Attributes of an alluvial river and their relation to water policy and management

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Rivers around the world are being regulated by dams to accommodate the needs of a rapidly growing global population. These regulatory efforts usually oppose the natural tendency of rivers to flood, move sediment, and migrate. Although an economic benefit, river regulation has come at unforeseen and unevaluated cumulative ecological costs. Historic and contemporary approaches to remedy environmental losses have largely ignored hydrologic, geomorphic, and biotic processes that form and maintain healthy alluvial river ecosystems. Several commonly known concepts that govern how alluvial channels work have been compiled into a set of ''attributes'' for alluvial river integrity. These attributes provide a minimum checklist of critical geomorphic and ecological processes derived from field observation and experimentation, a set of hypotheses to chart and evaluate strategies for restoring and preserving alluvial river ecosystems. They can guide how to (*i*) restore alluvial processes below an existing dam without necessarily resorting to extreme measures such as demolishing one, and (*ii*) preserve alluvial river integrity below proposed dams. Once altered by dam construction, a regulated alluvial river will never function as before. But a scaled-down morphology could retain much of a river's original integrity if key processes addressed in the attributes are explicitly provided. Although such a restoration strategy is an experiment, it may be the most practical solution for recovering regulated alluvial river ecosystems and the species that inhabit them. Preservation or restoration of the alluvial river attributes is a logical policy direction for river management in the future.

Since the 1990s, the physical and environmental consequences of river alteration and management have been openly questioned. Continued increases in flood losses, both financial and human, and the unanticipated and unwanted results of dams and channel straightening, invite reevaluation of river management. Reevaluation has even led to removing existing dams (e.g., Butte and Clear creeks in California, Elwha River in Washington), as well as implementing experimental releases of high flows (1, 2).

Historically, river policymakers and resource managers have been less attentive to a growing body of experience, experiment, and theory concerning geomorphic processes that form and maintain alluvial river ecosystems. There are several commonly known concepts that govern how healthy alluvial channels work that we have compiled as attributes of alluvial river integrity. These attributes can guide how to (*i*) restore alluvial processes downstream of an existing dam without necessarily resorting to extreme measures such as demolishing one, and (*ii*) preserve alluvial river integrity below proposed dams. This set of attributes is not a classification system or a substitute for individual study and observation on a river. It provides a minimum checklist of critical geomorphic and ecological processes derived from field observation and experimentation, a set of hypotheses to chart and evaluate strategies for restoring and preserving alluvial river ecosystems. At the ever-present risk of oversimplification, the attributes also can help policymakers appreciate many of the complex requirements of alluvial river ecosystems.

Alluvial river ecosystems persist through a complex, interacting array of physical and biological processes. For any impetus imposed on the river ecosystem (e.g., a recommended flow release), we should expect a response (e.g., scouring sand from a pool). The significance of an impetus will depend on an appropriate threshold beyond which a specific response is expected. A process, therefore, is comprised of an impetus and an expected response. To use the alluvial river attributes as guidelines for recovering or preserving critical processes, one must consider how the magnitude, duration, frequency, and timing of an impetus will exceed a threshold to produce a desired response. Rarely, however, is a single impetus imposed on a river ecosystem associated with a single response.

Floods are primary impetuses for all alluvial river morphology. An increase in discharge may initiate bed surface movement and bank erosion, once the force exerted by the flood event (the impetus) has passed some threshold for movement or erosion. This threshold may require a specific flow magnitude and duration before producing a significant morphological response. The timing and frequency of the flood also may have profound effects on a species or a population. Mobilizing sand from a pool in January may smother salmon eggs incubating in the downstream riffle. The impetus, therefore, cannot be prescribed as a simple measure of force, nor can the total reaction be as succinctly quantified or even fully anticipated. It is with this backdrop of uncertainty that the attributes were compiled.

The Alluvial River Attributes

The alluvial river attributes (3) can help river managers identify desired processes, then help prescribe necessary impetuses based on useful empirical relationships and thresholds developed by river geomorphologists and ecologists. All of the concepts deriving the alluvial attributes have been described among a wide range of professional journals, technical books, and agency reports (reviewed in ref. 2), but their compilation has not been previously published. They may not apply equally to all alluvial river ecosystems. Some rivers may not be capable of achieving certain attributes because of overriding constraints, e.g., a river passing through an urbanized corridor often is not free to migrate. These constraints do not eliminate the attributes' usefulness; knowing what might remain broken should influence what can be repaired.

Attribute No. 1. ***The primary geomorphic and ecological unit of an alluvial river is the alternate bar sequence.*** *Dynamic alternating bar sequences are the basic structural underpinnings for aquatic and riparian communities in healthy alluvial river ecosystems.*

The fundamental building block of an alluvial river is the alternate bar unit, composed of an aggradational lobe or point bar, and a scour hole or pool (Fig. 1). A submerged transverse bar, commonly called a riffle, connects alternating point bars. An alternate bar sequence, comprised of two alternate bar units, is a meander wavelength; each wavelength is between 9 and 11 bankfull widths (4). The idealized alternate bar sequence is

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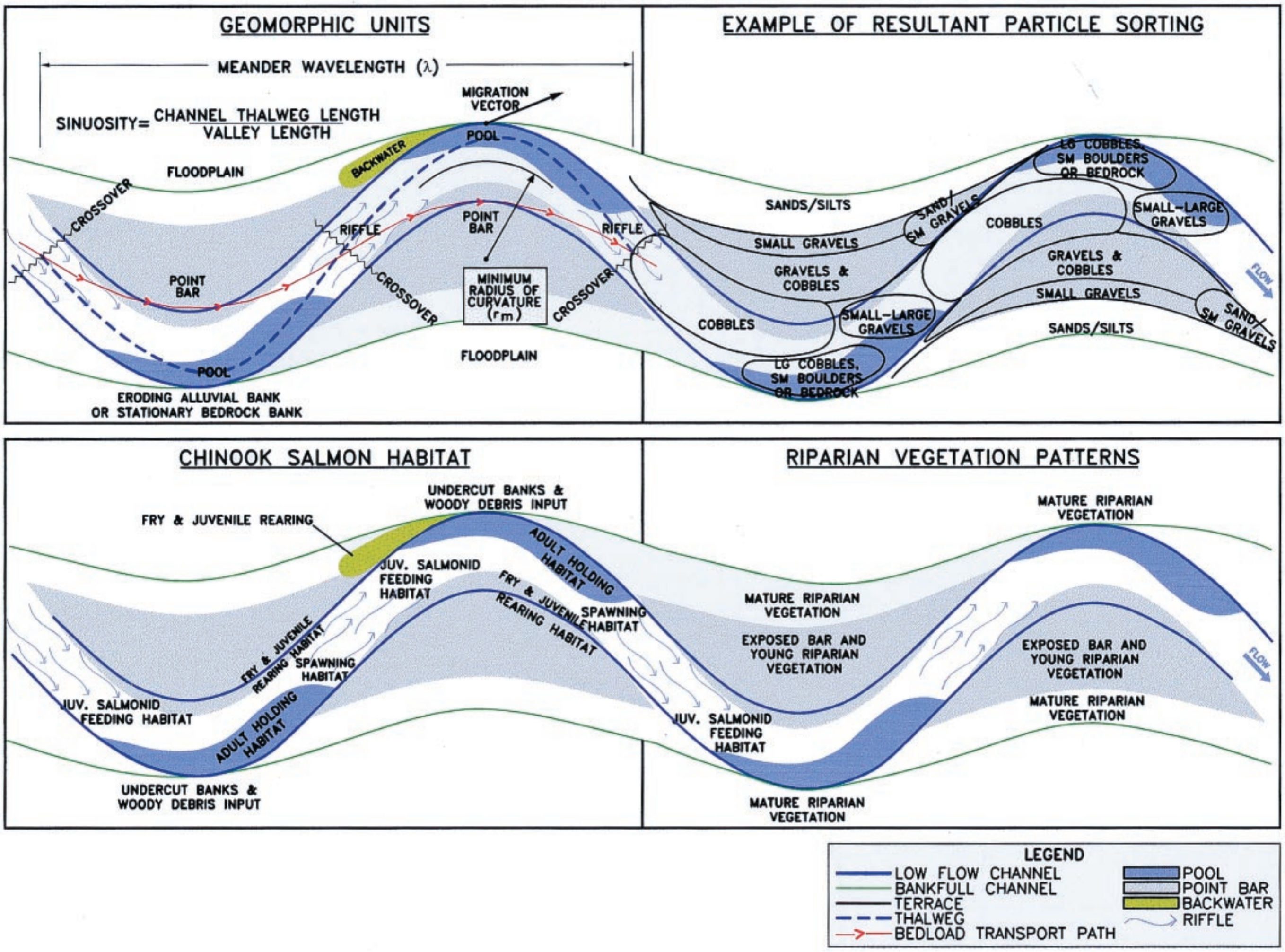

Fig. 1. An idealized alternate bar sequence showing geomorphic units, particle-sorting trends, typical salmonid habitats, and riparian vegetation succession patterns.

rarely found in nature, because natural geomorphic variability (e.g., valley width contractions, bedrock exposures, etc.) perturbs the idealized channel form shown in Fig. 1. Floods flowing through alternating bar sequences frequently rearrange the bar topography, producing diverse, high-quality aquatic and terrestrial habitat.

Attribute No. 2. ***Each annual hydrograph component accomplishes specific geomorphic and ecological functions.*** *Annual hydrograph components (including winter storm events, baseflows, snowmelt peaks, and snowmelt recession limbs) collectively provide the impetus for processes that shape and sustain alluvial river ecosystems. These components are uniquely characterized by year-to-year variation in flow magnitude, duration, frequency, and timing.*

Hydrograph components are seasonal patterns of daily average flow that recur from year to year. For many rivers in the western U.S., these hydrograph components include summer baseflows, rainfall- and rain-on-snow-generated floods, winter baseflows, snowmelt peak runoff, and snowmelt recession (Fig. 2). Each annual hydrograph component can be characterized by its interannual variability in flow magnitude, duration, frequency, and timing. A subset of all processes needed to create and sustain alluvial river ecosystems is provided by each hydrograph component. Eliminate or alter the interannual variability of the hydrograph components, and the ecosystem is invariably altered.

Attribute No. 3. ***The channelbed surface is frequently mobilized.*** *Coarse alluvial channelbed surfaces are significantly mobilized by bankfull or greater floods that generally occur every 1–2 years.*

As streamflow rises throughout a winter storm and during peak snowmelt, a geomorphic threshold for mobilizing the channelbed surface is eventually exceeded. This flow threshold typically occurs over a narrow range of streamflow and varies spatially, depending on the morphology, grain size, and location of sediment deposits (Fig. 3). In general, grains on the channelbed surface are mobilized many times a year, but sometimes not at all in other years, such that, over the long-term, the streambed is mobilized on the order of once a year. The duration of channelbed mobilization is a function of the duration of the high flow, which is typically on the order of days.

Attribute No. 4. ***Alternate bars must be periodically scoured deeper than their coarse surface layers.*** *Floods that exceed the threshold for scouring bed material are needed to mobilize and rejuvenate alternate bars. Alternate bars are periodically scoured deeper than their coarse surface layer, typically by floods exceeding 5- to 10-year annual maximum flood recurrences. Scour is generally followed by redeposition, often with minimal net change in the alternating bar topography.*

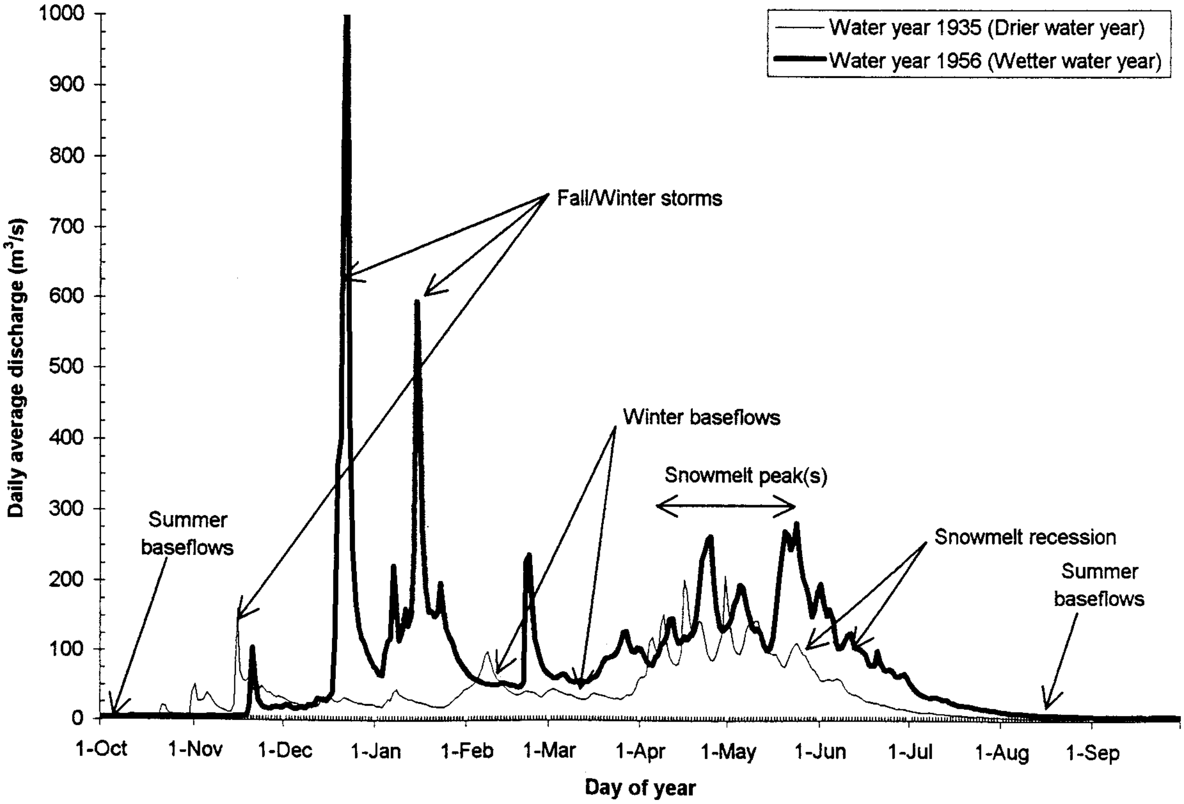

Fig. 2. Hydrograph components of an annual hydrograph by using 1956 (wetter year) and 1935 (drier year) unimpaired flows on the Trinity River in California.

Complex alternating bar sequences are partly created and maintained by providing the natural frequency and intensity of bed scour dependent on discharges that vary in magnitude and duration. During the rising limb of a hydrograph, after the bed surface begins to move, the rate of gravel transport rapidly increases and the bed surface begins to scour. The degree of scour can be significant, up to several feet deep. Infrequent, wet years typically generate storms with a high magnitude and long duration; scour depth will be substantial. On the receding limb of a flood hydrograph, gravel and cobbles redeposit, often resulting in no net change in channelbed elevation after the flood.

Attribute No. 5. ***Fine and coarse sediment budgets are balanced.*** *River reaches export fine and coarse sediment at rates approximately equal to sediment input rates.*

Although the amount and mode of sediment stored may fluctuate within a given river reach, channel-wide morphology is sustained in dynamic quasiequilibrium when averaged over many years. The magnitude and duration of high flows surpassing a flow threshold for channelbed mobility are critical for balancing the sediment budget. Chronic channelbed aggradation and/or degradation are indicators of sediment budget imbalances. A balanced coarse sediment budget implies bedload continuity; that is, the coarser particle sizes comprising the channel bed must be transported through alternate bar sequences.

Attribute No. 6. ***Alluvial channels are free to migrate.*** *During lateral migration, the channel erodes older flood plain and terrace deposits on the outside bend whereas it deposits sediment on the bar and flood plain of the inside bend. Although outer and inner bend processes may be caused by different hydrograph components, the long-term result is maintenance of channel width.*

Channel migration is one of the most important processes creating diverse aquatic and terrestrial habitats: Sediment and woody debris are delivered into the river and flood plains are rebuilt on the inside of the meander. That the stream has occupied numerous locations in its valley is evidenced by direct observations of its movement over time, and by indirect evidence obtained if one digs deeply enough into the flood plain. Gravel and cobbles laid down by the river many years before will be found. The channel does not typically migrate during periods of low flow, but migrates during flows approaching and exceeding bankfull discharge. Shear stress on the outside of bends exceeds that necessary to erode the materials on the outside of the bank. In lower gradient reaches of alluvial rivers, migration tends to be more gradual.

Attribute No. 7. ***Flood plains are frequently inundated.*** *Flood plain inundation typically occurs every 1–2 years. Flood plain inundation attenuates flood peaks, moderates alternate bar scour, and promotes nutrient cycling.*

As flows increase beyond that which can be contained by the bankfull channel, water spreads across the flatter flood plain surface. The threshold for this process is the bankfull discharge. This first threshold allows flow simply to spill out of the bankfull channel and wet the flood plain surface; a slightly larger discharge is required to transport and deposit the fine sediments that are in suspension. Flood plain inundation also moderates alternate bar scour in the mainstem channel by limiting flow depth increases within the bankfull channel during floods. As water covers the flood plain, flow velocity decreases. Sediment begins to settle, causing fresh deposits of fine sands and silts on the flood plain. This deposition promotes riparian vegetation regeneration and growth.

Attribute No. 8. ***Large floods create and sustain a complex mainstem and flood plain morphology.*** *Large floods—those exceeding 10- to*

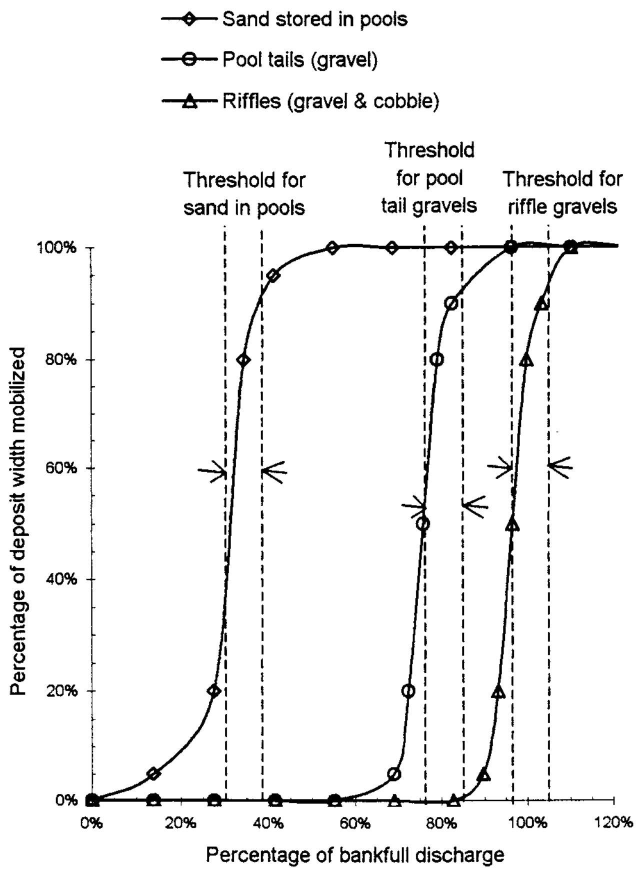

Fig. 3. Conceptual bed mobility thresholds, showing the narrow range in discharge that initially mobilizes the surfaces of selected alluvial features.

20-year recurrence events—reshape and/or redirect entire meander sequences, avulse mainstem channels, rejuvenate mature riparian stands to early successional stages, form and maintain side channels, scour flood plains, and perpetuate off-channel wetlands, including oxbows.

A still larger flow threshold than floodplain inundation is one that scours the flood plain. The streamflow necessary to surpass this threshold is typically many times the bankfull flow because shear stress on the vegetated flood plain surface must be high enough to cause scour. Infrequent large floods are critical for sustaining channel complexity because they change river location and morphology on a large scale and prevent riparian vegetation from dominating the river corridor.

Attribute No. 9. ***Diverse riparian plant communities are sustained by the natural occurrence of annual hydrograph components.*** *Natural, interannual variability of hydrograph components is necessary for woody riparian plant life history strategies to perpetuate early and late successional stand structures.*

Native riparian plant communities characteristic of alluvial river ecosystems are adapted to, and thus sustained by, a constantly changing fluvial environment. The magnitude and duration of annual hydrograph components needed for alternate bar scour, channel migration, floodplain inundation and scour, and channel avulsion provide necessary substrate conditions for successful seedling establishment and stand development. The timing and frequency of annual hydrograph components must coincide with seasonally dependent life history requirements, such as the short window of time when riparian plants are dispersing seeds. A sustainable supply of large woody debris from the riparian zone ultimately depends on variable age classes of woody riparian vegetation and a migrating channel.

Attribute No. 10. ***Groundwater in the valley bottomlands is hydraulically connected to the mainstem channel.*** *When flood plains are inundated, a portion of surface runoff from the watershed is retained as groundwater recharge in the valley bottomlands.*

The river corridor is hydraulically interconnected. Groundwater in the floodplain is closely connected to mainstem flows (5) and can be periodically recharged by mainstem flooding. Avulsed meander bends often create oxbow wetlands, which retain direct hydraulic connectivity to mainstem surface flows.

The alluvial river attributes can be used to recommend flow releases and other management activities below an existing dam. Although this strategy is being considered in other locations, we will use the Trinity River in Northern California as an example, where the recovery of Pacific salmon and steelhead trout is being linked with the overall goal of restoring an alluvial river ecosystem.

The Trinity River at Lewiston

The mainstem Trinity River in northern California was once an alluvial river capable of constantly reshaping its channelbed and banks. In 1963, the U.S. Bureau of Reclamation constructed a large storage reservoir and diversion tunnel to store and divert up to 90% of the natural streamflow from the Trinity River into the Sacramento River for power generation and agricultural/municipal water supply (6). Historically, Trinity River daily flows varied from less than 2.8 m^3/s baseflows in dry summers to near 2,800 m^3/s floods in wet winters. Snowmelt peak runoff and its recession limb were two critical annual hydrograph components generated upstream of Lewiston (Fig. 2). In wet years, snowmelt runoff typically peaked at 340 m^3/s or higher in late June or July, whereas in dry years the peak would only be 110 m^3/s or lower in mid-May through mid-June (7). Together they provided the magnitude and duration of flows needed to balance the sediment budget and accomplish a wide range of physical and biological processes. Both hydrograph components theoretically could have occurred at any time of the year and still have balanced the sediment budget. But seasonal timing of snowmelt runoff was critical to ecological processes.

Peak snowmelt runoff was an important environmental cue for juvenile salmonids to begin their migration to the Pacific Ocean (2). Amphibians needed snowmelt runoff to keep oxbow wetlands inundated. If the snowmelt recession limb did not extend into early June, the wetland might have dried out before amphibians could complete their aquatic life history stage. Interannual variability of timing, magnitude, and duration of snowmelt recession limbs determined whether a particular oxbow wetland could sustain an amphibian population. Successful cottonwood regeneration on freshly deposited floodplains also required specific snowmelt peaks and recession limbs to create favorable moisture conditions for seedling germination, as well as the absence of extreme winter storm events the following year to prevent seedling loss.

After the dam was completed, flows were kept nearly constant at 4.2 m^3/s; river managers thought that 4.2 m^3/s would provide ideal hydraulic conditions for chinook salmon spawning. What river managers did not foresee was that by eliminating hydrograph components they would set in motion a chain of predictable events. Seedlings, no longer scoured away by frequent winter and snowmelt floods, rapidly encroached onto the alternate bars. Prominent berms of freshly deposited sand and silt accumulated along the channel margins within the maturing dense riparian vegetation (Fig. 4), effectively isolating the floodplain from the mainstem river. High shear stresses of infrequent high flow events were then concentrated in the channel's center.

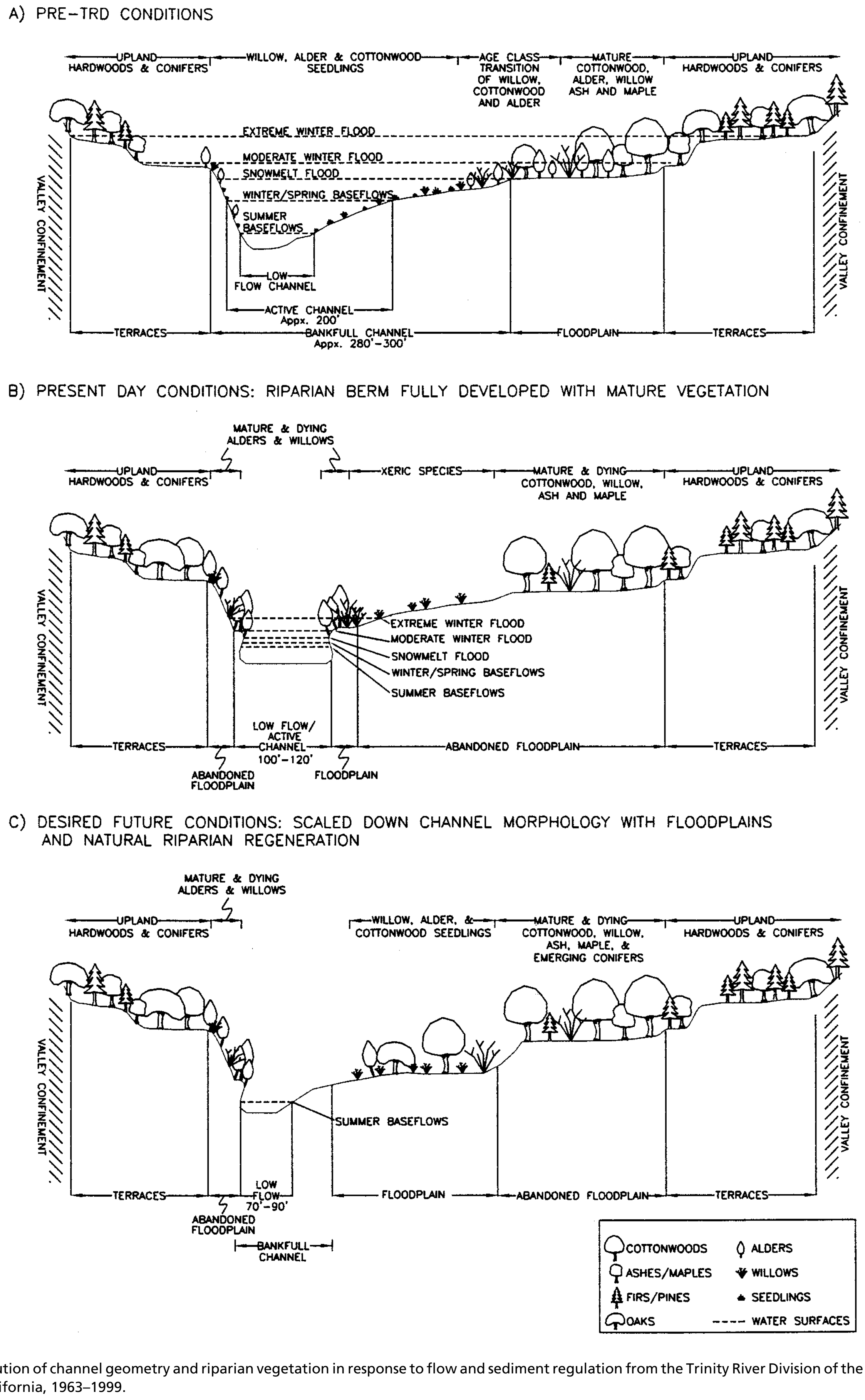

Fig. 4. Evolution of channel geometry and riparian vegetation in response to flow and sediment regulation from the Trinity River Division of the Central Valley Project in California, 1963–1999.

The river's complex alternate bar morphology was quickly transformed into a smaller, confined rectangular channel (Fig. 4) now unable to meander. Floodplains were abandoned. Cumulatively, this flume-like morphology and floodplain isolation greatly reduced habitat quantity and complexity important to numerous aquatic and riparian species.

Salmon populations were immediately and significantly affected. With most of their primary spawning and rearing habitat upstream of an impassable dam, the mainstem channel below Lewiston became the primary habitat provider. When young salmon emerge from spawning gravels as fry, their immediate habitat preference is for gently sloped, low velocity, exposed cobble areas typically found along predam alternate bar margins. In contrast, the vertical banks of the postdam channel allow excessive velocities to extend up to the banks' edges. Although the constant 4.2 m^3/s dam release temporarily accommodated spawning habitat needs, fry rearing habitat became a limiting factor to salmon production because of this rapid change in channel shape.

Was the widespread habitat loss in the Trinity River predictable? Managers who expected that spawning habitat would be preserved below the dams ignored the sediment budget (*Attribute No. 5*). Trinity and Lewiston dams prevent all bed material from passing downstream; the only sources for spawning gravels are downstream tributary inputs, minor flood plain scour, and occasional gravel introductions. The snowmelt peak and recession hydrograph components were completely eliminated (*Attribute No. 2*), even though this river ecosystem had been dominated by snowmelt runoff. Of the planned flow releases greater than 4.2 m^3/s, all were well below the threshold for mobilizing the channelbed (*Attributes Nos. 3* and *4*), routing bed load (*Attribute No. 5*), or inundating the floodplain (*Attributes Nos*. *7*, *8*, and *10*). Consequently, seedlings escaped being scoured and encroached onto the predam alternating bars (*Attribute No. 9*). Loss of the alternate bar morphology (*Attribute No. 1*) was inevitable; so was the loss of habitat created by it.

Was the widespread habitat loss on the Trinity River preventable? Anadromous salmonids cannot pass upstream of Lewiston Dam, therefore their habitat will never be completely replaced unless both dams are removed. The mainstem Trinity River below Lewiston Dam cannot be brought back to its original dimension. But a scaled-down alluvial channel morphology in equilibrium with its constrained sediment budget, reduced hydrograph components, and occasional bed material introductions could greatly restore habitat abundance and quality.

A new restoration approach for the Trinity River that is guided by the alluvial attributes is in its final planning stages. An environmental impact statement/report (6) includes this new restoration strategy, developed by the U.S. Fish and Wildlife Service and Hoopa Valley Tribe (2), as one fishery restoration alternative. The management goal would be to rebuild and maintain a self-sustaining alternate bar morphology and riparian community by using the attributes as a blueprint. Planned releases from Lewiston Dam would provide snowmelt peak and snowmelt recession hydrograph components (*Attribute No. 2*) to recreate physical processes that will recover an alluvial channel morphology (*Attributes Nos. 1*, *3*, *4*, and *6–8*) and sustain off-channel wetlands (*Attribute No. 10*). The sediment budget would be balanced by releasing appropriate hydrograph components with sediment transport capacities commensurate with sediment inputs (*Attribute No. 5*). If transport capacities exceed supply, as might occur during large flood releases in wet years, bed material would be introduced into the mainstem to compensate. Riparian berms on segments of fossilized alternating bars (in the upper 64 km) would be mechanically cleared as a precursor to reestablishing dynamic alternating bars (*Attribute No. 9*).

Conclusion

Society is embarking on a grand experiment. Recent dam removals are merely forerunners of a much larger task ahead. Many more dams will remain than are removed. In practice, we must rely on the crucial assumption that native species have evolved with the natural flow regime. Violating this assumption often results in consequences that can be highly significant and difficult to reverse. The intent to recover alluvial river ecosystems below dams, as proposed for the Trinity River in northern California, will be controversial. To obtain the societal benefits of water diversion, flood control, and hydropower generation, rivers will continue to receive less flow and sediment than under unimpaired conditions. But if important attributes are provided to the greatest extent possible, alluvial river integrity can be substantially recovered. The compromise will be a smaller alluvial river; it may not recover its predam dimensions, but it would exhibit the dynamic alternate bar and floodplain morphology of the predam channel. Although a restoration strategy guided by the alluvial attributes is an experiment, it may be the most practical direction toward recovering regulated alluvial river ecosystems and the species that inhabit them.

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