ChatGPT

Mixed Energy Estuarine Depositional System – Procedural Rule Set

1. Hierarchical Multiscale Structure of the Estuary

A mixed wave-and-tide influenced estuary exhibits a **nested, multiscale morphology** from the overall bay down to small sedimentary features. At the **estuary-wide planform scale**, the system is typically semi-enclosed by a sand barrier or spit at the mouth, creating a partially sheltered lagoon or bay behind it [1] [2]. The **inlet morphology** at the mouth is usually a narrow tidal channel cutting through the barrier; wave action tends to constrict the inlet with sand, while tidal currents scour it and maintain its depth [3]. Just seaward of the inlet, an **ebb-tidal delta** (subaqueous sand shoals deposited by outgoing tides) often develops on the open coast. This ebb delta is built from the coarsest sands and has a lobate or bar-form shape, representing the seaward dispersal of sediment by strong ebb currents [3]. Landward of the inlet, a corresponding **flood-tidal delta** or sand bayhead may form where incoming tides lose energy and drop sand inside the estuary, although its prominence varies with the wave-tide energy balance.

Inside the estuary, the central area forms a **broad central basin** that is typically mud-dominated and low-energy [2]. This central basin can include extensive intertidal flats (sand or mud flats exposed at low tide) and subtidal shallows. The basin is flanked by tidal channels and shoals: for example, multiple branching tidal channels may spread into the bay, separated by sand or mud shoals and bars. These **tidal bars and flats** are especially characteristic if tidal influence is strong – elongate sandbars and broad flats occupy the outer-middle estuary in tide-influenced systems [4]. Along the fringes of the central basin, in sheltered coves and the upper reaches, **salt marshes** and tidal wetlands develop on the high intertidal flats. Marsh vegetation colonizes the highest parts of the flats where fine sediment accumulates, creating a grassy marsh platform that floods only at high tide. These marshes typically fringe the estuary margins and the landward ends of tidal flats. Upstream, the estuary transitions into a **bay-head delta or fluvial zone** at the river's mouth [2]. This is the zone where the river delivers sediment into the estuary. It may appear as a small delta or network of distributary channels building into the head of the bay, especially if river sediment supply is high. The bay-head delta zone is influenced by both tidal backwater and river flow; channels here often show meandering patterns and mixed fluvial-tidal sedimentary structures. Overall, the estuary exhibits a tripartite zonation: a sandy marine-dominated mouth (barrier/inlet and tidal deltas), a mud-rich central basin, and an inner fluvial or bay-head delta zone [2]. Each of these broad zones contains finer-scale structures (bars, channel meanders, levees, marsh creeks) that reflect the local hydrodynamics and sediment supply.

At finer scales, **channel-shoal complexes** define the morphology. The main tidal channel(s) runs from the inlet through the estuary, often meandering through the central basin and then connecting with the river channel at the head. This channel may split into multiple tidal distributaries in the central bay if the estuary is large. Adjacent to channels are intertidal bars or shoals; for example, point bars on the inner bends of tidal channels, or mid-channel bars where flow diverges. Fine-grained **mud drapes** often cover these bars during slack water, leading to layered sand-mud couplets. In the marsh areas, a network of **tidal creeks** threads through the marsh platform, draining it at low tide. Upstream in the fluvial zone, classic fluvial features (e.g. point bars, levees, overbank splays) transition into tidal features (tidal point bars with mud drapes, etc.) as one moves seaward. This hierarchical structure – from the overall shape of the bay and barrier, down to channels, bars, and small bedding features – must be represented in a realistic analog. The key is that larger-scale features (like the presence of a barrier island and central bay) impose constraints on smaller-scale features (like where bars or marshes can form). Any generated image should capture this spatial hierarchy: a bay partially enclosed by a sand barrier at the mouth, criss-crossed by tidal channels and shoals, grading upstream into narrower riverine channels, with fringing marshlands at the margins.

2. Physical Drivers and Controls on Estuary Morphodynamics

The morphology of a mixed-energy estuary arises from the **interplay of tidal currents, wave action, and river input**, modulated by the basin's geometry and external forcings [5]. **Tidal forcing** drives water in and out of the estuary, creating tidal currents that erode and deposit sediment. The mean tidal range (e.g. spring tide range) is a key parameter: larger tidal ranges (meso- to macrotidal conditions) produce stronger tidal currents and larger tidal prisms, which tend to scour deeper channels and spread tidal influence further into the estuary [5]. Tidal currents are typically dominant along the main channel axis of the estuary, especially during ebb flows that drain the basin [6]. In mixed-energy estuaries, tides are strong enough to form sizable tidal deltas and channels, but not so strong as to eliminate wave-built features. **Wave action**, on the other hand, works primarily at the estuary mouth and along exposed coastal segments [5]. Wave energy (characterized by significant wave height and wave period, and influenced by storm frequency and wave approach angle) pushes sediment alongshore (littoral drift) and tends to build and maintain sand barriers or spits across estuary mouths. Waves crashing on the barrier can also drive washover deposition into the estuary during storms, and create cheniers or beach ridges if conditions allow. In a mixed-energy setting, waves and tides are both significant: waves try to **close off the inlet** by depositing sand in the mouth, while tidal currents **work to keep the inlet open** by scouring sediment and exporting it seaward [3]. This dynamic equilibrium between wave-driven inlet closure and tide-driven inlet maintenance is a hallmark of mixed energy systems. For example, strong littoral drift can form a sand spit that nearly seals the estuary, leaving only a narrow inlet channel; the tidal prism rushing through that channel on each tide can be sufficient to prevent complete closure by continuously scouring it [3]. If tidal currents reach peak velocities on the order of ~1 m/s or more in the inlet, they can flush out sand faster than waves deposit it, thereby **preventing the inlet from silting shut by longshore drift** [7]. If tidal currents weaken (or wave sediment supply overwhelms them), the inlet may shoal and eventually "weld" closed, fusing the barrier across the mouth.

River discharge and sediment supply is the third major driver [8]. The river provides freshwater and often a substantial load of sediments (both sand and mud) to the estuary from the landward side. The volume of river flow (especially flood events) can influence estuarine circulation and stratification, while the sediment load (especially the fraction of mud vs sand) controls how quickly the estuary infills. In a mixed-energy estuary, typically the **fluvial sediment supply is moderate** – enough to contribute to infilling over time (e.g. forming a bay-head delta), but not so high as to dominate the system (as in a purely river-dominated delta). If sediment supply is high and tidal dispersal is limited, a river may build a small delta into the head of the estuary, with progradational mouth bars and distributaries. Conversely, low sediment supply leads to a sediment-starved estuary where the central basin remains largely open water or mudflat. River flow also affects salinity gradients and can induce a stratification or a turbidity maximum zone where fresh and marine waters meet (though this is more a hydrological aspect, it can concentrate fine sediment deposition at a certain location along the estuary).

The **basin shape and geology** impose important controls as well. The geometry of the drowned river valley (or coastal embayment) sets the stage: a narrow, funnel-shaped estuary will amplify tidal range and favor strong currents, while a broad, wide-mouthed bay spreads out tidal flow and gives waves more influence. The depth of the basin influences tidal propagation and the tidal prism. For instance, a shallow basin with extensive flats can induce tidal asymmetry (flood vs ebb duration differences) due to flow expansion over flats [9]. Steep and confined valley sides may restrict lateral expansion of tidal flats, resulting in a more channelized system (often more tide-dominated in character), whereas a wide coastal plain allows for broad marsh and flat development (introducing wave influences on those flats via wind waves). Underlying **geologic controls** (like bedrock outcrops, headlands, or antecedent topography) can locally dictate where channels or sediment bodies form, by providing hard points or deeper paleo-valleys. Additionally, **sea-level change** is a critical external forcing over geologic timescales: modern estuaries largely formed during the Holocene sea-level rise, and ongoing sea-level trends (rise or fall) will drive the estuary to transgress landward or regress seaward. A rising relative sea level (transgression) increases accommodation space, often promoting the growth of the central bay and landward retreat of barriers and marshes, whereas a falling sea level or high sediment influx can cause the estuary to infill and the shoreline to move seaward (delta progradation) [10]. **Climate and storm regimes** also play a role by modulating extreme events – e.g. occasional storms can introduce large waves that reshape the inlet or barrier, and seasonal freshwater flooding can flush the estuary or alter salinity and sediment delivery.

Importantly, these drivers interact in non-linear ways. **Wave-tide interaction** at the inlet is a prime example: waves tend to deposit a sand bar at the inlet throat, while a sufficient tidal prism will sweep it out to form an ebb delta instead [3]. The relative dominance of wave vs tidal energy can be quantified by indices or classifications – for example, coasts are often classified as microtidal (tidal range < 2 m), mesotidal (2–4 m), or macrotidal (>4 m) [11]. Mixed-energy estuaries usually occur in mesotidal settings where tides are moderate and waves are also significant. In such settings, one might find **multiple tidal inlets** separated by barrier islands if the tidal prism is large (as in the Wadden Sea lagoon system) [12], or a single inlet offset by a long littoral drift spit if wave action is strong from one direction (e.g. Willapa Bay, WA or the Dyfi Estuary in Wales) [1]. **Tidal prism** (the volume of water exchanged each tide) is a master variable linking many controls: it depends on basin area (which relates to sea level and basin geometry) and tidal range, and it in turn governs inlet size and the extent of tidal delta development. The **wave climate** (average and storm wave heights, directionality) dictates how robust the barrier is and whether inlets tend to migrate or close. **Sediment grain size** is another factor: mixed-energy estuaries often have sand delivered from marine sources (beach and dune sand into the barrier and tidal deltas) and mud from the river; sorting processes distribute the sand to high-energy zones and mud to low-energy zones. Overall, a realistic model must incorporate how these controls jointly shape the estuary: for instance, increasing tidal range (all else equal) tends to widen tidal channels and increase the area of tidal flats, whereas increasing wave energy tends to build higher, more continuous barrier spits and reduce the number of open inlets [11]. The static snapshot of an estuary is essentially an equilibrium (or momentary balance) of these forcing factors, so the rule set must ensure consistency between the imposed drivers (like a given wave/tide ratio) and the resulting morphology (like inlet size, barrier continuity, and extent of tidal flats).

3. Time-Evolution Rules and Dynamics

Mixed-energy estuaries are highly dynamic systems that **evolve over time** in response to episodic events and gradual processes. A robust procedural model should encode rules for how the system changes: breaching or closure of barriers, infilling of basins, growth of marshes, shifting of channels, and overall transgressive or regressive trends.

Barrier breaching and inlet dynamics: One of the most dramatic evolutionary processes is the opening or closing of tidal inlets through the barrier. During extreme events such as storm surges or river floods, **barrier breaching** can occur – a new inlet is cut through the sand barrier by surge overflow or floodwaters [13]. Such breaches often happen at low, weak points in the barrier during high water events. If a breach occurs, the subsequent tidal flow through it will either establish it as a permanent inlet or it will heal. The rule set should reflect that a breach leads to **rapid tidal scour** if the tidal prism rushing in is large enough: strong tidal currents will widen and deepen the new channel, scouring sand out and depositing some of it as new ebb and flood deltas [14]. This can **permanently establish a new inlet** and even create a new estuarine sub-basin behind it if the back-barrier area is extensive. Historical examples in coastal plains (like the Dutch coast in medieval times) show multiple estuarine lagoons forming after successive breaches of a coastal barrier [15]. On the other hand, if the tidal flow is insufficient (small prism or quickly diminishing storm surge), wave action and littoral drift will **"weld" the barrier back together** by depositing sand in the breach. The model should include a threshold condition for inlet stability: for example, if the tidal prism through a breach falls below a certain volume relative to the longshore sand transport, the inlet shoals up and closes. **Inlet migration** is another time-evolution behavior – an existing inlet can migrate downdrift (along the barrier) under oblique wave action, especially if stabilized by tidal flows on one side. Over decades, an inlet might gradually shift position until a new breach forms (resetting the cycle). The rules can simulate inlet migration by moving the channel opening along the barrier in the direction of net drift, depositing a trailing recurved spit in its former location.

Tidal delta evolution and basin infill: Over time, the central basin of the estuary tends to accumulate sediment, gradually shrinking in volume – a process of **estuarine infilling**. Sediment is delivered both from marine sources (sand from the ebb/flood deltas and inlet) and fluvial sources (mud and sand from upriver). The model should represent **deltaic infilling at both ends**: at the seaward end, the ebb tidal delta may grow and weld onto the barrier or shoreline, particularly during phases of relative sea-level fall or excess sand supply. This can eventually form new barrier beach ridges or attach to the coast, effectively pushing the shoreline seaward (barrier progradation or inlet relocation). On the landward side, a **bay-head delta** may prograde as the river builds sediment into the head of the estuary. This bay-head delta advancement converts open water into deltaic wetlands and distributary channels. Time-evolution rules would gradually expand the delta front into the bay and fill accommodation; e.g. each time step could deposit a lobe of sand/silt farther seaward at the river mouth, coarsening-upward sequences indicating progradation. As the central basin area fills, the tidal prism may decrease (less water volume exchanged), which in turn can destabilize inlets (making them more prone to closure) – a **feedback loop** the rules should capture qualitatively. Ultimately, a fully infilled estuary becomes a tidal delta or strandplain if regression continues, marking the transition to a river-dominated delta environment.

Marsh expansion and floodplain development: In the quieter parts of the estuary (upper reaches of tidal flats and along protected edges), **salt marshes** gradually expand. As sediment accumulates on tidal flats, especially fine silts and clays, the elevation of the flat may rise to the high tide level, allowing vegetation to colonize. Once vegetated, the marsh traps more sediment (both mineral and organic), accelerating vertical accretion. The rule set should allow **marsh progradation** horizontally over time into open water areas as well: for example, a rule might say that any intertidal flat that spends a large percentage of time above water (e.g. only flooded on spring tides) will transition to marsh vegetation, thus converting to supratidal land. Marsh expansion is limited by tidal channel activity and wave disturbance. Tidal channels often **meander through marshes and can erode the marsh edges** [16], resetting marsh growth in those areas. The model could implement this by occasionally eroding marsh cells where a channel migrates (simulating lateral channel migration cutting into the marsh platform). Likewise, **storm waves** can cause episodic erosion or overwash of marshes from the seaward side [17]. Therefore, time-evolution should not be monotonic growth – there are setbacks where marsh edge retreats due to a channel avulsion or storm scour, followed by renewed sedimentation and plant re-growth. Over decades, though, the general trend in a sediment-rich estuary is that marshes expand and the intertidal area increases (until perhaps too much infilling turns the area into terrestrial land).

Channel network evolution: The tidal channel system in an estuary is inherently mobile. Tidal channels can migrate, bifurcate, or silt in, analogous in some ways to river channels but driven by tidal flow reversals. One important dynamic is **tidal channel meandering** – in the inner estuary, where flow might be ebb-dominant, channels develop sinuous bends and migrate sideways, much like rivers, creating point bars on the inside of bends and eroding outer banks (which might be marsh edges) [16]. The model should include channel migration rules (e.g. incrementally shift channel centerlines laterally in areas of erosion and deposition) and possibly cut-off events. Indeed, in mixed-energy estuaries, one can get **neck cut-offs** of highly sinuous tidal channels during major floods or due to tidal flow inefficiencies, analogous to oxbow formation [18] [19]. Such an event would straighten the channel and leave behind a tidal channel meander scar or tidal creek. Another process is the formation and migration of **tidal channel bifurcations and shoals**: near the inlet, the flow often splits around sediment shoals, and these shoals can grow, causing the flow to reorganize. Over time, a secondary channel might capture more flow and become the main inlet channel, while the former main channel shoals up (a phenomenon observed in some ebb-delta channel switching). The rules should allow channels to avulse or switch path if, for example, sediment deposition raises one channel's bed and an alternate low route is available (perhaps stochastically triggered or based on flow thresholds).

Estuary transgression or regression: On longer timescales, consider the trajectory of the whole estuarine environment under sea-level change or sediment surplus/deficit. If **transgression (sea-level rise)** is ongoing and outpaces sediment accumulation, the estuary will migrate landward. Barrier islands may roll over landward by storm overwash, the shoreline at the head of the estuary moves upstream, and previously terrestrial or marsh areas get flooded, expanding the bay. The rule set can implement this by shifting environmental zones landward each time step in proportion to sea-level rise, and by eroding shorelines and redistributing that sediment. The flooding of new areas can form new accommodation for tidal flats and marsh in inner parts – e.g. a coastal forest might transform into a tidal swamp and then a mudflat as transgression proceeds. Conversely, under **regression (relative sea-level fall or excess sediment supply)**, the estuary will shrink and possibly convert to a delta. The barrier may become attached to the mainland as the lagoon fills (forming a beach ridge plain), tidal channels may shorten and tidal prisms drop, and the river might extend its channels seaward (deltaic progradation). Land emergence can cause former subtidal areas to become intertidal and eventually supratidal land. The model could simulate regression by seaward growth of the delta and barrier shoreline, effectively reducing the central bay area over time. Importantly, **the transition from an estuary to a delta** is a continuum [10]. Our mixed-energy estuary, as it infills, will tend toward a more river-dominated deltaic system if sediment supply is very high or sea level falls. Conversely, if sea level rises significantly with not enough sediment, it can evolve into a deeper embayment or tidal bay (possibly eventually becoming an open embayment with barrier drowned). The procedural rules should be able to capture these broad trends by adjusting the positions of facies boundaries and the volumes of sediment in each environment over successive iterations.

In summary, time-evolution rules should treat the estuary as a self-adjusting system: **breaches open or close inlets** depending on event thresholds, **tidal prisms and sediment budgets change** as the basin fills or empties, **marshes and flats grow until disturbed**, and the entire estuarine prism shifts landward or seaward with sea-level trends [10]. The goal is to be able to not just generate one static image, but also to envision a sequence of images through time that show realistic changes (e.g. an inlet migrating a few kilometers over centuries, or the central basin gradually silting up and marshes extending). By encoding these rules, a generative model can simulate plausible “histories” for the estuary, which helps ensure that any given snapshot is consistent with some realistic evolutionary path.

4. Static Snapshot Generation Rules (Facies and Morphology Assembly)

To construct a **geologically plausible snapshot** of a mixed-energy estuary, the model should follow a set of rules that place the various facies and morphological elements in a consistent spatial arrangement. These rules translate the physical principles and typical patterns (from sections 1–3) into a recipe for generating an image or map at one point in time.

Define the estuary outline and base levels: Begin by specifying the overall estuary geometry. This includes the shoreline configuration and the extent of tidal influence inland. For example, define a drowned valley outline that widens toward the coast (common in transgressive estuaries). Set a **sea level** and tidal datum (mean high water, etc.) relative to the valley topography. All subsequent facies placements reference these elevations. The head of the estuary is at the landward limit of tidal facies (e.g. the tidal freshwater transition), and the mouth is at the seaward limit of coastal (open-marine) processes [20]. The model should ensure continuity: the estuary should connect to an open shelf or ocean on the seaward side and taper into a river channel landward.

Position and characterize the barrier/inlet system: In a mixed energy estuary, expect either a barrier island or spit partially enclosing the bay. The generation rule could be: *If wave dominance vs tide dominance parameter > 1 (waves slightly stronger), create a long barrier spit extending from one side of the bay mouth, leaving a single inlet offset to the side. If tide dominance is higher, consider multiple shorter barrier islands with more than one inlet.* For instance, a mesotidal estuary might have two inlets separated by barrier segments, whereas a microtidal one would likely have one inlet [12]. The barrier should be placed along the seaward boundary of the estuary, typically **parallel to the coast**. Its shape might be a recurved spit (if influenced by strong lateral drift) or a more symmetrical barrier island if waves approach head-on [1]. Ensure the barrier has a **breach/inlet opening**: define the inlet channel’s location and width. The inlet width can be set by an empirical relationship to tidal prism (see section 5), but qualitatively, a larger tidal prism or stronger tidal currents means a wider, deeper inlet. The barrier island itself can have features like beach ridges and washover fans on its interior, indicating wave overwash into the lagoon. Landward of the inlet, place a **flood-tidal delta** deposit: a lobe or swash bar accumulation of sand that fans into the lagoon just inside the inlet. On the seaward side, design the **ebb-tidal delta**: a field of shoals and channels. For example, the model can create several sandy shoal patches seaward of the inlet, oriented in a delta-like pattern (arc of shoals) opening to the sea. These should be in shallow water (below low tide, but above the surrounding seafloor), and the main inlet channel should cut through them. The ebb delta often has a bulge offset to the downdrift side if there’s strong littoral drift [1]. So one rule: *If a significant longshore drift is present, skew the ebb delta to the downdrift side and include a main channel hugging the downdrift barrier margin.* Conversely, if waves are more symmetric, the ebb delta can be more centered.

Lay out the tidal channel network: From the inlet inward, generate the main tidal channels that penetrate the estuary. Typically there is a primary channel that connects the inlet to the river mouth. This channel likely follows the deepest part of the drowned valley (thalweg). The model can trace a sinuous channel path through the central basin. Tidal channel geometry rules: channels often widen near the inlet (due to tidal prism convergence) and narrow upstream. Depths are greatest at the inlet throat (scoured by ebb jet) and decrease landward. The channel should meander to some degree in the central basin, especially if there is room laterally. The **channel meander wavelength** could be tied to channel width (e.g. 7–10 times channel width, similar to rivers), but note tidal meanders can be longer due to reversing flow. In the upper estuary, as tidal influence wanes, the channel might become more fluvial in character (higher sinuosity if low gradient). One might explicitly place a **bedload convergence point** – the zone where flood and ebb currents' sediment transport balances, often around the boundary between marine and fluvial dominance. This typically coincides with the maximum turbidity zone and sometimes a pronounced meander in mixed estuaries [18]. In practice, in the static snapshot, this might not be directly visible, but it helps to conceptually position where sand vs mud transitions occur along the channel. The rule could be: *Set a point 2/3 of the way up the estuary from the mouth as the bedload convergence (in a transgressive estuary), and make that the apex of channel sinuosity.* Upstream of that, channel deposits turn more fluvial (sandier point bars), downstream of that, channels might be sandy but with more tidal signatures (like two-direction ripple cross-laminae). **Secondary channels**: If the tidal prism is large relative to one channel's capacity, or if the geometry is broad, a second channel might exist. For example, many mixed estuaries have one main channel and a few smaller tidal creeks or secondary channels on the margins. The generation can add smaller branching channels heading off into shallow sub-embayments or connecting to marsh creeks. All channels should eventually funnel into the main inlet (or directly to sea if a secondary smaller inlet exists). Ensure that channels have **invert elevations** below mean sea level so they hold water at low tide, whereas adjacent flats might be at or above low tide.

Allocate intertidal flats and subtidal areas: The central basin likely contains large areas of intertidal flats – these are the areas that are alternately flooded and exposed. The model should delineate broad **sand or mud flats** flanking the channels. For instance, generate polygonal areas on either side of the main channel that lie between mean low water and mean high water elevation (thus intertidal). Their extent can be based on tidal range (larger tidal range allows wider flats because the vertical tidal prism can flood a gentler slope). Mixed-energy estuaries often exhibit a patchwork of **sandy vs muddy flats** depending on exposure. Closer to the inlet (outer estuary) and along the immediate channel edges, sand flats might dominate (since stronger currents and occasional wave action can winnow mud). Farther from the channel and landward into sheltered coves, mud flats dominate (low energy, fine sediment accumulation) [21]. A rule: *Distribute sediment grain sizes by energy:* assign coarse sand facies to the mouth bars, inlet channel, and ebb/flood deltas; assign mixed sand-mud to mid-estuary flats; assign mostly mud to inner flats and marsh areas [21]. The **planform shape** of the flats often mirrors the estuary shape – e.g. elongated along the shoreline for barrier lagoons, or more radial in a broad bay. The model can place higher elevation flats (those nearer to marsh elevation) toward the landward margins, where tidal currents are weakest and finest sediments settle [22]. Lower intertidal sand flats might occur adjacent to channels (forming point bars or linear shoals). Remember to include small-scale topography like creek networks on mud flats – e.g. dendritic tidal creeks draining a flat into the main channel.

Place salt marshes and supratidal zones: At elevations above mean high water (but within reach of spring tides and storm tides), **salt marshes** should be generated. Typically, marshes fringe the inner parts of the estuary and the landward edges of tidal flats [22]. They can also occur on the leeward side of barrier islands (back-barrier marshes) if sediment accumulates there. To implement this: identify zones in the model that are just slightly below high tide or up to some decimeters above it, and fill those with marsh (vegetated) facies. Marshes often have a patchy extent, following the protected areas where waves are minimal. For example, behind a broad sand flat or in an embayment away from the main channel, place marsh patches. The marsh areas should connect to tidal channels via narrow creeks. One could algorithmically carve narrow tidal creeks through the marsh polygons connecting to the main channel (ensuring every marsh cell is within a certain distance of a creek for tidal flooding). **Other supratidal features** might include tidal swamps or levees if the climate/setting suggests (e.g. mangroves in tropical estuaries, or wooded swamps at the upland fringe in temperate zones). These would be placed at the very head of the estuary or in areas infrequently flooded.

Facies boundaries and transitions: Clearly delineate boundaries between facies such as marine sand (yellow/beige on a map), tidal flat mud (gray/brown), marsh peat (green), fluvial sand (brown), etc. These boundaries should follow logical contours of energy and elevation. For instance, the **boundary between the central mud basin and the outer sand complex** could be drawn near the point where the estuary narrows and tidal currents accelerate (often around the middle of the estuary). This might coincide with a change from mud-dominated surface to sand-dominated (sometimes visible as a color or texture change in aerial images due to different sediment or benthic flora). Similarly, the **fluvial-to-estuarine transition** at the head can be marked by the upstream limit of brackish indicators (like the last tidal point bar with mud drapes, beyond which point bars are pure fluvial sand). In a static model, one could place this boundary at, say, the location where channel width starts to decrease more rapidly and marshes taper out – essentially the tidal limit. The **barrier-inlet vs open-coast boundary** is at the inlet mouth; seaward of this is open marine (e.g. a beach shoreline along the barrier island and the ebb delta offshore). If including offshore, one might draw the limit of the ebb-tidal delta roughly out to where waves dominate the seabed (maybe a couple of kilometers offshore or to ~10-15 m water depth in many cases).

Incorporate small-scale depositional features: Within each facies area, the model can add texture elements that geologists would expect. For example, on the ebb-tidal delta shoals, include swash bars oriented obliquely to the inlet throat, indicating how they migrate under wave and tidal action. Inside the inlet on the flood delta, perhaps add a central shallow platform with radiating channels (like the classic flood delta lobes and spillover channels). On tidal point bars in channels, add lateral accretion ridges to indicate growth of the bar into the channel. On the marsh, include the sinuous creek patterns and perhaps ponds or cut-off meanders as evidence of channel migration. Along the barrier, denote any inlet-adjacent features like **ebb shield** or **spillover lobes** (where the ebb delta attaches to the downdrift shore) or **storm washover fans** that extend landward into the estuary (sheets of sand that breach the dune during hurricanes, for instance). While these details might be fine, they contribute to the realism. A procedural approach might randomly generate some washover fan shapes behind low sections of barrier, or cut breaches in the barrier as per rules (point 3) and then show them either active (open inlet) or healed (swale line in the barrier).

Finally, ensure **consistency among elements**: the static snapshot must obey mass balance and spatial logic. For instance, if the tidal prism (which is related to estuary area and tidal range) is large, there should be either a wide single inlet or multiple inlets to accommodate it (a tiny inlet could not handle a huge prism without extreme currents). Likewise, extensive tidal flats and marsh indicate a lot of sediment has accumulated in the estuary; this should correlate with maybe a high sediment supply or an older/more mature estuary (and perhaps a smaller central open-water area). If instead the central bay is mostly open water (little flat), it suggests either a relatively sediment-starved or young estuary or one where sea-level rise recently outpaced sedimentation – the presence/absence of marsh should align with that narrative. All facies should connect logically: for example, the bay-head delta sand should connect with the river channel deposits upstream; the barrier island beach sand should connect with the ebb delta shoals continuously, etc., so that there are no abrupt discontinuities unless justified (like a rocky headland causing a gap, which would be a known geological control to include explicitly if present).

By following these static assembly rules, the generated image will reflect a plausible **snapshot in time** for a mixed-energy estuary. It will show the characteristic plan-view structure: a cuspate bay partially enclosed by sand barriers, an inlet throat with deltaic shoals, sinuous tidal channels feeding into mudflats, and marsh-fringed margins transitioning to a river at the head. The facies pattern – coarse sand at the energetic outer edges (barrier and tidal deltas), mud in the tranquil center, mixed sand-mud in channels and flats, and organic-rich fines in marshes – should be arranged as seen in real analogs.

5. Key Formulas and Quantitative Relationships

In modeling a mixed-energy estuary, certain empirical and semi-empirical formulas can guide the scaling of features and the balance between processes. These formulas act as quantitative rules ensuring the model's outputs are within realistic ranges.

Tidal prism vs Inlet Cross-Section (O'Brien-Jarrett relationship): A well-known empirical relationship connects the **tidal prism (P)** – the volume of water that flows in and out of an inlet on a tidal cycle – to the **inlet's cross-sectional area (A)** at the throat. In stable inlets with minimal longshore sediment bypassing, this tends to follow a power-law:

$$A \approx C \cdot P^m,$$

where *m* is typically around 0.85–1.0 and *C* is a coefficient that depends on regional factors (units, grain sizes, etc). For example, Jarrett (1976) found for U.S. inlets that $m \approx 0.86$ and $C \approx 7.5 \times 10^{-4}$ when P is in cubic meters and A in square meters [23]. This means larger tidal prisms require disproportionately larger inlet areas. In practical terms, the model can use this relationship to size the inlet channel width/depth. If one computes the prism (approximately estuary area times tidal range, adjusted for tidal efficiency), plugging it into the formula gives an equilibrium cross-sectional area for the inlet. The model should adjust the inlet geometry to match this target area (otherwise the inlet would either scour or shoal in reality). For instance, if our estuary has a prism of $5 \times 10^7\, m^3$ (moderate size), and using Jarrett's relation, we'd get $A \approx 7.5 \times 10^{-4} \times (5 \times 10^7)^{0.86} \approx 4000\, m^2$ (just an illustrative number). That cross-section might be achieved by, say, a 300 m wide and 15 m deep inlet channel. We can encode this by solving for width given an assumed depth (or vice versa). **Note:** If multiple inlets exist, the prism would be divided among them, and each inlet's area would be smaller accordingly.

Wave vs Tide dominance index: While there's no single universally adopted formula for wave vs tide dominance, several metrics exist to quantify their relative influence. One simple index is based on the **relative tidal range (RTR)** as per Hayes (1975): microtidal coasts (RTR < 2 m) tend toward wave-dominated morphologies, macrotidal coasts (RTR > 4 m) tend toward tide-dominated, and mesotidal (2–4 m) are mixed [11]. The model could incorporate this by varying barrier continuity and tidal flat extent as a function of tidal range. Another approach is to compare **wave power vs tidal power**. For example, one could define:

$$I_{wt} = \frac{P_{wave}}{P_{tide}},$$

where P_{wave} might be a proxy like $H_s^2 T$ (significant wave height squared times period, related to wave energy flux) and P_{tide} could be proportional to $(gH_t)^2$ or tidal current speeds (with H_t the tidal range, g gravity). While a precise formula might be complex, qualitatively if $I_{wt} > 1$, waves dominate (favoring features like long continuous barriers, smaller tidal inlets), and if $I_{wt} < 1$, tides dominate (favoring large inlet, sand shoals extending into estuary, multiple channels). The model can use such an index to blend between end-member templates. For instance, **number of tidal inlets** could be tied to tidal range: on a mesotidal coast (say 3 m range), you might allow 1–2 inlets for a given estuary size, whereas on a microtidal (say 1 m range) likely only 1 inlet (or even seasonally closed in small systems) [11] . Also, the **ratio of ebb-tidal delta size to barrier island length** can serve as a diagnostic: more tide-dominated estuaries have larger ebb deltas relative to barrier size, since more sand is moved seaward by tides. Empirical relationships exist relating ebb delta volume to tidal prism and wave energy – e.g. a high-level rule: Ebb delta volume increases with P and decreases with increasing littoral drift rate (Q_l). A formula by Walton and Adams (1989) relates delta volume to prism, but that might be too detailed; instead, the model can simply ensure that when tide influence is high, it creates a prominent ebb delta shoal (some fraction of the tidal prism's sand, perhaps 10–20%, is stored in delta).

Sediment settling and accumulation: For fine sediment (mud) deposition on tidal flats and marshes, **settling velocity and tidal period** give a useful timescale. The classic **Stokes' law** for particle settling can estimate how much mud settles out during a slack tide. For instance, a silt particle (~0.01 mm) might have settling velocity on the order of 0.1 mm/s; over a slack tide of say 1 hour, it could settle ~0.36 m if not resuspended. If the water depth over a flat at high tide is, say, 1 m, a large fraction of suspended mud can settle each tide. The model can use this concept: regions of low shear (like the far end of tidal flats) will accumulate mud each tidal cycle, whereas near channels (higher shear) much of the mud gets resuspended on ebb. This underlies the phenomenon of **tidal asymmetry and net landward transport of mud** [24] . One can express a criterion: if flood duration > ebb duration (common in shallow lagoons), then there is a net landward residual transport of suspended sediment. A formula for tidal asymmetry index could be $A_t = \frac{T_f - T_e}{T_f + T_e}$, where T_f, T_e are flood and ebb durations. A positive A_t (flood longer) often yields mud import. The model might not explicitly compute this, but it should enforce the result: **finer sediment is found landward and on the high flats** due to these asymmetries [22] . For example, the rule might be: "Place the finest grain size (clay/silt) at the landward extreme of the flat, adjacent to the marsh, since only the very fine particles make it that far before depositing" [22] .

Facies transition criteria: We can formalize some facies transitions with simple thresholds. For instance, the **sand-mud transition** along the estuary can be linked to the tidal energy gradient. A formula could use the **critical shear stress for deposition** of mud vs sand. If $\tau_c^{mud} \approx 0.1\,Pa$ (for fine silts) and $\tau_c^{sand} \approx 0.5\,Pa$ (for fine sand), then at locations where the peak bed shear stress (due to currents or waves) is below 0.1 Pa, mud will accumulate; if between 0.1 and 0.5 Pa, only mud will stick but sand might move (so you get mixed flat with lag sand); above 0.5 Pa, even sand won't settle (so only coarse lag or no deposition). The model could approximate shear stress from flow speed via $\tau \sim \rho C_f u^2$. Without getting too granular, one can say: main tidal channels (u ~ 1 m/s) have $\tau > 1 Pa$, so they'll be scoured to sand or gravel; tidal flats (u ~ 0.1–0.2 m/s in shallow flows) have $\tau\ 0.01–0.04 Pa$, allowing mud deposition. Thus, a **rule of thumb**: if depth-averaged flow speed < 0.2 m/s for significant periods, classify the bottom sediment as mud; if > 0.5 m/s regularly, keep it sandy. We can implement this by evaluating the distance from channel or the local water depth (as a proxy for flow speed). In practice, we already distributed facies qualitatively in section 4, but here we justify it with a physical threshold.

Sea-level rise rate vs sedimentation (marsh sustainability): Modern studies of marshes give formulae for vertical accretion needed to keep pace with sea-level rise. A simplified linear formula: $S_{acc} = SLR - C$, where SLR is the rate of sea-level rise (mm/yr) and C is compaction; if S_{acc} (sediment + organic accumulation rate) equals SLR, the marsh stays at equilibrium elevation. If the model wants to check marsh viability, it could use something like: **if SLR is 5 mm/yr and the available sediment supply yields only 2 mm/yr accumulation, the marsh will start to submerge** (which might prompt converting some inner marsh to tidal flat in the scenario). However, for the purpose of one snapshot, this might be beyond scope – instead, ensure that the elevations of marsh vs flat are consistent with a plausible tidal frame (e.g. marsh platform ~ mean high water spring, flats around mean tide level).

Channel hydraulic geometry: Similar to rivers, tidal channels have hydraulic geometry relationships. For example, average **channel depth (d)** might relate to tidal prism or discharge as well. A crude formula: $Q_{max} = Au$, where Q_{max} is max discharge (which is prism per half-tide), A is cross-sectional area, u ~ peak velocity (~1 m/s). So $A \approx P/(T/2 * u)$. We already used a form of that in the prism-area law. Additionally, **channel width to depth ratio** often is 20:1 to 40:1 in tidal channels (wider than river channels for equivalent flow, due to tidal flows being sheet-like). The model might set an initial channel depth and compute width from area, or vice versa. For instance, if we assume our main channel depth ~ one tenth the tidal range plus some scour (say ~5 m for a small estuary, ~15 m for a larger one), and we have A from above, we solve for width. Ensuring that width fits within the barrier opening is a consistency check – if not, one must adjust (maybe allow multiple smaller inlets if one big one is not feasible geometrically).

Indices of maturity (time evolution link): There are also dimensionless parameters to gauge how far along infilling an estuary is. One could define a **fill ratio** = (sediment volume in estuary accommodation) / (initial accommodation volume). In a snapshot, you might not explicitly compute this, but qualitatively: a high fill ratio means extensive marsh and flats (we see that in the facies). Another index: **relative tidal flat area** = (area of intertidal flats) / (total estuary area). Tide-dominated estuaries tend to have this ratio high (lots of flat), wave-dominated lower (more open water lagoon). Mixed should be intermediate. If our model produces an intertidal area fraction of, say, 50%, that suggests a strongly tide-influenced system (like the Bay of Arcachon example has ~2/3 of its area as tidal flat at low tide [25]). We can steer the generation by specifying target ranges for such indices based on energy regime.

Finally, when outputting quantitative annotations or making measurements on the generated analog image, these formulas help ensure consistency. For example, a user could measure the inlet width on the synthetic image and plug into O'Brien's law to see if the implied prism matches the estuary's area – our goal is that it does (within reason). Similarly, measuring the percent mud vs sand area and comparing to known modern estuaries can validate that the analog falls in the mixed-energy spectrum rather than looking like an end-member.

6. Visual Examples and Spatial Guidance for Model Calibration

Example satellite view of a mixed-energy estuary (Arcachon Bay, France). A barrier spit (Cap Ferret, left) with a narrow inlet encloses the lagoon (Bassin d'Arcachon, upper right). Note the large ebb-tidal delta shoals at the mouth (green sand banks in the ocean) formed by strong tidal currents, and extensive intertidal mudflats (brownish areas) with branching tidal channels inside the bay. Salt marshes fringe the inner bay around the Île aux Oiseaux (center). This real-world example illustrates the planform elements and facies distribution that the procedural rules aim to reproduce. [26] [27]

Real estuaries provide blueprints for our modeling framework. **Arcachon Bay** (shown above) is an excellent analog for a mixed wave-tide estuary: it demonstrates how a barrier and tidal inlet coexist with broad tidal flats and marshes. In Arcachon, the tidal range is about 3.5 m (mesotidal), and one can see the imprint of that in the huge extent of exposed flats at low tide (the purple-brown areas in the image are mudflats) [26] . The barrier spit (Cap Ferret) is shaped by wave action (note its smooth shoreline facing the ocean) but has a gaping tidal inlet kept open by tidal flow. Immediately outside the inlet, the **ebb delta** appears as a complex of sand bars (in shades of green in shallow water), indicating active sand transport by tidal currents ebbing out. Inside, just behind the inlet, lighter-toned sand accumulations mark the **flood tidal delta** and sand flats. Further inside, away from the inlet, the flats turn darker – those are muddier areas colonized partly by seagrass or algae, and higher up, by salt marsh vegetation. One can identify sinuous **tidal channels** snaking through the flats, linking to deeper parts of the lagoon. Arcachon Bay even has a tidal island (Île aux Oiseaux) surrounded by marsh and tidal flats, a product of intertidal sedimentation. This kind of feature can be replicated in the model by allowing high deposition spots in the central basin to vegetate and stabilize. The **lessons for modeling**: the image shows that in a mixed system, you get a patchwork of habitats – sand where the energy is high (near inlet, channels, outer coast), mud where energy is low (inner bay, high tidal flats), and a clear demarcation of channels and flats. Also, note how *the main inlet channel hugs the southern barrier (near the dune du Pilat) in the image*, which is a common pattern under dominant ebb currents and Coriolis deflection. The model's channel layout rules can mimic that by favoring one side of the inlet for the deepest channel. Using such imagery as a reference, one can calibrate model parameters like "tidal flat extent" or "marsh coverage" to fall in realistic ranges.

Another example to consider is **Willapa Bay, Washington (USA)**, a mixed-energy lagoon on a mesotidal coast with strong wave influence. Willapa is enclosed by a long barrier spit (Leadbetter Point) with a single inlet, and has expansive tidal flats and marshes. Historical maps and images of Willapa show how the inlet has migrated and how the ebb-tidal delta has large shifting sandbanks – providing inspiration for the model's time-evolution and morphology rules. Many smaller estuaries, such as the **Dyfi Estuary in Wales** or **Arcade estuary** (hypothetical), exhibit intermediate morphologies: a bit of a spit, a modest ebb delta, and a combination of narrow channels and broad mudflats. Comparing those, one sees that **oblique wave angle** causes spits (Dyfi has one extending across its mouth), while more head-on wave climates produce barrier islands (like in some parts of the Wadden Sea). Including a randomness or parameterization for wave angle in the model will allow generation of both scenarios – e.g. a user could dial a "littoral drift angle" parameter to swing the inlet to a side.

For **stratigraphic guidance**, we can look at facies models from literature (Dalrymple et al. 1992's diagrams, for instance). Although we cannot embed that figure here, it typically shows a cross-section with barrier sands (possibly showing seaward dipping beachface and tidal inlet fill cross-beds), central basin muds (often bioturbated), fluvial delta sands (with fining upward). In plan view, the corresponding facies tracts are arranged in belts. The model, when assigning facies, could output a similar facies map. If needed, the rules could be extended to 3D (thickness of facies), but at minimum, our 2D (planform) analog should reflect these belts. We could also use **Google Earth or satellite images** of places like the **Nile Delta's estuarine lagoons** or **Bramble Bay in Australia** – these often show the blending of wave-formed features and tidal channels.

One more visualization that can guide the spatial structure is the **concept of tidal channel networks on mudflats** – often analyzed in geomorphology. They resemble fractal, tree-like patterns. A procedural rule might generate them via an erosion or drainage algorithm on the intertidal surface. Visual references from nature (like aerial photos of the tidal creeks in the Bay of Fundy mudflats or the Humber Estuary, UK) show how these networks branch and maintain a certain density. By mimicking those, the analog image gains realism. For example, a typical spacing between tidal creeks is related to the tidal prism and marsh platform width – often creeks are spaced a few hundred meters apart on mature marshes. The model could implement a simple spacing rule for creek initiation.

In summary, visual references underscore that **mixed-energy estuaries are multicolored, patchy environments**: you'll see the blue of open water channels, the tan of sandy shoals, the brown of mudflats, the vibrant green of marshes, and the white of breaking waves on the barrier. Ensuring the generated imagery has this diversity in the right proportions is key. By studying real examples, we calibrate our expectations: e.g., roughly half the area might be exposed at low tide in a mesotidal estuary, barriers are perhaps a few kilometers long closing off bays tens of kilometers in size, channels typically meander with wavelengths on order of the bay width, etc. These numbers and patterns from reality will shape the random or algorithmic choices the model makes.

(For further guidance, the user can compare the generated outputs with published facies maps or satellite images of known estuaries, adjusting parameters until the analog "looks right" compared to these visual benchmarks.)

7. Pseudocode Framework for Generative Modeling

To implement the above rules in a generative model (for instance, a program that produces synthetic estuary maps), we outline a pseudocode workflow. This provides a structured approach to encode the multiscale features and ensure physical plausibility:

```
function generateMixedEnergyEstuary(inputs):
    # Input parameters might include: estuary_length, estuary_width,
tidal_range,
    # wave_height, wave_angle, river_discharge, sediment_supply, sea_level
(relative),
    # and perhaps random seeds for stochastic variation.

    # 1. Initialize global properties
    tidal_prism = estimateTidalPrism(estuary_area, tidal_range)
    # e.g., estuary_area * tidal_range * tidal_efficiency (simple approximation)
    wave_tide_index = wave_height / (tidal_range + 1e-6)  # a basic wave vs tide
metric
    estuary_shape = defineEstuaryPlanform(estuary_length, estuary_width,
coastal_plain_profile)

    # 2. Barrier-Spit and Inlet configuration
    num_inlets = 1
    if tidal_range > 2.0 and wave_tide_index < 1.0:
        num_inlets = min( int(tidal_prism / some_threshold_volume), 3 )
        # more inlets for larger prisms in mesotidal setting, capped at say 3
for simplicity
    barrier = drawBarrierIslandOrSpit(estuary_shape, wave_angle, num_inlets)
    inlet_positions = placeInletOpenings(barrier, num_inlets, wave_angle)
    for each inlet in inlet_positions:
        # width from tidal prism share using O'Brien relationship
        prism_share = tidal_prism / num_inlets
        inlet_area = 7.5e-4 * (prism_share ** 0.86)    # Jarrett's law [23]
        inlet_depth = estimateInletDepth(tidal_range, offshore_depth)  # maybe
~1.5 * tidal_range
        inlet_width = inlet_area / inlet_depth
        carveInletChannel(barrier, inlet, inlet_width, inlet_depth)
        createEbbTidalDelta(inlet, prism_share, wave_tide_index)
        createFloodTidalDelta(inlet, prism_share)

    # 3. Main channel and tidal creek network
    main_channel_path = traceThalweg(estuary_shape, inlet_positions,
river_entry)
    setChannelWidthDepth(main_channel_path, depth_at_mouth=inlet_depth,
depth_at_head=river_depth)
    # Decrease channel width moving landward proportionally to prism decrease
```

```
    for each segment along main_channel_path:
        local_prism = computeLocalPrism(segment)  # e.g. area of estuary
landward of that segment * tidal_range
        target_area = 7.5e-4 * (local_prism ** 0.86)
        segment_depth = interpolateDepth(segment.distance, inlet_depth,
river_depth)
        segment_width = target_area / segment_depth
        adjustChannelCrossSection(segment, segment_width, segment_depth)

    # Branching secondary channels (if any)
    maybe_branch = evaluateNeedForBranching(tidal_prism, estuary_width)
    if maybe_branch:
        addSecondaryChannel(main_channel_path, branch_point,
mouth_at_inlet_or_new)
        # possibly connect to a second inlet or merge back downstream

    # 4. Elevation and facies grid initialization
    grid = createGrid(estuary_shape, resolution)
    base_elevation = -estuary_depth_base  # set deepest part
    # define bathymetry roughly: sloping up from inlet (deep) to head (shallow)
    for cell in grid:
        distance_from_mouth = computeDistanceToMouth(cell)
        # linear elevation rise as first guess (to later adjust for channels/
flats)
        cell.elev = -inlet_depth + (distance_from_mouth / estuary_length) *
(river_depth + inlet_depth)

    # Carve main channel into grid
    for each cell along main_channel_path:
        cell.elev = -channel_depth_at_that_point  # carve channel to designed
depth
        markAsChannelFacies(cell)

    # Carve secondary channels similarly
    for each secondary_channel:
        lowerCellsAlongPath(secondary_channel, designed_depth, width)

    # 5. Allocate intertidal flats vs subtidal vs supratidal
    for each cell in grid:
        if cell not in channel:
            if cell.elev < -0.1:  # below mean low water (deep subtidal)
                cell.facies = "subtidal bay mud/sand"
            elif cell.elev < tidal_range * -0.5:
                cell.facies = "subtidal shallow"
            elif cell.elev < 0:  # between MLW (approx 0) and say -something:
intertidal
                cell.facies = "intertidal_flat"
            elif cell.elev < marsh_elev:  # 0 to MHW
```

```
                cell.facies = "intertidal_flat_high"
            else:
                cell.facies = "supratidal"

    # refine grain size by energy
    for each cell marked intertidal_flat:
        dist_to_channel = distanceToNearestChannel(cell)
        if dist_to_channel < X (e.g. within channel margin zone) or
local_flow_speed(cell) > 0.3 m/s:
            cell.sediment = "sand/silt mix"
        else:
            cell.sediment = "silt/clay"
    for each subtidal cell:
        if depth(cell) < some shallow threshold and near inlet:
            cell.sediment = "sand"
        else:
            cell.sediment = "mud"  # deeper basin
    # (This approximates coarse near inlet/channels, fine in quiet water)

    # 6. Place marshes on high flats
    marsh_mask = identifyShelteredHighFlats(grid, slope_threshold,
wave_tide_index)
    for each cell in marsh_mask:
        cell.facies = "salt_marsh"
        cell.sediment = "peaty mud"
        # add tidal creek channels through marsh if needed
    carveTidalCreeksThroughMarsh(marsh_mask, main_channel_path)

    # 7. Final touches: barrier island and beach
    for each cell on barrier/spit:
        cell.facies = "barrier_beach_dune"
        cell.sediment = "sand"
        # optionally add overwash fan on interior side of barrier if low
elevation

    # 8. Output the facies map and morphology
    return gridFaciesMap(grid), vectorFeatures(channels, barrier, deltas)
end function
```

The pseudocode above encapsulates many of the rules discussed:

- It starts by computing the tidal prism and an initial guess at how wave vs tide dominated the scenario is. This influences how many inlets and what kind of barrier to draw.
- It uses the **O'Brien-Jarrett law** to size the inlet cross-sectional area [23], then distributes that between width and depth.
- It traces a main channel and scales its cross-section along the estuary length (effectively following the idea that cross-sectional area decreases landward as local prism decreases).

- It then builds a grid (or some spatial data structure) of elevations and facies. Elevation is roughly set to create subtidal vs intertidal zones.
- The code marks channel cells distinctly (ensuring continuity of deep channel).
- It classifies areas into subtidal, intertidal flat, or supratidal by elevation relative to tidal range.
- Then grain size (sand vs mud) is assigned based on proximity to channels (representing higher energy) and depth (outer vs inner estuary), aligning with the idea that coarse sediments are near channels/mouth and fines in sheltered areas [21].
- High intertidal areas in sheltered zones become salt marsh, and a network of tidal creeks is cut into them to connect to main channels (reflecting how marshes drain to main channels).
- The barrier island cells are set as beach/dune sand facies, and we could add washover or tidal inlet scour based on earlier steps.
- Finally, the function would output a map of facies and morphologic features which could be visualized.

One can iterate with different input parameters to create a variety of estuaries: e.g., increase wave_height to see the barrier spit get longer (inlet pushed to a side), increase tidal_range to see multiple inlets and wider channels, increase sediment_supply to see more marsh and infilling. The pseudocode is of course a high-level guide – in practice, each function (like `createEbbTidalDelta` or `identifyShelteredHighFlats`) would have its own internal logic, possibly using randomness to avoid too regular patterns.

By encoding these rules and relationships, the generative model can produce estuarine analog images that are **multiscale (barriers kilometers long, channels hundreds of meters wide, creeks tens of meters) and physically consistent** with known process-form constraints. The result will be a synthetic yet realistic mixed-energy estuary, suitable for use in testing geologic scenarios or as training data for machine learning in geoscience, all while being grounded in actual coastal dynamics and geomorphology.

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