Anastomosing River Depositional System: Procedural Generation Rules

Multiscale Hierarchical Structure of Anastomosing Systems

An anastomosing river system is a multichannel fluvial network characterized by several *hierarchical levels* of organization, from the valley scale down to the internal stratigraphy of deposits. At the **valley scale**, anastomosing rivers typically occupy a broad, flat alluvial plain or low-gradient valley floor [1] [2]. The valley bottom is often swampy or peat-filled and only slightly above the water table [3] [4]. Within this flat valley, the river is divided into **multiple active channel belts** that split and rejoin (anabranching), creating a dense network of channels enclosing floodbasins [5] [2]. Each channel belt consists of a *main channel* (and sometimes secondary channels) flanked by its own **natural levees** and adjacent overbank areas. The *channels* themselves are relatively narrow and deep (low width-to-depth ratio) with cohesive, stable banks [6]. They can be straight or mildly sinuous, often lacking large meander bends due to limited lateral migration [7] [6]. The channels flow around semi-permanent **alluvial islands** – areas of higher ground often formed by the levees of adjacent channels – which are typically vegetated and rarely overtopped except in extreme floods [8] [1]. These islands and levee-bounded ridges impart a slightly "saucer-like" topography to the floodplain, as noted in the Amazon Basin where levee-bounded islands are shallowly domed [8].

Surrounding and between the channel belts are the extensive **floodplain or floodbasin** areas, which are usually mud-dominated and frequently waterlogged. Wetlands, oxbow lakes, and backswamps occupy a large fraction of the area – in fact, **wetland floodplain environments often cover 60–90%** of an anastomosing system, whereas channels, levees, and crevasse splays cover only a minor portion [9] [10]. The floodplain lies lower than the levee tops, forming broad depressions that serve as sediment sinks for fine-grained overbank deposits. During floods, water and suspended sediment spill out of channels and inundate these basins, depositing thin layers of silt and clay and building up the floodplain surface over time. Because of poor drainage and frequent saturation, floodplain basins often develop into **interchannel wetlands or peat swamps** (in humid climates) and may contain shallow lakes. Over long timescales, organic-rich mud and peat can accumulate in these areas, which is why **lacustrine clays and coal seams are commonly associated with anastomosing river deposits** in the stratigraphic record [9].

Zooming into the **channel-belt scale**, each active channel is flanked by a pair of natural **levees** – these are wedges of sand/silt that aggrade adjacent to the channel banks during flood overflows. Levees form subtle ridges paralleling the channel, typically a few meters higher than the adjacent floodplain (on the order of one channel-depth in height, as discussed later) [11] [12]. Levees tend to be narrow (extending a few channel-widths from the channel) and have a crest that grades outward into the floodplain elevation. They act as semi-confined channel margins, so flow in moderate floods remains within the levee-bounded corridor (a "levee-confined channel belt"). Where a levee is breached, however, sediment-laden water pours onto the floodplain as a **crevasse splay**. Crevasse splays are fan-shaped deposits of sand and silt that spread into the floodbasin, often initiating new channel paths. They are abundant in anastomosing systems and form an important link between channel and floodplain: *"overbank deposits commonly comprise* *abundant crevasse splay deposits and thick natural levee deposits"* [13]. Splays can evolve into new avulsion channels (see below) or simply form local lobes of sand in the floodplain.

Within each channel belt, the **internal stratigraphy** reflects these architectural elements. Anastomosing channel sand bodies are typically *narrow, ribbon-like* and laterally confined by muddy overbank deposits [14]. Individual channel fills often show only weak upward-fining trends and may have abrupt tops – this is because channels are commonly terminated by avulsion rather than by gradual meandering abandonment, so channel fills can end suddenly at an abandonment surface [15]. Adjacent to the channel sands, one finds wedge-shaped levee deposits that fine upward and outward (coarser at channel edge, finer toward floodplain). Further out in the floodbasin are laminated clays, paleosol horizons, and peat layers representing floodplain mud and swamp deposition. Notably, these fine overbank deposits *encase* the channel sand bodies, resulting in a high proportion of mud to sand in the overall deposit architecture [14]. It's common for anastomosed channel belts to stack vertically with minor lateral overlap, given that avulsions create new channels in different positions. As a result, in the stratigraphic record one might see *isolated ribbon sandstone bodies encased in thick floodplain muds*, sometimes with intervening coal layers – a distinctive signature of anastomosed fluvial systems [14] [9]. The lateral connectedness of channel sand bodies is low, because channels generally do not erode each other's deposits; instead, they are separated by preserved floodplain units. This architecture (multiple small channel sand bodies, high mud content) indicates the high preservation potential of anastomosing river deposits on geological timescales [16].

Summarizing the hierarchy: At the largest scale, an anastomosing river comprises *multiple interconnected channels that enclose floodplain islands/basins* [5]. At the intermediate scale, each channel belt consists of a single-thread (usually low-sinuosity) channel bounded by levees and separating the adjacent floodbasins. At the fine scale, the sedimentary elements include channel-fill sands, point bar or side bar deposits (if any minor lateral migration occurred), levee ridges of silt/sand thinning laterally, crevasse splay lobes protruding into floodplain, and extensive overbank muds with possible paleosols and organics. All these elements are arranged in a *multiscale nested fashion*, producing the complex but ordered patchwork that is characteristic of anastomosing fluvial landscapes.

Physical Drivers and Controls on Anastomosing Channels

Several key physical factors govern the formation and maintenance of anastomosing river systems. These factors influence why the river adopts a multi-channel, vertically accreting style rather than a single meandering or braided course. The primary drivers and controls include **stream power, bank cohesion, sediment supply vs. accommodation, flood regime, and tectonic/base-level context**:

- **Low Stream Power and Gradient:** Anastomosing rivers tend to occur in relatively low-energy settings – specifically, they have low channel slopes and/or moderate discharges such that the stream power is not high enough to scour a broad, mobile channel [17] [18]. Low gradient (often near a local base level or on broad flats) means the river's ability to incise is limited; instead, it deposits sediment within its channels and on the floodplain. Indeed, anastomosis is favored by *"a low floodplain gradient"*, which promotes aggradation of the channel belt [19]. The gentle slope also means excess energy is dissipated in overbank flows rather than carving a single deep channel.

- **Cohesive, Stable Banks (Vegetation and Fine Sediments):** Bank strength is a crucial control distinguishing anastomosing rivers from braided rivers. Anastomosing channels typically flow between **erosion-resistant, cohesive banks** – for example, banks reinforced by clay-rich sediments and dense vegetation [17] [20]. Stable banks inhibit lateral erosion and channel widening, leading to narrow, deep channels with low width/depth ratios [21]. This allows multiple narrow channels to carry the flow (rather than one wide channel). In contrast, if the banks were non-cohesive sand/gravel, the system would likely evolve into a single-thread meandering or braided pattern. In anastomosing rivers, riparian vegetation (roots, peat mats, etc.) helps stabilize banks and bar surfaces, so channels remain fixed in place over longer periods [22] [6]. The presence of vegetation also promotes vertical accretion by trapping sediments during floods.

- **High Sedimentation Rate and Channel Aggradation:** A fundamental driver of anastomosing morphology is the tendency for **channels to rapidly aggrade (fill) with sediment**, raising the channel bed and levees over time. Rivers with abundant suspended load and frequent overbank deposition will build up their alluvial ridges relatively quickly. When the in-channel deposition rate outpaces subsidence or floodplain aggradation, the channel becomes *superelevated* above the surrounding plain – a condition that primes the system for avulsions (discussed below). High **sediment supply** (particularly of fine sediment that is easily deposited in overbank areas) combined with low transport capacity (due to low slope) leads to clogging of channels and avulsion. For instance, upstream sediment overloading has been implicated in anabranching of the upper Columbia River, Canada [23]. Conversely, if sediment supply is extremely low, the river might remain incised or stable and not avulse. Thus there is an optimal range of sedimentation that promotes multiple channel belts: enough sediment to aggrade channels but not so much bedload as to cause braiding.

- **Accommodation and Subsidence:** Many anastomosing rivers develop in contexts of active **subsidence or rising base level**, which create accommodation space for thick overbank deposits and reduce the river's tendency to incise. A **rapid rise of base level** (e.g. due to sea-level rise or basin subsidence) is conducive to anastomosis [24]. For example, the Magdalena River in Colombia flows through a subsiding foreland basin and exhibits an anastomosing pattern with multiple channels and backswamps [10]. Subsidence allows the floodplain to accumulate fine sediment and organic matter without being flushed out, and channels must aggrade to maintain a gradient, which can increase avulsion frequency. While subsidence/base-level rise is not strictly required for anastomosing rivers to exist [24], it greatly enhances the vertical buildup of floodplains that characterizes anastomosing systems.

- **Flood Regime and Discharge Variability:** The hydrologic regime influences how and when channels avulse or migrate. Anastomosing rivers are often associated with **frequent overbank flooding** and/or *seasonal inundation*. Regular moderate floods deposit levee material and maintain wetlands, whereas episodic extreme floods can trigger avulsions by overtopping or breaching levees. A river with highly variable discharge (including large flood peaks) may produce more avulsion events, yet if variability is too high and banks are not cohesive, it might braid. Most anastomosing systems have a **moderately dynamic hydrograph** – for example, in the Narew River (Poland) the floodplain is inundated for weeks during seasonal high water [25], but baseflow still maintains distinct channels. Extended flood durations favor sediment settling on floodplains and levee growth [25]. Additionally, *flood frequency* interacts with sediment supply: frequent small floods steadily raise levees, whereas rare very large floods may catastrophically rearrange channels. Observations suggest many documented avulsions occur during or immediately after extreme flood events that overwhelm the channel capacity [24].

- **Avulsion Triggers – Jams and External Events:** Apart from long-term tendencies, specific **triggering mechanisms** often control the timing of avulsions in anastomosing rivers. These include: log or ice jams that suddenly divert flow out of the main channel, the formation of in-channel blockages (e.g. sand plugs or vegetation mats) that reduce capacity, or breaching of a natural dam. Makaske (2001) notes that *"extreme floods, log and ice jams, and in-channel aeolian dunes"* can serve as avulsion triggers [18]. In cold climates, ice jams during spring thaw can force water to carve new paths across the floodplain. In arid or fire-prone regions, large woody debris from riparian zones can dam a channel and cause flow to spill sideways. While these triggers might be associated with particular climates or events, the overall occurrence of anastomosing rivers is **not climate-specific** – such rivers are found in tropical, temperate, and even arid environments, as long as the necessary combination of low gradient, high cohesion, and aggradation exists [24].

- **Stable Base Flow and Partitioned Hydraulics:** Another subtle control is that in an anastomosing network, each channel carries a portion of the total flow and **channels operate somewhat independently** [26]. The flow partitioning means that at moderate discharges, no single channel is "dominant" enough to obliterate the others via lateral erosion. Hydraulic independence is aided by the fact that the channels are separated by distances (and often slight topographic highs) such that they do not readily capture each other's flow except at designed confluence points [26]. This separation is maintained by levees and floodplain vegetation. In essence, *multiple narrower channels with low width-depth ratio can be more hydraulically efficient than one wide channel*, as they can convey floodwaters with less frictional resistance in aggregate [27]. This is one reason anastomosing patterns can be stable – the flow is distributed in a way that large floods are handled by spreading across several channels (lowering shear stress in any single channel).

In summary, **anastomosing rivers occur when conditions favor vertical accretion and channel stability over lateral migration**. Fine-grained cohesive banks and vegetation inhibit lateral erosion, low gradients and sufficient sediment load cause aggradation and channel superelevation, and periodic floods trigger the formation of new channels. Any factor that increases vertical deposition (e.g. subsidence, frequent sediment-laden floods) or decreases lateral mobility (e.g. plant roots, mud banks) will push a system toward an anastomosing morphology [17] [6]. Conversely, if stream power increases (steeper slope or higher discharge) or if banks become less cohesive (sandy banks or vegetation removal), the river may shift to a single-channel braided or meandering pattern. Anastomosing rivers thus represent one end-member of fluvial styles, optimized for low-energy, high-cohesion, aggradational environments.

Time-Evolution Rules: Avulsion Cycles and Floodplain Development

Anastomosing rivers evolve through repeated **avulsion cycles**, wherein channels gradually build up and then relocate, producing the multi-channel pattern. The time-evolution can be described as a cyclical sequence of **channel aggradation, avulsion, and floodplain stabilization**:

1. **Channel Aggradation Phase:** Initially, a given channel occupies a course on the floodplain and carries the bulk of flow. Over years to centuries, this channel undergoes *vertical accretion*. During each flood, sediment deposits on the channel bed and especially on the adjacent levees. Because the main flow is largely confined between levees in moderate floods, significant sediment may also deposit within the channel (as sand bars or in-channel benches) and raise the bed. The net effect is that the channel belt is built upward relative to the floodplain. The channel becomes **superelevated** – perched on a mound of its own deposits. Floodwaters spilling over the banks drop sediment right

at the channel margins, so levee crests rise in tandem with the channel bed [28] [11]. Meanwhile, the interchannel floodplain might also receive sediment, but in many cases the floodplain aggradation rate is much slower than the channel levee aggradation rate [29]. This disparity (channel belts aggrading faster than floodbasins) is what sets the stage for avulsion. Over time, the channel's banks may stand significantly higher than the surrounding basins, increasing the potential energy of water in the channel relative to water on the floodplain. For example, historical observations and models suggest that alluvial rivers typically **aggrade to about one channel-depth above the floodplain** before avulsing [11]. During this phase, flow is still mostly confined to the existing channel, which may lengthen via minor meandering or extend via progradation of its downstream end.

2. **Avulsion Initiation (Threshold and Trigger):** Eventually, the **avulsion threshold** is reached. A common rule is that when the channel's levee crest has built up to roughly the same height as the channel depth (i.e. the channel bed is about one bankfull depth above the floodplain), the river becomes prone to avulsion [11]. Essentially, the river is "perched" and even a small increase in water level can send flow spilling laterally. At this point, any significant high-water event can breach the levee or overtop it for an extended period, finding a new route to lower ground. The avulsion may begin with a **crevasse splay**: during a flood, water cuts a small breach in the levee and deposits a splay lobe outward. If conditions favor, this splay erosion can enlarge into a new channel. Alternatively, the avulsion might be more abrupt – for instance, a log jam or ice jam might suddenly divert the main flow out of the channel, or a *cutoff* could occur if the river finds a shorter path to the sea or lake. Once triggered, the water will exploit any topographic low or erodible path on the floodplain to establish a new course. The path of an avulsion often follows the gradient advantage: the flow seeks a route with a steeper descent to the downstream reach or outlet than the existing channel's path. Thus, avulsions commonly *short-circuit* a lengthy, superelevated channel by cutting across the floodplain on a shorter, steeper path, rejoining the trunk channel or another anabranch downstream [10].

3. **Avulsion Mechanics and Channel Re-establishment:** Avulsions in anastomosing rivers can happen in two general modes (which are not mutually exclusive) [30]:

4. *Avulsion by Bypass (Gradual Relocation):* In this scenario, a new channel is carved while the old channel is **not immediately abandoned** [30]. A crevasse channel might start small and gradually enlarge over multiple floods, capturing more flow over time. The new course may develop *downstream progression*: the splay extends and connects back to the main river downstream, creating a "bypass" channel. For a period, the older channel and the new channel flow concurrently, splitting the discharge (anabranching). The older channel may slowly lose capacity (due to sediment plugging or flow diversion) and eventually become subordinate or even dry up, but this *"slow abandonment of old channels"* can take decades [31]. This process leads to long-lived multi-channel belts, since the old channel remains active for an extended time as the new channel establishes itself.

5. *Avulsion by Channel Splitting (Instantaneous Branching):* Here, during a major avulsive event, the diverted flow **scours multiple new channels on the floodplain essentially at once** [30]. The flood might break out in several directions, creating a splintering of flow that carves several anabranches that may later reconnect. This might occur on a localized part of the floodplain (e.g., downstream of a breakout point). Such multi-channel splays are often seen as an intermediary stage – essentially a *crevasse splay complex* with several distributary-like channels radiating – which later organizes into perhaps one or two dominant channels. Makaske (2001) notes that this "splitting" type of

anastomosis usually represents a short-lived stage in the avulsion process on part of the floodplain [32]. Over time one of the splintered channels might enlarge and capture most flow, while others silt up, leaving behind remnant deposits.

In practice, both modes can occur in one river system [31]. Frequent avulsions and slow abandonment favor a persistent multi-channel network (the hallmark of anastomosing rivers). If avulsions happen only rarely but completely (old channel abandoned quickly), the river might just hop around leaving oxbow lakes, without maintaining simultaneous channels. Anastomosing rivers, however, experience avulsions frequently enough or with enough overlap that multiple channels **coexist for long durations** [31].

1. **Development of New Channel and Floodplain Adjustments:** After an avulsion initiates, the **new channel** undergoes a period of stabilization. Initially it may be underfit (too small for the diverted flow) and may enlarge by eroding its banks or scouring its bed. Over a relatively short time (years to decades), the new channel builds its own set of levees as floods continue to occur, and it takes on the characteristic narrow, deep form. The gradient of the new channel is often steeper (shorter path) than the old, so it might erode headward to fully establish itself. Downstream, it reconnects to the older network, possibly at a confluence. The confluence of anabranches can be dynamic – sometimes one branch will capture most flow, effectively beheading the other. In other cases, both channels remain, dividing flow in some proportion. With the addition of the new channel, the planform now has one more anabranch, increasing the anastomosing complexity.

The **old channel's fate** depends on whether the avulsion was partial or complete. Often in anastomosing rivers, the old channel *remains active at reduced discharge* (an anabranch) rather than drying up entirely [32]. It may become a secondary or "lost" channel: its downstream end could be plugged by sediment (forming a splay into it) or it could simply carry lower flow and gradually infill with fine sediment. Overbank processes may continue to deposit clays in the old channel bed (forming an *oxbow lake* or plugged channel fill). In some cases, especially if the avulsion was triggered by a major flood, the old channel may rapidly silt up at the avulsion node and only carry local runoff thereafter (becoming a series of cutoff lakes). But **slow avulsion** is more typical in anastomosing rivers: multiple channels remain water-bearing and connected for a long time [33]. This creates the classic anastomosing pattern of coexisting channels enclosing floodplain segments.

1. **Interchannel Wetland Formation and Floodplain Building:** During the periods between avulsions, the **floodplain surface is built up** by deposition and biological activity. Fine sediment from overbank floods slowly raises the floodplain elevation, although usually not as fast as channels raise their levees. The areas between channels often turn into wetlands – for example, backswamps that eventually accumulate peat. Because flow is spread among channels, some floodplain pockets might receive little current and become stagnant swamps or shallow lakes (often termed *"occluded floodplain lakes"* behind levees [10]). These wetlands can expand in the low-lying areas left by prior channel belts. Over centuries, a complex mosaic of **interchannel wetlands, soil-rich plains, and abandoned channel lakes** evolves. This wetland development further stabilizes the floodplain by anchoring sediment with vegetation and creating local topography (e.g. peat domes). In essence, the floodplain "heals" between avulsions: abandoned channels are plugged and vegetated, and the whole plain aggrades closer to the level of levee tops (though never fully catching up in a dynamic system).

2. **Repetition and Long-Term Evolution:** The cycle then repeats. Each new avulsion might occur in a different part of the floodplain, gradually spreading sediment over a wide area. Over long timescales, the river may **migrate in a broad sense by avulsion relocations** rather than by meandering. In a fully developed anastomosing system, at any given time there may be **channels of different ages**: some recently avulsed (occupying new courses with fresh levees), others older (silting and becoming more sinuous or vegetated), and perhaps some segments in the process of being abandoned. The result is a patchwork of channel belts of various ages criss-crossing the plain. If external conditions remain stable (subsidence, climate, sediment input), this pattern can persist for millennia, building a vertically accreted fluvial succession. Indeed, anastomosing rivers have high preservation potential because they tend to **avoid eroding earlier deposits** – later channels skirt around or between earlier ones instead of scouring them out [14] [34]. This leads to stacked sequences of floodplain mud and isolated channel fills in the stratigraphy. Paleogeographically, anastomosing systems can maintain their planform over long distances and times because avulsion tends to occur *proximal* (near the channel belts) rather than wholesale relocation to a far-away course. This results in a *gradual shifting of channel positions within an overall valley*, often described as an "avulsion belt." For instance, a developing avulsion belt may start with a crevasse splay complex that progrades and then rejoins the main channel downstream, eventually enclosing parts of the floodbasin and adding an anabranch [35].

In summary, the time-evolution of anastomosing rivers is dominated by **vertical building and punctuated lateral shifts**. Channels aggrade until a threshold is reached, then avulse to a new location, creating new channels while retaining old ones. The **avulsion frequency** is a critical parameter: it can be estimated by the time required to accumulate enough sediment to raise the channel by one depth. For example, if a channel needs to aggrade ~5 m to trigger avulsion and the net aggradation rate is 1 cm/year, the avulsion cycle might be on the order of 500 years (this can vary widely with sediment supply and flood frequency). In many modern anastomosing rivers, avulsions (small or large) are observed on the scale of centuries or less [19], which keeps multiple channels active. The interplay of continuous levee/floodplain deposition and episodic channel jumping yields the distinctive multi-threaded, long-lived networks of anastomosing rivers.

Static Snapshot Generation Rules (Constructing a Plausible Anastomosing Planform)

To generate a geologically plausible **static image or model** of an anastomosing river system, one must reproduce the characteristic spatial layout: multiple interconnected channels, levee-confined channel belts, and extensive mud-rich floodplain between them. The following set of **procedural rules** can guide the construction of such a snapshot:

1. Define the Valley Framework: Begin with a broad, low-gradient valley or coastal plain surface. The valley bottom should be nearly flat (slope on the order of 10^−4 or less) and relatively wide compared to individual channel widths [1]. For example, if channels are ~100 m wide, the valley might be several kilometers wide, allowing multiple channel belts to exist side by side. Set an overall downstream slope for the water surface – gentle enough to encourage aggradation. The valley surface can be given minor undulations or shallow basins to represent prior floodplain topography (e.g. legacy levees or peat domes). If simulating an incised valley, ensure the valley fill top is broad and flat so the river isn't confined to a single course.

2. Layout of Channel Belts: Create **multiple channel traces** across the valley. These should be arranged as an interconnected network: channels should split (bifurcate) and rejoin (confluence) in several locations, rather than running parallel without interaction. A practical approach is to start with one sinuous channel thread (the "trunk" channel) and then add avulsion channels: for instance, choose a point on the trunk where an avulsion occurred and draw a new channel course diverging from that point and connecting to the trunk again further downstream. Repeat this for additional avulsion events to produce a braided-island network, but note that unlike braided rivers, the anastomosing channels *do not recombine immediately* – they form separate stable paths that only rejoin downstream after significant separation [2]. Ensure that **each anabranch rejoins the system** at some point – anastomosing channels typically enclose floodbasins but ultimately flow back together or into a common trunk outlet (they are not independent distributaries going to different end points, unless at a delta). The resulting planform should show **"belts of variable width and length which by turns split and join"** [2]. Some channels may carry more water (dominant channel belts) and appear slightly larger, while others are secondary. Importantly, *no single channel occupies the whole valley*; instead, the channels are distributed so that large portions of the floodplain lie between them.

3. Channel Geometry and Pattern: Shape each channel as a relatively **low-sinuosity** curve. Anastomosing channels can have gentle meanders, but tight bends and oxbows are uncommon on active channels (oxbows more often represent old courses). Use sinuosity indices typically <1.3 for active channels [7]. You might include a mix of straight and slightly meandering segments. If one channel is older and has experienced some lateral migration before avulsion, you can include subdued meander scrolls or point bars within its levee belt, but keep these moderate – large point-bar complexes would signal a meandering river, which is a different style. The channels should be **narrow and deep**: in a schematic, channel width might be drawn small relative to its meander wavelength. A rule of thumb: set channel width such that width/depth ratio is low (e.g. W/D on the order of 10 or less) [36]. This could mean, for instance, channels 50 m wide and 5 m deep, or 200 m wide and 20 m deep, depending on scale. The channels should **not** have the very wide, shallow cross-section typical of braided rivers. Also, space the channels apart so that each has room for its levees and an intervening floodbasin. The **spacing between channel belts** is usually large relative to channel width – often on the order of *kilometers*. Essentially, each channel belt occupies only a small fraction of the valley cross-section, with floodplain expanse in between [9]. You can introduce some asymmetry (one side of valley may have more channels) but maintain that wide separation.

4. Construct Levee Belts: For each channel trace, delineate a **levee or channel-belt zone** around it. This can be done by drawing parallel lines along both sides of the channel to represent levee crests. Typically, levee width (from channel bank to where floodplain elevation equalizes) might be on the order of 1–5 times the channel width. These levees are the highest elevations on the floodplain aside from any terraces. Represent levee crests as ridges that run continuous along the channel, possibly with minor undulations. The levee height should be greatest at the channel edge and taper outward. For a static view, one can indicate relative height (e.g. shading or contour lines): levee tops might be **~1 channel depth above the adjacent floodplain** [11]. For example, if channel depth is 5 m, levee crests might be ~5 m above floodplain immediately at the channel bank and slope down to near 0 m above floodplain at the outer edge of the levee belt. Where two channels run close by, their levee systems might merge or overlap, forming a combined elevated ridge between them. Label or visually distinguish levee surfaces as slightly higher ground often hosting different vegetation (e.g. levees might have natural levee forests, whereas floodplain basins have marsh).

The levee-constrained belts should indicate that channels are **confined within narrow ridges**. In a rendered image, one could use a lighter color or texture along the channel margins to show sandy levee deposits, and a darker or greener tone in the floodbasins. It's useful to note that levees often decrease in height downstream (as sediment load drops out upstream), so levee prominence might lessen along the flow direction. Also, at confluences where channels rejoin, levee ridges might converge and then diverge again after the junction.

5. Add Crevasse Splays and Avulsion Nodes: Identify a few points along the channels where avulsions or major floods have occurred, especially where a new channel branches off. At these points, **breach the levee** and fan out a small **crevasse splay deposit** into the floodplain. A crevasse splay can be drawn as a lobate feature emanating from the channel: wide near the levee break and tapering out into the basin. Indicate the direction of flow on the splay with subtle flow ridges or distributary channels. Splays should be located where one would expect avulsion beginnings – e.g. on the outer bank of a slight channel bend (where water might overtop) or near an upstream end of a floodbasin (where water finds a low area). The **sediment texture** of a splay is sand to silt, coarser than the surrounding floodplain, so you might represent it with a lighter tone. Some splays may connect to the next channel if the avulsion was successful (in fact, one method of constructing the network is: draw a splay lobe from Channel A toward where Channel B begins, effectively linking them). Other splays might terminate in the floodplain, forming splays that have not yet scoured a full new channel. According to observations, *"crevasse splays evolving in anastomosed channels"* can lead to partial avulsions that incrementally build new pathways [37]. Therefore, you can include partially developed splay-channel complexes to increase realism. Where you have a splay that did turn into a new channel, that location is an **avulsion node** – highlight it as an area of complex channel pattern (perhaps a small anastomosing knot by itself). Often an avulsion node will have multiple small channels (from the initial breakout) in its vicinity [35], so you could draw a cluster of tiny distributary-like channels there, merging into the main new anabranch.

6. Mud-Dominated Floodplain Fill: The areas **between channel belts** should be depicted as flat, low-lying floodplain, predominantly fine-grained. To emulate this, fill the interchannel polygons with a uniform darker color or texture representing clayey soil or open water wetlands. Scatter some floodplain lakes or oxbows: for instance, in abandoned segments of old channels, draw crescent lakes, or in lowest parts of the basin draw irregular ponds. One might include subtle *"occluded lakes and wetlands behind [levees]"* [10] – i.e. immediately landward of levees you often find elongated floodplain lakes parallel to the channel, where water gathers in the lee of the levee. Representing a few of these (long, narrow lakes along the inside of river bends or behind levee breaches) would match descriptions. The floodplain surface can also have **paleochannels**: ghost channels or swales from previous positions of the river. Draw faint curvilinear depressions in the floodplain connecting some oxbow lakes – these are traces of former channels (since anastomosing rivers often avulse to a new route, the old route might remain visible as a topographic low for some time). Vegetation could be indicated: for example, levees might support natural levee forest (trees line the active channels), whereas floodbasin might be marshy (reed and grass, no tall trees in constantly wet areas). In plan view, this could be shown by a change in texture or by adding symbols for trees along the levee ridges.

7. Internal Stratigraphy Hints: If the analog image requires showing a cross-section or block diagram, incorporate stratigraphic rules: Channel fills should appear as sand bodies (e.g. yellow/brown in a lithologic cross-section) that are narrow and encased in floodplain fines (gray or dark layers). Levee deposits would be wedges of silt that thin laterally away from the channel. Crevasse splays appear as lens-shaped sand bodies extending outward from channels, often thinning and fining distally. Floodplain deposits would be thick packages of clay with occasional thin peat (coal) streaks. Show that channel sand bodies of different ages are *stacked vertically in slightly offset positions* rather than amalgamated. One could include a vertical profile through a channel belt: for instance, a fining-upward channel fill overlain by a clay plug, flanked by outward-fining levee beds. Indicate that multiple such channel stories occur at different stratigraphic levels, separated by floodplain material. Static rules for stratigraphy: *ribbon geometry* for channel sands, levee thickness on the order of a few meters at channel edge decaying to zero over ~100s of meters [12], crevasse splay thickness maybe 1–3 m at entry point thinning out to cm-level laminae at far end.

8. Overall Composition Checks: Step back and verify the snapshot has the expected proportions and morphology. A correct anastomosing layout will show *more area in floodplain than in channel*, multiple sinuous blue lines (channels) threading through a green/brown floodplain, with branching and merging visible. The channels should look stable (not too braided or choked with bars – you might draw mid-channel bars only sparingly if at all, since anastomosing channels typically don't have extensive mid-channel braid bars). The levees should frame the channels clearly, giving the impression of slightly raised banks. No channel should be excessively large relative to others (though one can be largest); dominance should be shared. Check that there are indeed *enclosed floodbasins*: i.e. loops of channels around an island. At least one island area should be completely encircled by channels, exemplifying the definition of anastomosis ("interconnected channels enclosing floodbasins" [38]). If the environment series expects a labeled schematic, label features like "Levee", "Crevasse Splay", "Abandoned Channel (Oxbow)", "Peat Swamp", etc., to reinforce the elements present.

By following these static construction rules, the resulting image or model should capture the essential look of an anastomosing river depositional system: a patchwork of levee-bounded channel corridors and intervening wetland basins, with multi-scale features (from small splay fans to large alluvial islands) arranged in a geologically plausible manner.

Key Quantitative Formulas and Parameters

In modeling or analyzing anastomosing river systems, certain **quantitative rules** and formulas help describe thresholds and spacing. Here are some key metrics and relationships:

- **Avulsion Superelevation Threshold:** A simple criterion for avulsion is that it occurs when the channel belt has aggraded sufficiently that the channel is **approximately one channel-depth higher than the floodplain** [11]. In formula form, one can express the normalized superelevation S_e as:

$$S_e = \frac{H_{\text{levee crest}} - H_{\text{floodplain}}}{D_{\text{bf}}}$$

where D_{bf} is the bankfull channel depth. Avulsion is traditionally thought to occur when $S_e \approx 1.0$ (i.e. levee crest about one channel depth above floodplain) [11]. This encapsulates the idea that once the channel is perched, it's as easy for water to flow out across the floodplain as to stay in the channel. Empirical studies (e.g. Mohrig et al. 2000) support this threshold in alluvial rivers. In practical modeling, one might set a critical superelevation $S_{e,crit} \approx 0.7–1.0$; when reached, an avulsion is triggered.

- **Avulsion Frequency / Timescale:** The time between avulsions can be estimated by how quickly aggradation builds the required superelevation. A simplified formula is:

$$T_{\text{avulsion}} \approx \frac{H_{\text{crit}}}{(w_{\text{c}}\, A_{\text{c}} - w_{\text{fp}}\, A_{\text{fp}})}$$

where H_{crit} is the critical levee height ($\approx$ one channel depth), A_{c} is the aggradation rate on the channel bed (inside levees), A_{fp} is the aggradation rate on the adjacent floodplain, and $w_{\text{c}}, w_{\text{fp}}$ are weights (fraction of time or proportion of sediment going to channel vs floodplain). In many cases floodplain aggradation is much smaller than channel belt aggradation (the floodplain might receive only fine washload), so one can approximate $T_{\text{avulsion}} \approx H_{\text{crit}}/A_{\text{c}}$ if A_{fp} is negligible [29] . For example, if a channel needs to accumulate ~5 m of sediment and it aggrades at ~1 cm/year (0.01 m/yr) net, then T_{avulsion} ~ 500 years. Shorter avulsion cycles (e.g. decades) imply very rapid aggradation (common in small crevasse channels), whereas longer cycles (millennia) imply slow aggradation or significant floodplain leveling that delays the superelevation.

- **Gradient Advantage (Avulsion Path Selection):** When a river avulses, it often chooses a path that maximizes slope. A simplified rule is to compare the slope of the existing channel S_{ch} (which may be reduced by meandering lengthening) with the slope of the potential new path over the floodplain S_{fp} . An avulsion is favored when:

$$\frac{S_{\text{fp}}}{S_{\text{ch}}} > \gamma$$

for some threshold γ slightly above 1 (often around 1.1–1.5 in studies) – meaning the floodplain route is 10–50% steeper than the current channel [39] [40] . This can be implemented by checking if the downstream distance to a given elevation drop via a new route is significantly shorter than along the channel. In deltaic systems, a related concept is that avulsion length is tied to the backwater length where slope advantage manifests; in inland anastomosing rivers, one might use a more local slope ratio.

- **Levee Deposition Profile:** Levee height and width can be described by an exponential or power-law decay of sediment deposition with lateral distance from the channel. One formulation (after the Rouse profile of suspended sediment fallout) is:

$$h_{\text{levee}}(x) = h_0 \exp\Big(-\frac{x}{L_d}\Big)$$

where h_0 is levee height at the channel edge (perhaps ~bankfull depth) and L_d is a characteristic decay distance (which might be on the order of a few channel widths). Field studies confirm that levee thickness is greatest at the channel margin and tapers off, often becoming negligible at ~100–300 m away for moderate-sized rivers [41] [42] . In anastomosing rivers with cohesive banks, levees are relatively **narrow but high**. For example, levee height ~1–2 m above floodplain and levee half-width ~50–200 m are reasonable for many systems [12] . A levee's **height-to-width** ratio can also be given: levees are broad low ridges (height maybe a few percent of their width). Quantitatively, one study found levee height ≈1.0–1.2 m and levee width ≈ 100–300 m in a vegetated anastomosed river [12], which is consistent with these rules.

- **Channel Depth and Belt Thickness:** As noted, anastomosing channel-belts (channel plus levee deposit) are typically limited to about **2× channel depth in vertical thickness** [29]. This is because the channel aggrades one depth and then avulses, so it does not build significantly thicker sequences in one place. For instance, if bankfull depth is 5 m, the channel belt sand plus levee might be ~10 m thick at most before avulsion redistributes sediment elsewhere [29]. This is in contrast to submarine channels which can super-elevate much more. Thus, in setting model parameters: channel depth D_{bf} sets the scale for levee height (~D_{bf}) and channel sand body thickness (~D_{bf} to $2D_{\mathrm{bf}}$ including internal bar deposits).

- **Channel Belt Spacing and Avulsion Radius:** While not a single formula, a guideline for **channel belt spacing** is related to how far an avulsion can reach laterally. In many anastomosing rivers, new channels avulse into adjacent floodbasins, often *at a distance on the order of the channel belt width or the floodplain compartment width*. If W_{valley} is total valley width and N is the number of active channel belts across it, a rough spacing is W_{valley}/N . More dynamically, one can use an avulsion *radius* or *nodal distance* – e.g. assume an avulsion node can feed new channels within a radius of a few kilometers. For instance, the distance between major anabranch belts in the Magdalena River's anastomosing reach corresponds to the width of interchannel swamps on the order of 5–10 km [43]. In smaller systems like the Narew, Poland, channel belts might be spaced only a few hundred meters apart because the whole valley is ~2–3 km wide [23]. There isn't a universal formula, but **backwater length** (for large rivers) or empirical observation can inform this spacing. In generative models, one strategy is to limit avulsion channel lengths so that new channels rejoin the main stem within some multiple of channel belt widths downstream, inherently setting spacing.

- **Width-Depth Ratio Limits:** To maintain an anastomosing pattern, enforce a **low width/depth ratio** for individual channels. This could be parameterized: $\mathrm{W/D} < 20$ (for instance). In practice, many anastomosing channels have W/D between ~5 and 15 [36] (compare to braided rivers where W/D can be >100). A tighter control related to stream power is **specific stream power per channel** (ω = γQS/W, where γ is specific weight of water, Q discharge, S slope, W width). Keeping ω below a threshold helps avoid braiding; this can be achieved by narrower widths for a given Q and S.

These quantitative rules inform the **constraints in a generative model** – e.g. when randomly creating channels, one must check that levee height and superelevation criteria are met, and when connecting channels, ensure the slope advantage criterion is satisfied, etc. In summary, the formulas above ensure that the model respects known limits: channels aggrade to ~1 depth above the plain (then avulse), levees are about that high and decay exponentially in thickness, and multiple channels maintain separation according to avulsion lengths and valley width.

Examples and Visual References for Spatial Layout

Real-world examples of anastomosing rivers and schematic analogs provide guidance for how these systems appear in planform and in outcrop:

- **Magdalena River, Colombia (Momposina Basin):** This tropical river system is a classic modern example of an anastomosing pattern in a subsiding foreland basin. **Satellite images** show the Magdalena splitting into numerous winding channels that enclose marshy islands. The channels have well-developed levees; behind these levees lie floodplain lakes and swamps. Researchers note *"multiple anastomosing channels with levees and splays into flood basins"* in the Magdalena reach [10]. Some reaches also show minor lateral migration, but overall the planform is stable. An image taken in 2001 (Landsat) illustrates the Magdalena's multi-thread network: levees appear as bright overbank areas, and one can see **occluded (cut off) lakes** on the floodplain that were once channel segments [10]. This provides a real template of how levee-bordered channels and floodplain water bodies are arranged.

- **Narew River, Poland (Narew National Park):** The upper Narew is a well-known **European anastomosing river**, often called the "Polish Amazon." It flows through a broad wetland valley with very low gradients. Historical accounts describe how it used to split into multiple coexistent channels forming a mosaic of wetlands and islands [44]. A photograph or map of the Narew shows a dense network of narrow channels threading through reed beds. In high water, the whole valley floods, but at low water the channels are distinct and interconnected. The Narew example highlights an anastomosing system formed by **slow avulsions in a post-glacial flat** [23]. Planform images from Google Earth (Gradziński et al. 2003) depict several nearly parallel channels connected by short cross-links, creating a lattice of water. This case underscores the role of vegetation: the channels are highly vegetated and their banks rarely move laterally, making the pattern persist. The **spatial layout** in Narew's satellite imagery shows channels diverging around marsh islands then rejoining, very much matching the procedural rules we outlined (with levees less pronounced but channels truly anabranching).

- **Upper Columbia River, British Columbia, Canada:** In its upper reaches (Columbia Wetlands), the Columbia River flows as an anastomosing system through a montane valley. There are multiple relatively straight, narrow channels separated by swampy islands stabilized by peat and vegetation. It is a **vegetation-controlled anastomosing system** with cohesive banks. Field studies (e.g. Makaske et al. 2002) reported that this river has channels of low sinuosity that frequently avulse due to upstream sediment (from glaciers) filling them [23]. A map or aerial photo will show the Columbia's channels splitting around large peat islands and rejoining downstream, with many abandoned channels visible. The interchannel areas are largely peatland, emphasizing the wetland-dominated floodplain (over 60% of area as mentioned before). This example is instructive for spatial layout because it shows how **upstream sediment supply and mild gradients** produce a pattern of repeated avulsions that pepper the valley with channels.

- **Rio Negro, Brazil (Anabranching Amazon tributary):** Parts of the Rio Negro in the Amazon basin exhibit anabranching (anastomosing) planforms, especially where the river has low gradients approaching the Amazon floodplain. An image referenced by Latrubesse and Franzinelli (2005) shows the Rio Negro with **numerous elongated islands** and multiple channel threads [10]. The islands are bounded by prominent levees, and behind those levees are dark-water floodplain lakes (the Rio Negro has blackwater swamps). This provides a visual of **extensive levee systems with lakes behind them** [10] . In a generative sense, it guides how to include floodplain water bodies: long narrow lakes parallel to the channel, often separated from it by a strip of higher ground (the levee). The Rio Negro also illustrates that anastomosing rivers can occur in large river basins, not only small streams.

- **Paraguay River in the Pantanal (Brazil):** The Paraguay in the vast Pantanal wetland is largely an anastomosing system. In satellite images, it shows a broad unconfined floodplain with a maze of channels and intervening swamps at the terminus of the Taquari megafan [45] . It's a good reference for **megafan anastomosis** – the channels are distributary-like but interlinked, adjusting to a fan's subsidence and sedimentation. Large portions of the Pantanal flood annually, leaving only levee zones slightly above water. The spatial arrangement here includes multi-kilometer spacing between channels and very large flood basins, demonstrating a low-density anastomosing network.

- **Outcrop Analog – Coal-bearing Floodplain Facies:** Ancient examples of anastomosed river deposits can be seen in some coal-bearing strata (e.g., the Carboniferous Coal Measures or certain delta plain successions). In outcrop or cross-section diagrams, these show *isolated channel sand bodies encased in mud and coal*. A classic ancient example described by Smith & Putnam (1980) is in Alberta, Canada: they documented laterally connected sandstone bodies surrounded by overbank mud and coal, interpreting them as anastomosed river channel belts [14] . These outcrops guide the rule that channel sands should be narrow and laterally discontinuous, and that one should expect organic-rich floodplain material between. If providing a **schematic cross-section**, one might cite such ancient analogs to justify the drawn architecture.

Each of these examples reinforces certain spatial patterns: **Tonlé Sap River in Cambodia** (as shown by Makaske's Fig.1) is another anastomosing example in a deltaic lake environment, demonstrating multi-channel flow into a lake [46] . **Australian Anastomosing Rivers** like the Lachlan or the fly River distributaries highlight anabranching in semi-arid plains with scrolls only on individual channels but no oxbows for the system as a whole.

In summary, when guiding spatial layout, **visual references confirm**: channels should split and coalesce around persistent islands (Narew, Magdalena), levees should be present and create linear topographic highs (Rio Negro, Magdalena), floodplain should be largely wetlands with prior channel traces (Columbia Wetlands, Pantanal). Incorporating these real patterns into the generative rules ensures the synthesized image is grounded in actual geomorphology.

(While embedding actual images is beyond this text, the cited descriptions serve to calibrate the model – e.g., one could compare a generated planform with the Magdalena or Narew imagery to check for realistic complexity and spacing.)

Pseudocode for Generative Model of Anastomosing Rivers

Finally, to translate the above rules into an algorithmic form, here is a high-level **pseudocode** that a generative model could implement to create a multiscale anastomosing river system:

```
INITIALIZE domain with flat valley grid (X by Y), slope = S_valley (small).
Set base_level at downstream end, and water_flow_direction along slope.

# Parameters for river and sedimentation
set channel_depth = D_bf
set channel_width = W (ensure W/D ~ 5–15)
set levee_decay_length = L_d  (distance for levee thickness to drop by ~e-fold)
set avulsion_threshold = D_bf  (levee height for avulsion trigger)
set next_channel_id = 1

# Data structures to hold channels and floodplain
channels = []  # list of active channel polylines and their attributes
floodplain_elev = [[0]]  # 2D array of floodplain elevation increments (start
flat)

# 1. Create initial main channel
main_channel = create_sinuous_channel(polyline_length = domain_length,
                                      sinuosity ~1.1, width=W)
main_channel.id = next_channel_id; next_channel_id += 1
main_channel.elev = base_level + S_valley * distance_to_outlet  # long profile
channels.append(main_channel)

# 2. Evolve system with aggradation and avulsion cycles
time = 0
while time < T_final:
    for ch in channels:
        # Aggrade channel bed and levees
        ch.bed_elevation += aggradation_rate_channel * dt
        # Build levee height until threshold
        levee_height = ch.bed_elevation + ch.depth -
floodplain_elev[ch.position]
        if levee_height >= avulsion_threshold:
            # Trigger an avulsion from this channel
            avulsion_node = ch.select_avulsion_node()  # e.g., near
superelevated bend
            new_path = find_steepest_path_to_downstream(ch, avulsion_node)
            if new_path is not None:
                new_channel = carve_channel(new_path, width=W, depth=ch.depth)
                new_channel.id = next_channel_id; next_channel_id += 1
                channels.append(new_channel)
                # Mark levee breach and create crevasse splay deposit
                create_splay(avulsion_node, ch, new_channel)
                # Optionally reduce flow in parent channel (partial abandonment)
                ch.flow_fraction *= 0.5  # half flow remains, half to new
channel
    time += dt
```

```
# 3. After evolution, construct static output (channels + floodplain)
for ch in channels:
    draw_channel_on_map(ch.geometry, width=ch.width)
    # Draw levee buffers along channel
    draw_levee(ch.geometry, height=D_bf, decay_length=L_d)
# Fill floodplain areas between levees
fill_between_channels_with_fines(channels, floodplain_elev)
place_wetlands_and_lakes(channels, floodplain_elev)
```

This pseudocode outlines the dynamic aspect (for understanding), but one can simplify it for a **static generation** by deciding apriori where avulsions happened. For a static snapshot creation:

```
Generate base main channel geometry.
Determine N_avulsions (number of branch channels) desired.
For i in 1..N_avulsions:
    pick an avulsion location on an existing channel (based on spacing or
random).
    carve a new channel from that point to a downstream reconnection (simulate
find_steepest_path).
Mark levee zones along all channel segments.
Around each avulsion location, add a crevasse splay fan connecting to new
channel.
Populate floodplain with appropriate elevations (levee ridges next to channels,
low in basins).
Populate floodplain with lakes in low areas and traces of any fully abandoned
channels.
```

During the generation, incorporate the **quantitative rules**: ensure levee height ~ channel depth at the avulsion node, ensure new channel route has slope advantage, ensure channel width and depth meet the ranges. The model should also enforce that channels are *hydraulically connected* (flow from upstream channels enters downstream ones).

In code or algorithm, after laying out channels and levees, you would **assign sedimentary facies**: for each pixel or cell, decide if it's channel (sand), levee (silt), splay (sand-silt mix, lobate shape), or floodplain (clay/peat). Pseudocode might include routines like `label_facies()` to do this classification based on proximity to channels and elevation above floodplain.

The above pseudocode is just a framework – a full implementation would refine each function (e.g., `find_steepest_path_to_downstream` could use a Dijkstra algorithm on a DEM to simulate flow path of flood breakout). But following this scaffold will produce a synthetic anastomosing river that respects geological realism: multiple stable channels, levee-bordered, avulsion-generated connections, and a stratigraphy consistent with known examples.

In conclusion, by applying these detailed rules and algorithms, one can generate analog images or models of anastomosing river systems that are **geologically accurate** – capturing their multiscale architecture, physical controls, evolutionary behavior, and spatial complexity as observed in nature [47] [10]. Such models are invaluable for interpreting ancient fluvial deposits and for simulating how these intricate river networks form and change over time.

Sources: The rules and parameters above are synthesized from fluvial geomorphology studies including Makaske (2001) on anastomosing rivers [48] [19], levee deposition research [11], and modern observations from rivers like the Magdalena and Narew [10] [2], among others as cited throughout. Each aspect – hierarchical structure, controls like cohesion and gradient, avulsion mechanics, and depositional elements – is grounded in empirical data and literature to ensure the generative analog honors real-world river behavior.

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