Physical Rules for Generating Fluvial, Aeolian, and Estuarine Environments

To realistically **generate geologic depositional environments** in a model, one must incorporate the **physical processes** and controls that shape each environment. The rules should be **hierarchical across multiple scales**, reflecting both large-scale architecture and fine-scale structures. They should also allow for either **time-evolving simulations or static outcomes**, depending on whether you want to simulate dynamic formation processes or generate a final depositional pattern directly. In what follows, we outline the key physical rules for **fluvial**, **aeolian**, and **estuarine** environments, then discuss modeling considerations like explicit vs. implicit driving variables and optional variability modifiers.

Fluvial Depositional Environments (Rivers)

Aerial view of a meandering river showing point bars (deposition on inner bends) and cut banks (erosion on outer bends). Such fluvial systems illustrate the lateral migration of channels over time.

Fluvial environments are dominated by **flowing water** (rivers and streams) that erodes, transports, and deposits sediment. The **channel pattern** can vary from **meandering (single-channel)** rivers to **braided (multi-channel)** rivers, controlled by slope, sediment supply, and bank stability [1]. In meandering rivers, water flow velocity is highest on the **outer bend**, scouring the bank (erosion at the *cut bank*), while slower flow on the **inner bend** causes sediment accumulation in *point bars* [2]. This results in lateral migration of the meander bends and formation of oxbow lakes when loops get cut off [3]. Braided rivers, by contrast, form where slope and sediment load are high, causing multiple shifting channels with mid-channel bars of sand/gravel [4]. These bars can emerge as braided islands, and they tend to be less stable, reworking frequently with floods.

Hierarchical multi-scale structure: Fluvial deposits exhibit features at various scales. At the **basin scale**, rivers form an overall drainage network and valley system. At the **channel belt scale**, a single river may carve a sinuous path and over time create a **channel belt** (the area of channel migration) with stacked point bar deposits. Zooming in further, within each point bar there are **cross-bedded sand bodies** from lateral accretion and ripple marks from shallow flows [5]. This hierarchy means any generative model should first lay out the large-scale channel geometry, then superimpose smaller-scale sedimentary structures (like bar deposits, levees, and bedforms). Empirically, fluvial planforms often show **fractal patterns** or self-similarity across scales, so a rule-based model might use iterative or fractal algorithms to mimic how small meander bends add up to a sinuous river course.

Time-evolution vs. static outcome: A realistic simulation of fluvial deposition would **evolve over time** – for example, iteratively moving a channel via cut-bank erosion and point-bar deposition. Time-evolving rules could include: water flow erodes outer banks and deposits inner banks each time step, channels avulse (jump to a new course) when gradients or sediment plugs force a change, and periodic floods deposit overbank sediments. Over time this produces a stratigraphic record of fining-upward point bar successions and interbedded floodplain muds [5]. However, one can also generate a **static snapshot** of a fluvial environment by procedurally drawing sinuous channel patterns and positioning deposits without simulating the full history. In a static approach, rules might place point-bar sand bodies on inner curves and levee ridges along channel banks, to mimic the end result of repeated floods.

Key physical processes and controls in fluvial systems:

- **Flow velocity distribution:** Because faster currents carry more and coarser sediment, the model should route high velocities to outer bends (causing erosion) and low velocities to inner bends (causing deposition) [2]. This reproduces the point bar/cut bank dynamic that creates meanders. Flow velocity also depends on channel slope and depth – steeper slopes or higher discharge yield more erosive power.
- **Sediment load and grain size:** The amount and size of sediment delivered by the river influences channel form. High bedload (abundant sand/gravel) and variable flow tend to produce braided channels with deposition of sands and gravels around bars [6] [4]. Lower sediment load or more cohesive banks (often due to fine sediment or vegetation) favor a single meandering channel. The rules could explicitly include a **sediment budget** and grain size distribution: e.g. coarse material drops out in-channel, while fines travel farther to floodplains.
- **Floodplain deposition and levees:** During floods, water spills over the banks and loses energy, depositing thin layers of sand and silt near the channel (forming natural levees) and clay farther out [7]. A physical rule can reflect this by creating levee deposits paralleling the channel comprised of sand grading outward to mud. Over successive floods these build up slightly raised banks. Beyond, flat floodplain areas accumulate fine sediment and organic material, which a model could add as an extensive mud blanket with possible crevasse-splay sand patches (from levee breaches during big floods).
- **Channel migration and avulsion:** Over time, meandering channels gradually **migrate** laterally and downstream due to the cut-and-fill processes [3]. The model can implement a slow lateral shift of the channel centerline, leaving behind a point bar depositional pattern (often concentric scroll bars visible in satellite images) and eventually cutting off loops. Meanwhile, **avulsion** events (when the river abruptly takes a new course, often during a flood) reset the location of the active channel and leave abandoned channel fills. Including occasional avulsion rules introduces realistic reorganization, producing the characteristic patchwork of old channel scars in fluvial plains.
- **Hierarchy of features:** As noted, fluvial environments require rules at **multiple scales**. For example, you might first generate a broad **valley gradient** (macro-scale control), then a sinuous thalweg path for the river (meso-scale), and then details like **bars, oxbow lakes, levees, and crevasse splays** (micro-scale features). This hierarchy ensures consistency – e.g. the orientation of point bar cross-bedding aligns with the local channel curvature, and the overall channel follows the regional slope. By capturing this nested structure, the model can reproduce realistic variograms and spatial statistics (e.g. channels and bars impart certain correlation lengths and fractal dimensions to the sedimentary pattern).

Aeolian Depositional Environments (Desert Dunes)

Aerial view of an extensive sand dune field (Great Kobuk Sand Dunes, Alaska). Aeolian environments feature dune complexes shaped by wind, with distinct crestlines, slip faces, and interdune areas.

Aeolian environments are governed by **wind flow** transporting and depositing sediment (typically sand-sized or finer). The primary agents are **air currents** which, like water, can move sediment by **traction**

(rolling), saltation (hopping grains), and suspension in the atmosphere [8]. Because air is less dense than water, it preferentially transports fine particles (sand, silt) and tends to winnow out the very fine dust from the sand. The physical rules for aeolian deposition revolve around how wind interacts with the surface to form dunes and related bedforms.

Hierarchical multi-scale structure: Desert depositional systems are highly **multiscale**, from small **ripples** only a few millimeters high to enormous **dune ridges** hundreds of meters tall, and even larger mega-dunes called *draas* several kilometers long [9]. A modeling approach should reflect this hierarchy: for instance, on a flat sand sheet, wind generates centimeter-scale ripples, which coalesce into meter-scale dunes, which themselves may align into kilometer-scale dune fields. The model might start by generating large dune positions/shapes (perhaps as broad sinusoidal ridges), then superimpose smaller scale undulations or crest defects to mimic secondary dunes and ripples. **Internal structures** like cross-bedding are also part of the hierarchy: each migrating dune forms angled cross-strata as sand avalanches down its slip face, which are preserved in the deposit.

Time-evolution vs. static outcome: Aeolian landforms are inherently dynamic – dunes **migrate** downwind as sand is eroded from the upwind side (stoss) and deposited on the downwind side (slip face). A time-evolving simulation could iterate: pick up sand grains from windward slopes (especially if wind speed exceeds a threshold), carry them a short distance (saltation), and drop them in the lee of the dune or wherever wind velocity falls. This would gradually build a dune that moves and changes shape. Over time, dunes can merge or split, and wind direction shifts can rework dune patterns. A **static approach**, on the other hand, might generate a snapshot of a dune field by algorithmically shaping Gaussian mounds or ridges with certain height and spacing distributions, then carving a slip face on each with the characteristic lee-side slope (~30-34°, the angle of repose for sand). The static rules would ensure dunes are **oriented** relative to prevailing wind (e.g. transverse dunes perpendicular to wind, or barchan dunes with horns pointing downwind) and possibly include a mixture of dune types if wind directions are variable.

Key physical processes and controls in aeolian systems:

- **Wind transport mechanics:** The model should incorporate how wind moves sediment. Fine sand is typically moved by **saltation** – grains bouncing in jumps – which is the dominant mechanism building dunes [10] [11]. Very fine particles (silt, clay) go into **suspension** and can travel far (creating loess deposits elsewhere), whereas larger grains only **creep** short distances when nudged by impacts [12] [13]. A threshold wind velocity must be exceeded to start motion (the *fluid threshold*), and once grains are moving, a slightly lower speed can sustain transport (due to aerodynamic feedback) [14]. In generation, one could set a wind speed and compute how much sand shifts per time step, or simply use a rule that areas exposed to open wind undergo sediment removal and downwind accumulation.
- **Dune formation and morphology: Dunes** form where transported sand is eventually **deposited**, often when wind slows down (e.g. behind an obstacle or where vegetation anchors sand). Key controls on dune shape include **sand supply**, **wind intensity**, and **wind directional variability** [15]. For example, a unidirectional wind with limited sand produces *barchan dunes* (crescent-shaped with horns), abundant sand with one wind forms *transverse dunes* (long ridges), whereas multiple wind directions yield complex shapes like *star dunes*. The rules can encode this by varying dune orientation and branching: e.g. in a model, if wind directions switch seasonally, the dune grows multiple arms. **Availability of sand** could be an explicit parameter: high supply results in larger,

more continuous dunes versus low supply leading to isolated dunes or nebkhas (dunes around shrubs).

- **Slip face and cross-bedding:** A fundamental physical effect is the development of a **slip face** on the lee side of a dune at the angle of repose (~30°). Sand accumulates until that slope is reached, then avalanches down, producing a steep face. In the subsurface, this creates **cross-bedded layers** inclined in the downwind direction [16]. A realistic generative model might enforce that each dune has an asymmetric profile (gentle windward slope, steep lee slope) and internally, one could include stylized cross-stratification (for instance, by drawing lines or using a texture indicating inclined layers). While the fine details of cross-strata might not appear in a large-scale image, acknowledging them in rules (like preserving directionality of lee deposits) ensures consistency with physical processes.
- **Interdune areas:** Not all areas in a dune field are active dunes. **Interdunes** are the spaces between dunes, which can be flat sand sheets or sometimes wet or vegetated patches that trap sediment. Physically, if an interdune area is wet (e.g. a dry lake bed that occasionally has water), it might accumulate mud or evaporite minerals and prevent dunes from migrating into it [17] [18]. A comprehensive model could allow optional **interdune modifiers**: for example, specify if an interdune is dry (then wind can blow sand across, maybe with smaller ripples) or wet (then a hard surface that halts dune movement and collects finer sediment). Interdune flat areas often have **low-angle stratification** or lag deposits of coarse grains that the wind can't move [19]. Representing this, one might flatten the elevation between dunes and sprinkle some coarse material or shell if near coasts. These details add realism, but could be toggled off for simplicity if not needed.
- **Vegetation and moisture effects:** Even sparse **vegetation** or surface moisture dramatically affects aeolian deposition by stabilizing sand. In modeling terms, one could include a parameter for vegetation cover or ground moisture; if above a threshold, dunes will not form because the sand is anchored [20]. Instead, wind may only form small coppice dunes around bushes or no movement at all. This is an example of an **optional variability** one might include: e.g. a toggle for "vegetated dunes" which, when on, generates smaller, discontinuous dunes with fixed positions (like coastal dunes with grass), versus a bare sand scenario with freely migrating dunes.

Estuarine Depositional Environments (River-to-Marine Transition)

Aerial view of a tide-dominated estuary (Westerhever tidal flats, North Sea coast of Germany) at low tide. Notice the branching tidal channels and broad sand/mud flats exposed – hallmark features of an estuarine environment shaped by both river and tidal processes.

Estuaries are complex environments at the **transition between rivers and the ocean**, influenced by a mix of fluvial processes, tides, and waves. Physically, an estuary is typically a **funnel-shaped inlet** where fresh water from rivers mixes with seawater. Sediment in estuaries comes from both the land (river-borne sediment) and the ocean (marine sand from tidal currents or wave action). The balance of **river flow vs. tidal currents vs. wave energy** determines the characteristic deposits and morphology of a given estuary [21] [22]. We can distinguish two endmembers: - **Wave-dominated estuaries** have strong wave action at the coast but relatively smaller tides. - **Tide-dominated estuaries** have large tidal ranges/currents that outweigh wave effects.

Hierarchical multi-scale structure: Estuarine systems also exhibit multiple scales of organization. At the largest scale, an estuary sits in a **coastal embayment or drowned river valley** defined by past sea-level rise. Within that, there may be a **bay-head delta** (where the river feeds in), broad **central basin** (often a quieter water body that can accumulate mud), and a **barrier or inlet** at the mouth if wave action forms a sand bar or spit. Within the tidal channels, smaller-scale features include **point bars and tidal sand bars**, analogous to river bars but formed by reversing tidal currents, and extensive **tidal flats** that are alternately submerged and exposed. On the micro-scale, estuarine sediments show distinctive structures like **tidal rhythmites** (thin alternating layers of sand and mud from each tidal cycle), **flaser or lenticular bedding** (wavy beds where mud and sand intermix due to fluctuating energy), and bioturbation from abundant organisms in brackish water [23]. A generative model should try to capture these scales – for example, outline the overall estuary shape and zones (mouth, mid-estuary, river end), then embed the channel patterns and bar forms, and even texture the surfaces with periodic bedforms or mud drapes to suggest tidal action.

Time-evolution vs. static outcome: Estuarine environments are dynamic on multiple time scales. Over **daily cycles**, tides ebb and flood, moving sediment back and forth. Over **seasonal or annual scales**, river floods may bring pulses of sediment that prograde small deltas into the estuary, or storms might breach barrier spits. Over **long-term (geological) scales**, sea level changes can drown or expose portions of the estuary. A time-evolving simulation of an estuary could be quite complex, perhaps coupling a river sediment input at the head with an oscillating tidal flow at the mouth. At each time step, one would simulate sediment transport by the currents: during flood tide, marine sand is pushed in and deposits in slack zones; during ebb, riverine sediment might be carried seaward but some gets trapped. Such a simulation could naturally form **tidal channel networks** and deposit alternating sand/mud layers. However, a simpler static generation can still enforce the *end-state* patterns known from estuary models: for instance, place **coarser sand bodies near the mouth** (due to waves/tides winnowing fines) and **muddy deposits in inner reaches and flats** (where flow energy dissipates) [24]. One can explicitly carve tidal channels through a mudflat, and add a barrier island or spit at the mouth if wave-dominated [25]. Static rules might also include creating a gradient of salinity or energy: e.g. define a zone in the middle (the mixing zone) that gets a lot of fine sediment accumulation due to flocculation of clays in brackish water (this often corresponds to the **estuarine turbidity maximum** where suspended sediment concentrates) [26]. The outcome should be a plausible estuarine facies distribution without needing to simulate every tide.

Key physical processes and controls in estuarine systems:

- **Tidal currents and cyclic deposition:** Tides flowing in and out form **bidirectional currents** that can reverse twice a day. These currents create and maintain **tidal channels** that often meander through the estuary or across tidal flats. The **flood tide** (rising water) may be a bit stronger or shorter in duration than the ebb in some estuaries, leading to a net landward transport of sediment [27] [26]. A rule to include this is to bias deposition slightly landward in each cycle, so that over time sand migrates into the estuary (unless a strong river flushes it seaward during floods). Tidal currents deposit sand in low-relief bars and rework the sediment into small-scale ripple marks on the channel floors at low tide. Conversely, during **slack water** (high or low tide stands), fine silts and clays settle out of suspension onto mudflats. This alternating process produces **flaser bedding and laminae** – thin mud layers draped over rippled sand – which is a diagnostic physical effect of tidal deposition [28]. In a static model, one might texture parts of the tidal flat with a pattern representing these interbedded sand/mud streaks, or at least mention them in an annotation, to reflect that tidal variability.
- **Wave action and estuary mouth morphology:** In wave-dominated settings, **waves and longshore currents** push sand along the coast, which can form a **barrier spit or barrier island** partially closing off the estuary mouth [25]. Behind this barrier, a quiet **lagoon** or central basin can form, where mud

accumulates in low energy conditions. The model should account for this by potentially placing a sandy barrier feature at the seaward end (if wave-dominance is specified) and reducing wave energy inside. If the environment is *tide-dominated*, no continuous barrier will form; instead, the mouth is usually wide and funnel-shaped to let large tides in, and the energy is dissipated across broad tidal sand shoals at the entrance [29] [24]. Thus, a generation rule could branch: *if wave-dominated, add a narrow inlet with a beach/spit; if tide-dominated, create a wider mouth with sand bars and tidal delta deposits*. In both cases, coarser sediment (sand or shell) tends to concentrate at or near the mouth where energy is highest, whereas finer sediment travels farther into the estuary [24].

- **Freshwater input and stratification:** The **river discharge** entering an estuary brings not only sediment (often fine-grained if much was deposited upstream) but also fresh water that is less dense than seawater. The meeting of fresh and salt water causes **density stratification** and often a circulation that traps fine sediment. Specifically, as fresh water flows seaward on top and salt water pushes landward underneath (estuarine circulation), a zone of high turbidity can form where clays flocculate (stick together) and settle. Although modeling full hydrodynamics is complex, one can incorporate a rule that **fine sediment (clay, silt)** is mostly dropped in a certain central zone (say around the middle of the estuary length) to mimic this *turbidity maximum* effect [26]. This results in a wedge of muddy sediment in the inner estuary and can form muddy tidal flats or even wetlands (salt marshes) on the upper fringes where calm water allows deposition. In a physical sense, the presence of *brackish-water fauna* (oysters, mangroves, etc.) also influence sedimentation by stabilizing mud or trapping sediment. While biological factors may be beyond the scope of a simple generator, one could optionally sprinkle indicators like shell beds or organic-rich mud in low-energy zones to signify this ecological influence.
- **Sea-level changes:** Over geological time, **sea-level rise or fall** can shift estuarine deposition. A rising sea level (*transgression*) will cause the estuary to migrate landward, drowning existing river valleys (creating new accommodation space for sediment), whereas a falling sea level (*regression*) may turn the estuary into a delta or river plain. If you include a temporal element, you could simulate these changes by gradually expanding or contracting the estuary boundaries and adjusting sedimentation accordingly (transgression might cause more mud blanketing as energy decreases, while regression might concentrate channel sands progradationally). In a static model, you could allow an **optional modifier** for relative sea-level position: e.g. a higher sea level scenario yields a larger, flooded estuary with more marine influence (perhaps more tidal deposits), whereas a lower sea level might shrink the estuary, making it more river-dominated with channel sands extending to the ocean.

Modeling Considerations: Scale Hierarchy, Temporal Dynamics, and Variability

In designing the generator for these environments, a few overarching considerations emerge from the above physical rules:

- **Hierarchical, Multi-Scale Approach:** It is advisable to implement the generation in a **hierarchical manner**, capturing multiple scales of deposition. This means structuring the model to first generate **large-scale framework** (basin shape, overall slope, main channel or dune field layout, estuary outline), then progressively adding **meso-scale features** (individual channels, major dunes, tidal channels, bars), and finally **micro-scale details** (cross-beds, ripples, mud drapes, etc.). Hierarchical rules ensure consistency and reduce complexity by breaking the problem into scales. For example, one module could lay down a sinuous river path across a domain (macro-scale), another module could populate that path with point bar shapes and levee edges (meso-scale), and yet another could add textures or small-scale heterogeneity (micro-scale). This layered approach mirrors how nature builds depositional environments and will help produce realistic variograms and fractal properties. It also makes the model **modular** – users could turn off the micro-scale detail if they only need the broad architecture, for instance.

- **Time-Evolving vs. Static Generation:** Deciding whether to simulate the **time evolution** of processes or to generate a **static end-state** pattern is crucial. A time-evolving model is more physically rigorous – it will naturally create features like downstream fining or channel migration if the rules are correct – but it can be computationally intensive and harder to control. A static model is more direct: you specify the final outcome based on known characteristics (e.g. place an oxbow lake here, a dune there) without simulating how it got there. In practice, a hybrid approach can be effective: use time-stepping for critical processes (like letting a river carve its course for a number of iterations) and then "freeze" the result for output. Alternatively, offer both modes to the user. **If accuracy and process fidelity are priorities**, a time-evolution simulation (even a simplified one) will capture the *overprinting of events*, such as one channel erasing another or dunes climbing over older dunes. **If efficiency or simplicity is more important**, a static rule-based generator that still obeys physical constraints (e.g. ensuring deposition occurs on inner bends, or dunes align with wind) may suffice. In our designs above, we often described both: e.g. fluvial meander migration vs. drawing a sinuous channel in one go. Ideally, the tool could allow toggling a "dynamic mode" for a more animation-like buildup versus a "static mode" for immediate results.

- **Explicit vs. Implicit Driving Variables:** You asked whether making driving variables explicit or implicit makes more sense. The answer depends on user needs and model complexity:

- **Explicit driving variables** means the user (or model) directly sets parameters like *water discharge, flood frequency, wind speed, predominant wind directions, sediment supply rates, tidal range,* etc. Explicit variables offer **transparency and control**. A user can, for example, increase the river discharge and immediately see the model produce a wider channel or more braiding, or set a high wind variability and see star dunes appear. This can be very powerful for testing scenarios or matching specific real-world cases. It also helps in understanding the model ("the dunes look this way because wind speed was X and sand supply Y"). However, exposing many variables can overwhelm users and requires the model to translate each parameter into realistic outcomes (which might involve complex calibration).
- **Implicit variables** hide the detailed parameters and instead let the model internally decide values or use qualitative settings. For example, instead of the user specifying exact wind speed and sand supply, the model might offer a dropdown: "barchan dunes" vs "star dunes", and behind the scenes it picks appropriate wind parameters for that choice. Implicit approaches make the tool **easier to use** and ensure combinations of variables remain physically plausible (since the model builder pre-defines them). The downside is less flexibility – the user might not be able to create a fringe scenario outside the presets.

In a rigorous research or exploration context, **explicit variables are often preferred** because they allow probing the sensitivity of the environment to different controls (like seeing how fractal dimension changes if you tweak flow variability). Since your work involves analyzing variograms and fractal dimensions, being able to explicitly vary things like flow regime or sediment heterogeneity could be valuable. On the other hand, for a more automated or artist-friendly generator, implicit might be fine. **A good compromise** is to make the primary controls explicit (those that define the major character of the environment, e.g. overall energy level, sediment size, flow rate) while keeping more nuanced or derived parameters implicit. For instance, you could ask the user for “relative wave vs tide dominance” on a scale, rather than asking separately for wave height, wave period, tidal range, etc., and internally map that to an appropriate set of values. This keeps the interface manageable but still grounded in physical input.

- **Incorporating Variability as Optional Modifiers:** Natural systems have a lot of inherent **variability** – random fluctuations in flow, storms, changes in climate, etc. Incorporating some stochastic or random variability can make generated environments look more realistic and less “textbook perfect.” For example, real rivers are seldom perfectly periodic in their meanders; there are irregularities due to variable floods or bank collapses. Dune fields often have superimposed small dunes irregularly spaced, and not every tidal channel is evenly spaced either. **Optional modifiers** could allow the user to add this noise or variability on top of the base model. Some ideas:
- **Stochastic flood or storm events:** In a fluvial simulation, you could randomly have some larger floods that carve new channels or extend levees more than usual. In a static model, you might just randomize the curvature of the channel a bit or erode some banks more than others to avoid a perfectly smooth sine-wave river.
- **Heterogeneous sediment supply:** You could introduce variations in grain size or sediment volume over space and time. For instance, an upstream landslide might suddenly input a slug of coarse sediment, creating a local braided section in an otherwise meandering river. An optional rule could scatter a few gravel bars or extra sand patches to simulate such events.
- **Wind direction shifts:** For dunes, allow an option to simulate seasonal wind changes or multilateral winds. If toggled on, the model would create more complex dune shapes (or a mix of dune orientations, hints of older dune trends beneath newer ones, etc.). If off, dunes all line up neatly to one wind.
- **Sea-level oscillations:** In estuaries, an optional long-term sea-level rise/fall can be added as a modifier. Turn it on to get transgressive surface (e.g. a bayhead delta that backsteps and muddy peat layers in upper estuary) or regressive deltas prograding. Turn it off for a simpler static estuary at equilibrium.

The key is that these modifiers are *optional* – the base scenario should already be a credible environment under steady conditions, and the modifiers just add realistic imperfections or additional complexity. By keeping them optional, you allow a user to decide whether they want a **clean, controlled environment** (better for isolating factors like fractal dimension in analysis) or a **highly realistic, varied environment** (better for visual realism or stress-testing the analysis).

In conclusion, building physical rules for depositional environment generation requires balancing **geologic realism** with **modeling practicality**. A hierarchical, multi-scale rule set ensures that large framework features and fine details are consistent. Time-evolution can be used when process fidelity is needed, while static shortcuts can produce a plausible end state efficiently. Choosing which environmental controls to expose explicitly versus implicitly will affect usability and flexibility; generally, expose what is necessary for the intended use-case and keep the rest under the hood. Finally, nature is variable, so enabling controlled randomness or variability through optional modifiers can greatly enhance the authenticity of the generated analogs. By following these guidelines and the environment-specific rules outlined for fluvial, aeolian, and estuarine settings, you can capture *“all of the physical effects”* that govern the formation of these depositional environments – from river meander migration and dune dynamics to the interplay of tides, waves, and rivers – in a rigorous yet user-guided modeling framework.

Sources: The physical characteristics and processes described here are based on well-established sedimentological principles and environmental models. Key references include sedimentology textbooks and summaries [30] [5] [15], as well as research on specific environments (e.g. fluvial meandering [2] [3], aeolian dune formation [9], estuarine facies models [25] [23]). These sources document how factors like flow velocity, sediment load, wind regimes, and tidal versus wave energy shape the depositional features observed in nature. The rules outlined above translate those process understandings into a form suitable for generative modeling. The hierarchical and multi-scale approach is supported by observations that depositional patterns (like channel sand bodies or dune topography) exhibit organization over a range of scales [9]. By leveraging such insights, the model ensures that synthetic outputs honor the real-world physics and geometry of the environments in question.

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