally generated wind waves inside the lagoon can still resuspend mud on tidal flats during storms, influencing marsh development (persistent wave chop can prevent fine sediment from accumulating on flats or erode the marsh edge) [12]. Overall, a **high wave-energy, microtidal setting** is characteristic for classic wave-dominated estuaries [18] (e.g. many lagoons along microtidal coasts worldwide).

- **Tidal Range and Prism:** Waves dominate these systems, but **tides** still play a role in water exchange and sediment transport. Typical wave-dominated estuaries occur on **microtidal coasts** (tidal range < ~2 m), meaning tidal currents are relatively weak compared to waves [19]. Nonetheless, the **tidal prism** (the volume of water entering/exiting each tide) influences inlet stability and morphology. A larger tidal range or basin area yields a larger prism, which tends to scour wider/deeper inlet channels and build larger tidal deltas. For instance, where even a small tide exists, strong flood currents through a narrow inlet deposit sand in an inland *flood-tidal delta*, and ebb currents may form an *ebb-tidal delta* seaward [7]. If tidal prism is very small, the inlet may struggle to stay open against wave-driven sand infilling. Thus, **tidal forcing controls** the minimum inlet cross-section needed to convey the flow (see formulas below), and it helps ventilate the estuary (prevent stagnation). Additionally, tides contribute to a **flood/ebb asymmetry** in sediment transport – often, flood tides bring in marine sediment that settles on flats, and ebb tides, being slightly weaker or shorter in duration in these geometries, may not remove it entirely [10] [20]. The result is net landward sediment transport, aiding estuary infill over time. However, in a strongly wave-dominated estuary, tide influence is secondary; the entrance is narrow relative to the lagoon, meaning limited daily exchange (long water residence time inside).

- **River Discharge and Sediment Supply:** The **fluvial input** to the estuary – both water discharge and sediment load – governs the development of the bay-head delta and the long-term infilling rate [17]. **River flow** delivers *freshwater* into the estuary, which can stratify over denser salt water, creating a *salt-wedge estuary* with an estuarine circulation. This stratification (freshwater over salt) typically causes a zone of high turbidity where the two meet (flocculation of clays, etc.), enhancing deposition of mud in the upper estuary. **Sediment load:** If the river brings substantial sand, a bay-head delta will form rapidly, and coarser sediment may propagate farther into the estuary. High mud supply from the watershed (common in tropical rivers with intense weathering, for example) will accelerate filling of the central basin with fine-grained sediment [17]. In contrast, minimal fluvial sediment yield means the estuary relies on marine-derived sand (from the coast) and in situ organic production for infill. **Balance of sources:** Wave-dominated estuaries often have **small catchments** and thus modest river discharge (many are fed by streams rather than large rivers). This is why they are sometimes called *"coastal lagoons"*, as they receive limited freshwater [4]. Nonetheless, even small rivers produce a local delta at the head if conditions allow. Seasonal or episodic flooding can bring pulses of sediment that build bay-head delta lobes or create crevasse splays into the lagoon. The **grain size** of fluvial input (sand vs silt vs clay) also matters: sands will be deposited near the river mouth (contributing to the delta and channel point bars), whereas finer silts and clays may stay suspended and be carried deeper into the basin or out with the tide. The interplay of river vs marine sediment is part of Dalrymple's definition of an estuary [21]: *"contains facies influenced by tide, wave, and fluvial processes"*. In wave-dominated cases, **marine processes and sediments (sand)** shape the mouth, while **fluvial processes and sediments (silt/sand)** shape the head.

- **Coastal Geomorphology and Basin Configuration:** The *geological setting* and antecedent topography strongly modulate estuary shape and behavior. Wave-dominated estuaries often form in **drowned river valleys on coastal plains**, so the geometry of that valley (width, depth, side-slope) sets the stage. A wide, gently sloping valley can accommodate a broad lagoon and extensive marshes, whereas a narrow valley yields a more funnel-like estuary. The presence of **headlands** at the mouth can pin the barrier in place. The offshore bathymetric slope influences how readily waves can build barriers – a shallow shelf provides ample sand and causes waves to break further offshore, aiding barrier formation. **Coastal alignment** determines littoral drift patterns: a straight, open coast might allow spits to grow far, while an embayed coast can trap sediment. Also, any **antecedent sand deposits** (e.g. an old coastal sand ridge) can be reworked into the barrier. These inherited factors mean no two estuaries are identical [22], but those with similar forcing conditions tend to develop analogous features. In modeling an analog, one might set parameters for basin size, valley shape, and initial topography to mimic these natural controls.

- **Sea Level (External Forcing):** Although not a daily "driver" of morphology, **relative sea-level change** (rise or fall) is a critical long-term control. A rising sea level (transgression) tends to create and expand estuaries by drowning river valleys, whereas a falling sea (regression) causes estuaries to shrink and potentially convert to deltas or river plains. During the Holocene post-glacial sea-level rise, many wave-dominated estuaries were formed as rising seas overtopped coastal ridges and filled valleys; in modern times, **sea-level rise** continues to impact them by increasing accommodation space (which can lead to deeper lagoons if sediment supply doesn't keep up) [23]. We consider sea-level effects more under Time-Evolution, but in terms of control: *If* sedimentation rates are high relative to sea-level rise, the estuary can infill or even shoal up to become tidal flats; *if* sea-level rise outpaces sedimentation, the lagoon will deepen or expand (possibly leading to erosion of barriers or conversion to open embayment). For modeling, the present sea level sets the baseline depths (e.g. how much of the valley is flooded) and one can adjust it to simulate transgressive vs regressive scenarios.

- **Climate and Storm Frequency:** The **storm climate** (frequency and magnitude of coastal storms like hurricanes or cyclones) is a crucial control on short-term morphology in wave-dominated estuaries. Major storms generate large waves and storm surges that can overtop or breach barriers, introducing washover sands into the lagoon or creating new inlets. Thus, a high frequency of strong storms tends to lower barrier integrity (more overwash and breaches) but can also deliver sand into the central basin via washover fans. Storm wind can also drive set-up in the lagoon and cause *wind-driven currents* that resuspend sediment. Over long periods, a stormy climate can keep the barrier in a more transgressive, reworked state (with frequent washover deposits and perhaps intermittent closure of the lagoon if breaches occur). In contrast, a milder wave climate allows the barrier to stabilize (perhaps with vegetated dunes) and the lagoon to accumulate finer sediment undisturbed. In generative rules, one might include stochastic storm impacts to decide if a breach or overwash fan is present in a given snapshot.

- **Human Impacts (if any):** Though not a natural driver, it is worth noting that real estuaries are often modified by humans (jetty construction at inlets, dredging, etc.) [24]. For a purely natural analog model, we typically **exclude** engineered structures. However, if needed, one could simulate the effect of jetties by fixing inlet position and cross-section (jetties tend to stabilize inlet location and prevent migration [25]). Similarly, upstream dams drastically alter fluvial sediment supply, potentially starving the estuary of sand and causing erosion or expansion of the lagoon [26] [27]. These factors are beyond the basic scope but can be toggled in advanced scenarios.

In summary, **wave energy** is the dominant sculptor of the estuary's outer shape, **tidal prism** governs inlet/channel dimensions, **river input** feeds the bay-head deposits and affects stratification, and **sediment supply vs sea-level** sets the pace of infill vs drowning. All these controls must be parameterized in a modeling framework to achieve physically realistic outcomes.

Time-Evolution Rules and Dynamics

Wave-dominated estuaries evolve over a range of timescales – from storm events that instantly reshape the barrier to millennial-scale changes as the basin fills. A procedural model should capture both **short-term dynamics** (like inlet breaching/closure) and **long-term evolutionary trends** (transgression or infill). The following rules outline key temporal processes:

1. Initial Formation (Transgressive Creation of the Estuary): Wave-dominated estuaries often originate during periods of rising sea level or highstand. An **incipient estuary** may form when the sea **floods a river valley or coastal lowland**, and waves build a barrier across the new embayment. One common mechanism is **barrier breaching of a coastal sand ridge:** a severe storm surge can break through a coastal dune ridge or barrier beach, suddenly allowing tidal waters to inundate the hinterland depression [28]. If the newly flooded area is large enough (and tidal range sufficient) that the tidal flow can prevent immediate closure by littoral drift, a permanent inlet and estuarine system will establish [29]. Another pathway is through gradual inundation: as sea level rises, **longshore sand transport** forms spits or barrier islands enclosing the transgressing shoreline, leading to a lagoon forming behind the barrier [1] [5]. Early in transgression, the estuary is at its maximum extent – a large water body with relatively deep central basin and only nascent sediment accumulation. Sediments derived from the previous landscape (e.g. floodplain soils) might be eroded and reworked during this phase. *Rule:* To simulate initial formation, start with a coastal plain topography and gradually raise sea level or allow a storm breach, then deposit sand at the mouth to form an embryonic barrier. Ensure the initial tidal prism vs littoral drift conditions allow the inlet to remain open (see stability indices below).

2. Inlet Dynamics – Breaching, Migration, and Closure: The inlet (or inlets) of a wave-dominated estuary is highly dynamic over time, controlled by the balance between tidal flows and wave-driven sand input. **Closure cycles:** During fair-weather periods with low river outflow, waves can choke the inlet with sand, **narrowing or closing** it entirely [30] [31]. Many small wave-dominated lagoons (e.g. in microtidal Australia or South Africa) experience intermittent closure when river discharge and tides are insufficient to keep an inlet scoured; the barrier then becomes temporarily continuous ("barrier closed state"). Conversely, **breaching events** occur during episodes of high water flux: *Floods* from the river or *storm surges* from the sea will raise the water level enough to either overtop and cut through the barrier or re-open a silted inlet [31]. A classic rule: **the barrier will be naturally breached during periods of high runoff or extreme storms, re-establishing an inlet where it was closed** [31]. This creates a cyclical behavior in some estuaries: long periods of restricted exchange (lagoon fills with freshwater, sediment settles) punctuated by dramatic opening events flushing the system. *Breaching location:* Often the breach occurs at the lowest or narrowest point of the barrier, but strong river floods can force new outlets near the river mouth, while storm surges can breach anywhere along the barrier (sometimes multiple cuts). After breaching, tidal currents will usually widen and deepen the new inlet until a quasi-equilibrium is reached. *Inlet migration:* In wave-dominated settings, inlet channels tend to **migrate downdrift** (along the barrier) over time due to littoral drift feeding one side of the inlet. The updrift side accumulates a sand spit that extends into the inlet mouth, pushing the channel toward the downdrift side (this is commonly observed in unjettied inlets). Over years to decades, an inlet might move hundreds of meters, until possibly welding to the downdrift shore and closing, at which point a new breach may occur elsewhere.

Generation rules for inlets: In a time-evolving model, one can implement a **threshold criterion for breaching vs closure**: for example, if the lagoon water level exceeds the barrier's dune elevation by a certain amount (during storms or floods), initiate a breach and carve a new inlet. Conversely, if littoral sand transport exceeds the scouring capacity of the tidal flow for an extended period, slowly constrict the inlet cross-section to simulate closing. The **inlet stability index** (described below) can guide this: a low index (waves dominant) suggests the inlet will eventually close if no major event intervenes, whereas a high index (tidal flow dominant) suggests a stable inlet. Each inlet has a finite lifespan unless maintained by stable conditions – the model can randomly or deterministically relocate inlets based on sediment bypassing and hydrodynamics.

3. Barrier Evolution and Washover: The barrier island or spit itself evolves under the influence of storms, sea-level trends, and sediment supply. **During calm periods,** dunes build up on the barrier (increasing its height) and vegetation might stabilize it. The barrier may slowly migrate landward via wind-blown sand and minor overwash, especially if sea level is rising. **During major storm events,** waves overtop the barrier, depositing *washover fans* of sand in the back-barrier marsh or lagoon. Overwash processes effectively transfer sand from the ocean side to the lagoon side, causing the barrier to **roll over** landward. If the barrier is relatively low or narrow, storm overwash can be frequent; if it's high and wide, overwash is rarer (sand stays mostly on the beach face or dunes). In extreme cases, storm surge and waves remove large sections of the barrier (forming breaches as described). A key rule is that **barrier width and height relative to storm surge determine its fate**: if the barrier is thin or low, a given storm's overwash may erode enough sand to create a permanent inlet rather than just a washover deposit [32]. *Analytical criterion:* A breach tends to occur when the volume of sand removed by overwash exceeds the volume of the barrier's dune and beach sediment (i.e. the barrier's "subaerial" volume) [33]. In other words, *if* `V_overwash > V_barrier`, the barrier is effectively broken [33]. A **pseudocode** trigger could be: "if storm_surge_height > barrier_dune_height by X and barrier_width is below Y, then breach = True". Empirical studies confirm that **storm surge height (water level) and barrier width** are two primary controls on breaching [32]. So over time, one might model that each big storm checks this condition – narrow barriers get breached, wider ones only get washover deposition. Additionally, the barrier can **prograde or retrograde** depending on sediment budget. In periods of abundant sand supply (e.g. longshore drift from an updrift eroding delta lobe), the barrier may widen seaward (progradation) by forming new beach ridges. In contrast, under sediment starvation or rapid sea-level rise, the barrier erodes and moves landward (retrogradation). These trends should be reflected in the model by adjusting barrier position/width gradually.

4. Estuary Infilling and Sedimentation: Over decades to millennia, a wave-dominated estuary usually undergoes **infill**, transitioning toward either a tidal flat or deltaic environment. Several processes contribute:

- **Central basin infill:** Fine-grained sediment accumulates in the lagoon through time. Fluvial muds and silts delivered to the estuary get trapped in the low-energy central basin (often facilitated by estuarine circulation and turbidity maxima). Marine-derived fine sediment (e.g. re-suspended shelf mud or organic matter) can also settle in the lagoon. In addition, each overwash event adds a pulse of sand to the back-barrier area. As these sediments build up, the lagoon's depth decreases and intertidal flats expand. *Rule:* Simulate a gradual increase in elevation of the central basin floor over time, fastest near the head (where fluvial input is) and slowest near the inlet (which might be scoured by tidal currents). You might create timeline "snapshots" where the lagoon area shrinks and islands or tidal flats emerge. **Marsh development** occurs atop these flats once elevations approach high tide level, accelerating sediment trapping via vegetation. Over centuries, the upper estuary and margins can turn into marshland, effectively reducing open water area (a key feedback: marsh growth can decrease tidal prism, leading to smaller inlet size and further reduced flushing, which encourages more sedimentation – a positive feedback for infill).

- **Bay-head delta growth:** Concurrently, the bay-head delta at the river input progrades outward as the river delivers sediment. Initially the delta is small, but with continuous sediment supply it builds over the central muds. The channels may avulse or bifurcate, depositing sands further into the estuary over time. Eventually, multiple lobes might form if the river migrates. A mature bay-head delta could fill a large portion of the former lagoon, converting it into a delta plain with distributary channels. For example, the Shoalhaven estuary in Australia infilled to become a wave-dominated delta – the former central basin sands now dominate as the fluvial delta captured the space [34]. In modeling terms, one can increase the extent of sandy deposits from the head with each time step, reducing lagoon volume. The process is self-limiting: as the delta grows, the accommodation for new fluvial sediment decreases, and eventually the river may bypass the estuary entirely, feeding a delta into the ocean instead (the end-member "wave-dominated delta" stage).

- **Tidal inlet and delta evolution:** If tidal influence is present, the *flood-tidal delta* inside the lagoon will also accumulate sediment over time, especially marine sands that are transported through the inlet. This deposit can grow and contribute to infilling the lagoon from the seaward side. On the outside, an *ebb-tidal delta* (if any) may either accumulate (if waves are not too strong) or be reworked alongshore. In a wave-dominated case, often the ebb delta's sand is pushed back into the barrier or downcoast, so it doesn't build up permanently. But if conditions shift to more tidal influence (say, an increase in tidal prism due to sea-level rise flooding more area), an ebb delta could enlarge. **Channel changes:** As the estuary shallows, tidal channels may become more sinuous (since more of the area is intertidal flats, and channels cut through them) and possibly shift position (channel migration can erode established marsh, etc. as a dynamic equilibrium seeks to form [12]). Eventually, with significant infill, the inlet might become disproportionately large for the shrinking lagoon and could begin to behave more like a tidal creek mouth than a bay inlet.

- **Stratification and water dynamics over time:** In early stages, a wave-dominated estuary might be relatively deep and strongly stratified (salt wedge). As it infills and becomes shallower, it tends to become more *well-mixed* due to wind mixing and the large area of intertidal flats (which promote vertical mixing during tidal flooding). So over time, the water column might shift from stratified (which fosters a distinct turbidity maximum and localized mud deposition zone) to mixed (more uniform sediment distribution). This can broaden where fine sediment settles. Additionally, if the inlet duration changes (like long closure periods), the salinity regime may swing from brackish to nearly fresh (lagoon becomes like a lake when closed) to sudden salt intrusion when open – affecting sediment flocculation and deposition patterns episodically. A fully infilled system may essentially lose its estuarine circulation and behave as either a delta (river-dominated) or a coastal lake (if completely closed and freshwater).

5. Sea-Level Change Effects: Estuarine evolution is tightly coupled to sea-level trends:

- *During rising sea level:* The estuary tends to **expand and deepen** unless sedimentation keeps pace. A rule of thumb can be expressed by a dimensionless ratio of **sediment supply vs accommodation creation**. Define, for instance, an accretion rate S (vertical sediment accumulation per year, or equivalently sediment volume input per year relative to area) and the sea-level rise rate R (e.g. mm/year). If $S \ge R$, the estuary can fill or at least maintain its depth; if $S \ll R$, the estuary "drowns" – water depth increases and the central basin may actually grow. As one study notes, even **nearly sufficient sediment may not prevent drowning** if sea-level rise is too fast [35] [36]. In practice, moderate sea-level rise tends to enlarge the tidal prism (flooding more area), which can enlarge inlet channels and tidal deltas initially [37]. But as the basin enlarges, if the barrier cannot retreat landward fast enough, it might undergo higher erosion. In an analog model, one can implement **sea-level rise by increasing water depth and shifting the shoreline**, then apply sedimentation rules to see if infill keeps up. Often, there is a *lag* between sea-level rise and sedimentary response – a newly created accommodation from sea-level rise may take decades to centuries to fill [38] [39]. The model could include such a lag factor, especially for larger estuaries.

- *During falling or stable sea level:* If sea level falls or remains static while sediment continues to arrive, the estuary will infill progressively. In a falling sea level scenario (regression), the shoreline moves seaward, effectively converting the estuary into a prograding delta or coastal plain. The barrier might weld to the mainland or become a series of beach ridges. Tidal prism shrinks, likely causing the inlet to migrate or close. Many estuaries in the late Holocene, with stable sea level, have indeed filled significantly – e.g. the Nile or Yellow River estuaries have silted up when sediment supply was high, turning into delta plains [40] [41]. *Rule:* If accommodation (space below sea level) diminishes faster than created, the environment transitions out of an "estuary" classification. In the final stages, one might no longer have a central lagoon – instead, you have a coastal delta (river-dominated) or an aggrading coastal wetland. The model's 9-environment series likely handles those as separate environments, but it's worth noting the continuum: a wave-dominated estuary can evolve into a wave-dominated delta (when fluvial sediment fills it) or into a wave-dominated lagoon with restricted exchange (if fluvial input stays low and the inlet closes often).

In summary, the time-evolution rules depict a system that **naturally silts up and changes character** unless reset by transgression. In a multiscale model, you'd simulate these changes by updating geometry and facies over iterative steps, maybe producing intermediate "snapshots" that could themselves be used for image synthesis at different stages (e.g. an early-stage estuary with big lagoon vs a late-stage estuary almost filled with delta and marsh).

Static Snapshot Generation Rules (Geologically Plausible Layout)

To generate a single **geologically plausible snapshot** of a wave-dominated estuary, the model should incorporate the above structural elements and drivers into a coherent spatial layout. The following rules provide a recipe for constructing a realistic planform and facies distribution at one point in time (assuming known parameters like tidal range, wave climate, etc.):

A. Planform Geometry and Boundaries: Define the *coastal outline* with a barrier spanning the estuary mouth. The planform of the estuary behind should reflect a **drowned valley or embayment** shape – for example, widening toward the sea and tapering inland. Often a **roughly triangular or rectangular lagoon** is appropriate (broad in the middle, narrowing to the river inlet) [2]. The **landward end** should connect to a river valley or alluvial plain. Ensure the total area is consistent with the intended tidal prism (larger area for larger prism). *Rule of thumb:* the ratio of estuary length to width might be on the order of 2:1 to 5:1 (many lagoons are longer along the coast than they are across). Place **headlands or shorelines** at the mouth sides that anchor the barrier ends. If modeling a spit, attach one end of the barrier to the updrift shoreline and leave the downdrift side opening at the headland on the opposite side.

B. Barrier-Inlet Morphology: Construct the barrier island or spit with realistic dimensions. **Width** should be sufficient to hold dunes and washover deposits – e.g. 500 m to a few kilometers, depending on scale. **Height** should include a dune ridge maybe 3–8 m above mean sea level (for a medium-sized barrier; adjust with storm climate). For an open barrier island (not attached), include an inlet on each end or at specified breaks. For a spit configuration, the inlet will be at the downdrift end by default. Decide the **number of inlets** based on wave angle and tidal prism: *use one inlet* for strongly oblique waves or microtidal conditions, *or multiple small inlets* if wave approach is near shore-normal and the tidal prism is moderately large [6]. Each inlet should cut through the barrier at sea level; define its *channel width* using tidal prism constraints (next rule). **Barrier continuity:** Optionally include low spots on the barrier with evidence of overwash fans (especially if the barrier is narrow). Washover fans can be drawn as aprons of sand extending landward from the barrier into the lagoon, typically a few hundred meters wide, lobate in shape. **Barrier termini:** If barrier islands (multiple segments) are used, leave **tidal inlets** (~0.5–2 km wide) between them. If a single barrier, just one inlet gap of appropriate width. The seaward side of the barrier should have a **beach and nearshore slope**; the landward side might show washover deposits or a fringing marsh. Make sure to include a **dune ridge** line if the barrier is stable (a crest line just inland of the ocean beach). The **barrier should roughly parallel the coastline**, possibly curving with the shore. For a spit, curve the distal end into the inlet.

C. Tidal Inlet and Channel Dimensions: For each inlet, set its **cross-sectional area** and width according to tidal prism. A well-known empirical relationship is $A_c = C \, P^n$, where P is the tidal prism (volume of water exchanged in one half-tide) and A_c the equilibrium cross-sectional area of the inlet channel. For example, on U.S. Atlantic coast inlets, a typical fit is $A_c \approx 9.3 \times 10^{-4} \; P^{0.84}$ (with P in cubic meters, A_c in m^2) [42]. This yields on the order of $A_c = 1000$–$5000~\text{m}^2$ for moderate lagoons (prisms 10^6–$10^7~\text{m}^3$). Use such a formula to compute a realistic throat area. Then choose a combination of channel *width* and *depth* to match A_c (e.g. assume ~5–10 m deep throat at high tide; then width might be $A_c/ depth$). For instance, if $A_c = 2000~\text{m}^2$ and depth ~8 m, then width ~250 m. **Place a single main channel** through the inlet gap in the barrier, meandering slightly maybe due to Coriolis or asymmetry (curving towards one bank as inlets often do). Also depict the inlet channel extending into the lagoon as a **flood channel** and seaward onto the shelf as an **ebb channel**. The inlet channel inside the lagoon might bifurcate into two ebb-directed channels (forming the flood-tidal delta lobes between them). The channel outside can feed into the ebb delta lobes. Ensure channel banks are drawn with some levee or margin that transitions to shoals.

D. Tidal Deltas and Shoals: On the **lagoon side** of each inlet, generate a **flood-tidal delta** feature. This typically looks like a fan or delta of sand that spreads out from the inlet channel into the lagoon's interior. It often has a *distinctive shape*: a main channel (the inlet) feeding into a lobate sand shoal with branching secondary channels around its perimeter. You can model it as a semi-circular or triangular sand body, shallow (exposed at low tide except in channels). Place small **islands or bars** on this delta to represent subaerial parts (often called "ebb shields" or "swash bars" in real flood deltas). On the **ocean side**, depict an **ebb-tidal delta** if appropriate: a shallow sand platform seaward of the inlet, with linear bars radiating from the inlet mouth along the coast (often downdrift side has a larger bar due to sand bypassing). In wave-dominated estuaries, ebb deltas might be smaller and welded to the shore; you could show a slight bulge of shallow sand outside the inlet and perhaps a downdrift bar where sand exits the inlet and rejoins the littoral drift. Depth on these deltas is typically shallow (a few meters). These features create a natural **morphologic linkage** between the inlet and the adjacent shoreface. *Facies:* mark these delta areas as sandy (similar grain size to barrier sands) and likely cross-bedded. Including them in the analog helps guide where channels dissipate energy.

E. Central Basin and Facies Zones: Allocate the central part of the estuary as a **low-energy basin**. In map view, this is the open water or tidal flat area behind the barrier. For a realistic snapshot, decide how much of it is subtidal vs intertidal. For instance, perhaps 50% is open water (at high tide) and 50% intertidal mudflat and saltmarsh (which would be exposed or wetted at low/high tide respectively). **Draw depth contours or zones:** deeper water (2–5 m) near the inlet and middle, grading to shallower (<2 m) toward edges and head. Mark **mudflats** along the margins – especially in sheltered coves or far from the inlet. These could be shown as gray/brown areas that might be exposed at low tide. At the landward end of these flats (around mean high water level), delineate **salt marshes** (vegetated areas) if the snapshot suggests mature conditions. Salt marsh typically fringes the upper reaches and sides of the estuary where sediment accumulation has built the surface to high-tide level. Represent marsh with a textured green pattern and perhaps a network of tiny tidal creeks (sinuous lines through the marsh connecting to the main channels) to emphasize realism. The central basin's sediment facies is mostly **mud** (clay, silt) with perhaps thin sand layers from storms. You can note or color-code it as "Estuarine mud facies". If the estuary is in an intermediate stage, there might be isolated **mud islands** or bars forming (indicating infill; e.g. a mid-lagoon tidal flat island).

F. Bay-Head Delta and River Channel: Design the upstream end where the river enters as a small delta protruding into the lagoon. Place a **river channel** coming from the hinterland – likely meandering if the terrain is flat. At the point of entering the estuary, it should split or widen, depositing a **bay-head delta lobe**. Show one or more distributary channels and triangular *delta front* extending into the lagoon's head. The delta might have topset beds that are at high-tide level, creating mini-delta plains with marsh or forest, and subaqueous foresets of fine sand/silt into the lagoon. Ensure the delta front does not extend too far – usually it occupies a semi-conical region at the estuary head. The *sediment texture* here is relatively coarse for the estuary (fine to medium sand, perhaps with organics), so color/label it distinctly (e.g. "bay-head delta sand"). The **river channel** feeding it should have natural levees (slightly elevated banks of silt/sand) and adjacent **floodplain** or marsh on either side. You can incorporate some oxbow shapes or crevasse splays on the floodplain to mimic realistic fluvial features. Connect this river channel network to whatever upstream environment (could just fade it out of the modeled area). The number of distributaries depends on size: small river might just have one channel swinging into the lagoon, while a larger one could split into 2–3 distributaries at the mouth. *Tidal influence:* If the tide penetrates this far, indicate slight widening of the channel or a tidally influenced backwater (maybe a zone of slack water where fine sediment accumulates – often the ETM zone around here). The bay-head delta typically *progrades*: for a static view, show its current position and maybe stranded older delta lobes or marshy islands landward, if any.

G. Channel and Creek Networks: Beyond the main inlet and river channels, add **smaller channels** to ensure connectivity and realism. From the inlet's flood delta, draw tidal channels snaking into the central basin (they may dissipate in the flats or connect to the river channels). Along the edges in the marsh, include tidal creeks: these are like branchlets that link marsh interiors to the main water body. A fractal-like dendritic pattern for creeks is realistic in saltmarsh zones. Their scale: creek widths of tens of meters in marsh, narrowing inland. They often join the main channels at acute angles. You can programmatically generate these by treating high marsh areas and connecting them to main channels at spacing intervals. If the marsh is extensive, ensure at least one creek per ~1–2 km of shoreline. **Channel-facies mapping:** mark the main channels (inlet, tidal channels, river) as sandy or coarse lag (shell + sand) on the bottom because of current scouring. Mark point bars or inner bends of channels where deposition occurs – e.g. in the river meanders at the head, you'd expect point bar sands on inner bends and cut-bank erosion on outer bends. In tidal channels, point bars are less pronounced but still can exist if meandering.

H. Facies Distribution Summary: After laying out geometry, assign each zone a facies label for clarity (which can be used by the analog model for textures/colors). For example: **Barrier/Spit:** well-sorted fine sand with cross-bedding (pale beige color, dune and beach structures). **Inlet Channel:** medium sand with shell fragments (active channel, maybe dark blue line for water but conceptually coarse lag). **Ebb Tidal Delta:** medium sand shoals (subtidal bars, shaped by waves – might have breaker bar patterns). **Flood Tidal Delta:** medium to fine sand, possibly bioturbated, in lobes inside lagoon (perhaps expose at low tide). **Central Lagoon Floor:** clayey silt, massive to laminated mud (dark gray/brown), with intertidal parts having mud-cracks or algal mats. **Salt Marsh:** peat and mud with dense vegetation (dark green, organic-rich). **Bayhead Delta Tops:** fine sand and silt, fluvial bedding (light brown), becoming silty mud in prodelta. **Fluvial Channel and Levee:** sand/silt (levees being slightly coarser than floodplain). **Floodplain/ Backswamp:** silty clay with soil development (if exposed, possibly colonized by terrestrial vegetation beyond tidal reach). These facies should transition logically (e.g. sand of bayhead delta interfingers with mud of central basin, barrier sand pinches out into marine shelf mud beyond the ebb delta, etc.).

Using these static rules, one can compose a snapshot that *looks* and *feels* like a real wave-dominated estuary: a sandy barrier with an inlet, a quiet muddy lagoon with tidal flats and marsh, and a river feeding a small delta at the back. It's important to maintain **consistency with physical controls**: for instance, if you choose a wide inlet, ensure the tidal prism (hence lagoon area or tidal range) is accordingly large; if you depict a very narrow barrier that's heavily washover-dominated, perhaps include an ongoing storm or recently closed inlet to justify it. By aligning the static layout with the dynamic rules, the image will be grounded in reality.

I. Example Parameter Adjustments: To refine a particular model run, you might adjust parameters like *relative energy* (wave vs tide) – e.g. in a slightly tide-influenced case, draw more extensive tidal flats and perhaps multiple inlets with larger flood deltas; in an extremely wave-dominated (almost lagoon) case, draw a long continuous barrier with perhaps an intermittent inlet (maybe even an closed inlet and freshwater lake state). Adjust *sediment supply* – a high-supply estuary will have a bigger bayhead delta and more turbid waters (lots of sediment plumes), whereas a low-supply one might have clear water and a sediment-starved central basin (even scouring to deep basin if negative budget). These static variations can represent different end-members within the wave-dominated estuary class.

Key Quantitative Formulas and Indices

Including quantitative rules helps ensure the generated analog honors known geologic relationships:

- **Tidal Prism–Inlet Size Relationship:** As noted, use $A_c = C P^n$ to link inlet cross-sectional area and tidal prism. For quick reference, **Jarrett (1976)** found for U.S. inlets: Atlantic coast $n\approx0.84, C\sim9.3\times10^{-4}$; Gulf coast $n\approx0.91, C\sim2.8\times10^{-4}$; Pacific $n\approx0.86, C\sim7.5\times10^{-4}$ [42] [43]. In practice, one formula often applied is $A_c \approx 5 \times 10^{-4} P^{0.85}$ (in metric). If our estuary has, say, area 50 km^2 and tidal range 1 m, then $P \approx 50 \times 10^6~\text{m}^3$ (assuming half the tidal range effectively fills the area), giving $A_c \approx 5e-4 * (5e7)^{0.85} \approx 1500~\text{m}^2$. This could be, for example, a channel 200 m wide by 7.5 m deep. We then make our inlet ~200 m wide in the plan (scaling to the model's units). **If multiple inlets** are present, you might distribute the prism among them (e.g. two inlets might each take roughly half the flow, though often one becomes dominant). This formula essentially encodes the **O'Brien-Jarrett law** for stable inlet dimensions and should be respected to avoid unrealistic huge gaps or tiny slits that wouldn't carry the volume.

- **Inlet Stability Index (Bruun–Gerritsen criterion):** A dimensionless index r can gauge whether an inlet will remain open. It is defined as the ratio of tidal prism (P per tidal cycle) to the gross longshore sediment transport volume (M) over the same period (often yearly littoral drift) [44]. In simple terms, $r = \dfrac{P}{M_{\text{annual}}}$ (units: typically cubic meters per year for both P and M). **Thresholds:** $r > 150$ indicates a very stable inlet with deep channels (tide-dominated regime), while $r < 50$ indicates an inlet likely to shoal and close under wave action [45]. Values in between (50–150) mean moderate stability with significant ebb shoals (mixed regime) [45]. For example, if an estuary has $P = 20 \times 10^6~\text{m}^3$ (roughly a moderate lagoon) and the littoral drift $M = 1 \times 10^5~\text{m}^3/\text{yr}$ (typical for a sandy coast), then $r = 200$, suggesting a stable inlet (which might imply one well-defined inlet with large ebb delta and minimal bar bypassing) [45]. Conversely, a small lagoon with $P = 1 \times 10^6~\text{m}^3$ on a coast with $M = 2 \times 10^5~\text{m}^3/\text{yr}$ yields $r = 5$, implying waves will dominate – the inlet will tend to silt up or migrate, and the system might become an intermittently closed lagoon. In generation, you can use r to decide if you draw the inlet as open-water or plug it with a sand bar. For a stable case (high r), show a clear inlet channel and maybe jetties if human-maintained; for a low r (wave-dominated) case, consider drawing a very narrow or even a temporary sand berm across the inlet, indicating closure.

- **Barrier Width and Storm-Overwash Criterion:** To reflect barrier stability, use a simple volumetric or geometric threshold. **Volumetric rule:** as mentioned, breach if $V_{\text{overwash}} > V_{\text{barrier}}$ [33]. In practical terms, one can estimate V_{overwash} from storm parameters (surge height, wave runup, storm duration) and V_{barrier} from barrier morphology (width * dune height * alongshore length of section). Rather than simulate a storm, our static model can enforce that any barrier depicted without a breach has V_{barrier} comfortably larger than the plausible V_{overwash} for typical storms. For instance, if a 100-year storm might run ~1 m of water over the island for some hours over a 1 km stretch (order $10^5~\text{m}^3$ of water and sand movement), and the barrier section contains $5 \times 10^5~\text{m}^3$ of sand, it likely survives with just washovers (no full breach) [32] . **Geometric rule:** use *barrier width vs surge height*. For example, a rule could be: if barrier width < (some factor * surge flow length), then expect a breach channel. Empirically, barriers narrower than ~100–200 m often cannot withstand even moderate storms without breaching. So in our static layout, if we choose to draw a barrier narrower than that, perhaps we intentionally include a breach or washover channel cutting through it (for realism). Conversely, wide barriers (>1 km) should show signs of washover only in extreme low spots, not fully breached. Another geometric indicator is dune/berm height: ensure **dune height > expected storm surge + setup** for a barrier to remain intact. For example, if storm surge + wave setup = 3 m, dunes of 5 m height give some safety margin; dunes of 2 m would likely fail. So a formula: if $H_{\text{dune}} < \eta_{\text{surge}}$, then mark barrier as overtopped (and deposit washover sand). In code, one might randomly vary dune height and then decide breach occurrence accordingly.

- **Sedimentation vs Accommodation (Infill Ratio):** As mentioned, define $I = \dfrac{\text{sediment volume input per year}}{\text{new accommodation volume created per year}}$. Accommodation volume per year is basically estuary area * relative sea-level rise per year. If $I > 1$, the estuary is infilling faster than sea-level is adding space – so it will shallow up over time (potentially building deltas, tidal flats, etc.). If $I < 1$, the estuary might deepen or at least not fill completely, meaning transgressive features will dominate (e.g. active retreat of marsh edges, etc.). For example, if an estuary has area 20 km^2, RSLR 3 mm/yr (creating $60,000~\text{m}^3/\text{yr}$ of new space) and the river plus marine sources supply 120,000 m^3/yr of sediment, then $I = 2$ – expect rapid infill and the need to depict extensive tidal flats and perhaps a growing bayhead delta. Conversely, if sediment supply is only 10,000 m^3/yr, $I = 0.17$ – the lagoon likely deepens and might even show expansion (marsh drowning). In such a case, depict deeper water, eroding marsh edge, maybe sediment-starved conditions (like the lagoon floor might be sandy from reworking, as mud can't accumulate). The model can use I to adjust how much of the lagoon is mud-filled vs open water. Notably, wetlands can **keep up with moderate RSLR given enough sediment** – there are modern examples where marsh accretion outpaces sea-level rise [46] . So if your scenario includes robust sediment supply (e.g. deltaic river or plentiful tidal import), you might maintain marshes even as sea-level rises; if not, the marshes submerge and turn to open water.

- **Barrier Dimensions (Width–Height Ratio):** Many natural barrier islands have a width-to-height ratio on the order of 100:1 or more. For example, a 5 m high barrier that's 500 m wide has ratio 100; a big barrier 1.5 km wide and 7.5 m high has ratio 200. This ratio matters because it correlates with stability: a high ratio (wide, low island) can absorb overwash without breaching (volume is spread out), whereas a low ratio (narrow, tall ridge) is precarious. In generation, one could enforce a **minimum width for a given dune height**. A simple rule: $W_{\min} \approx 20 \times H_{\text{dune}}$ (just as an order-of-magnitude guide). So if you set dune height = 5 m, ensure width at least ~100 m; if dune height = 10 m (very high dunes), width should be ~200 m or more. This prevents drawing improbably skinny but tall islands. If you violate this (for creative reasons), then at least show evidence of chronic overwash (since a narrow tall island would get washover fans from any storm that overtops it). In essence, **dune height should scale with island width** because wider islands tend to allow larger dune fields to form. Also, *barrier freeboard* (dune height above surge) might be e.g. ~1.5–2.0 m for a stable island – if dunes are much higher than needed, the extra sand often comes from a wide base and multiple dune ridges. So including maybe 2–3 dune ridges on a very wide barrier adds realism.

- **Channel Meander Geometry:** For completeness, if simulating channel patterns (like the bayhead river meanders or tidal creek meanders), you might use empirical ratios like meander belt width ~ 5–10 times channel width, radius of curvature ~ 2–3 times channel width, etc., to lay out realistic sinuous channels. Also, tidal channels often show fractal scaling: many small creeks join bigger ones at confluences. While not as globally quantified as river meanders, one could apply Hack's law style scaling to creek lengths vs drainage area (though beyond scope here). Still, keeping channels smoothly sinuous rather than angular is key for realism.

In applying these formulas, remember they are guidelines – natural variability is high, so some deviation is acceptable (and even desirable to avoid an overly "perfect" look). But they ensure the analog images are **physically consistent**: e.g. you won't have a gaping 2 km inlet for a tiny lagoon, or a huge river delta with no apparent river feeding it, etc. By incorporating these quantitative checks, the generated environment will stand up to expert scrutiny.

Visual Examples and Spatial Layout Guidance

Satellite image of a real wave-dominated estuary (Curonian Lagoon, Baltic Sea) viewed from above. ***Top:*** The long **Curonian Spit** (light-toned sand barrier) encloses a broad lagoon on the right, exemplifying a wave-built barrier separating ocean and estuary. Only a single inlet at the far north (outside this frame) connects the lagoon to the sea, consistent with a microtidal, wave-dominated setting. ***Center:*** Note the **smooth shoreline** of the lagoon and the shallow water (turquoise colors) near the spit, indicating extensive sandy shoals or flats just inside the inlet [47] [48]. On the seaward side (left), a thin line of beach is visible along the barrier, while on the lagoon side there are indented bays where wind-wave erosion or minor washovers have carved into the spit [49]. Vegetation (dark green) stabilizes much of the barrier except the actively moving dunes (off-white patches) along its length [49]. ***Bottom:*** In the lagoon's far end (top of image), the **Nemunas River delta** protrudes (dark green, triangular area) into the lagoon [48]. This real-world example reflects many model rules: a single inlet due to strong littoral drift, a large central basin accumulating fines, and a bay-head delta from the river. It also highlights how **wave dominance produces a large sand barrier** that mostly isolates the lagoon from open-ocean conditions. A generative model can use such imagery as a spatial template – ensuring the barrier length and continuity, lagoon expanse, and delta size are all in plausible proportion.

For additional guidance, schematic facies models (e.g. Dalrymple et al. 1992's classic tripartite estuary diagram) illustrate the division of environments. In those models, one sees the barrier/back-barrier sand complex grading landward to central mud basin, then to fluvial sands – exactly as we have described [4]. Cross-sectional sketches show how a barrier estuary might have a sand "cap" at both seaward and landward ends with mud in between. When constructing a cross-section through your model (say along the estuary's axis), it should reveal: beach and dune sands at the barrier (with seaward surf zone deposits), an abrupt deepening at the inlet channel, then a shallow central bay floor of mud, and near the head a wedge of fluvial sand thinning seaward under the mud. Including such cross-sectional consistency (even if implicit in the planview) will yield more geologically accurate images.

Finally, consider using real examples as calibration for your model. Besides Curonian Lagoon (a large wave-dominated lagoon), examples like **Pamlico Sound (NC, USA)**, **Great South Bay (NY, USA)**, **Lagoa dos Patos (Brazil)**, or smaller Australian barrier estuaries (e.g. **Narrabeen Lagoon** or **Swan Lake** in NSW) can be studied. They all show the common elements: inlet(s) often stabilized by modern works, a barrier with washover fans, a central water body with fringing marsh, and a minor river input. If possible, incorporate satellite or aerial textures derived from such examples to inform color and tone in the analog images (e.g. turbid brown water near the river, clearer green water near the inlet, bright white sand on barriers and deltas, dark green for marsh forests, etc.). This will enhance visual realism.

Pseudocode for Generative Model Scaffold

To implement these rules in a procedural generation context, here is a high-level pseudocode outline. This scaffold assumes input parameters (wave vs tide vs river influence, geometry scales) and generates a 2D grid or vector representation of the environment:

```
function generate_wave_dom_estuary(params):
    # Unpack key parameters for control:
    L_estuary = params.length       # total estuary length (km)
    W_estuary = params.width        # max estuary width (km)
    tidal_range = params.tidal_range  # in m
    wave_angle = params.wave_angle    # wave approach angle (deg from normal)
    river_discharge = params.Q_river  # river flow (m3/s) for context
    sed_supply = params.sed_supply    # annual sediment volume (m3/yr)
    sea_level = params.sea_level      # current sea level (ref datum)
    # Derived key values:
    area = L_estuary * W_estuary * 1e6        # area in m2 (approx rectangular
assumption)
    tidal_prism = area * (tidal_range/2)
# simplistic prism (m3), half tide cycle
    littoral_drift = estimate_littoral_transport(wave_angle, wave_climate)  #
m3/yr

    # 1. Initialize spatial grid or vectors
    grid = create_empty_grid(extent = [0:L_estuary, -W_estuary/2:W_estuary/2],
resolution = params.res)
    # coordinate system: x along estuary axis, y across (y=0 centerline)

    # 2. Draw coastal barrier across the mouth
    barrier = draw_barrier_island(grid, length = W_estuary, width =
choose_barrier_width(params), dune_height = choose_dune_height(params))
    # barrier spans y from -W_estuary/2 to +W_estuary/2 at x ~ L_estuary
(seaward boundary)

    # Decide number of inlets based on wave angle and prism vs drift
    r_index = tidal_prism / max(1, littoral_drift)
    if wave_angle > some_oblique_threshold or r_index < 50:
```

```
        num_inlets = 1
    else if r_index > 150:
        num_inlets = max(1, round(tidal_prism / 1e7))  # more prism can sustain
more inlets (simple heuristic)
    else:
        num_inlets = 1  # default one inlet for simplicity

    inlet_positions = place_inlets_along_barrier(barrier, num_inlets,
wave_angle)
    for each inlet_pos in inlet_positions:
        # 3. Carve inlet channel through barrier
        carve_channel(grid, barrier, center = inlet_pos, width =
compute_inlet_width(tidal_prism, num_inlets), depth =
compute_inlet_depth(tidal_prism))
        # Place ebb and flood deltas
        draw_flood_tidal_delta(grid, inlet_pos, tidal_prism,
orientation='landward')
        draw_ebb_tidal_delta(grid, inlet_pos, tidal_prism,
orientation='seaward')

    # 4. Central basin: assign depths and sediment type
    for x from 0 to L_estuary:
        for y across width:
            dist_to_inlet = compute_distance_to_nearest_inlet(x,y)
            depth = baseline_depth - (x/L_estuary) * depth_gradient  # deeper
near mouth, shallower near head
            # Add intertidal shallows towards edges
            if |y| > 0.4*W_estuary:  # near edges
                depth = depth * 0.5  # shallower edges (flats)
            grid.depth[x,y] = max(depth, min_depth)
            grid.facies[x,y] = 'mud'  # default central mud

    # 5. Bay-head delta and river
    river_channel = carve_river_channel(grid, mouth_width =
estimate_river_width(river_discharge), sinuosity = params.river_sinuosity)
    place_bayhead_delta(grid, river_channel.mouth_position, volume = sed_supply
* delta_time, spread_angle = 60_deg)

# The bay-head delta will deposit sand in a wedge at the head of estuary and
adjust depths there
    grid.facies[region=bayhead_delta] = 'sand'

    # 6. Marsh and tidal flats:
    identify_intertidal_zones(grid, tidal_range)
    for cell in grid:
        if cell.elevation between MHW and MLW:
            if distance_to_land(cell) < marsh_proximity_threshold:
                grid.facies[cell] = 'marsh'
```

```
# fringing marsh on high intertidal near edges
            else:
                grid.facies[cell] = 'tidal_flat'
    generate_tidal_creeks(grid, marsh_regions = grid.facies == 'marsh',
connect_to = main_channels)

    # 7. Apply overwash/breach features if needed:
    if r_index < 30 or barrier.width < critical_width:
        # simulate a recent storm breach or overwash
        create_washover_fans(grid, barrier, volume =
overwash_volume_estimate(barrier))
        if barrier.width < critical_width:
            open_temporary_breach(grid, location = barrier.lowest_point)

    # 8. Smooth and finalize
    smooth_bathymetry(grid.depth, preserving channel lows and shoal highs)
    finalize_facies_transitions(grid.facies)
    return grid
```

This pseudocode is quite simplified, but it incorporates many rules: it computes a stability index `r_index` to decide inlet count, uses tidal prism to size inlets, draws delta deposits, populates the lagoon with mud, adds a river delta if sediment supply exists, and even considers barrier overwash if conditions indicate. One would need to flesh out sub-functions (`draw_barrier_island`, `carve_channel`, etc.) with more detailed geometric constructions (e.g. barrier shape could be a simple straight line or slightly recurved spit; channels could be sine-generated curves). The “smooth and finalize” step would ensure no abrupt changes (making it look natural).

Note: The actual implementation can be refined using known coastal engineering models (for inlet cross-section) and fluvial models (for river channel meanders). The key is that the model iteratively places sedimentary features in a logical order: first the framework (barrier, channels), then the deposits (deltas, flats), then the fine details (creeks, washover). This ensures consistency; for instance, we carve channels before labeling facies so that channel cells can later be assigned “sand” or “open water” appropriately.

With this framework and careful parameter tuning, the generative model can output a variety of **wave-dominated estuary analogs**, all grounded in the hierarchical structure, physical controls, and evolution patterns we’ve described. Each output “image” can represent a plausible state of such an estuary, useful for training or analysis in geologic interpretation contexts.

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1 2 5 6 7 9 10 11 12 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 37 40 41
Morphology of estuaries - Coastal Wiki
https://www.coastalwiki.org/wiki/Morphology_of_estuaries

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