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RESEARCH ARTICLE

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Estimating catchment-scale sediment storage in a large River Basin, Colorado River, USA

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Abstract

Catchment-scale sediment storage is conceptualized as increasing in magnitude downstream, although reach-scale controls may override this trend. We use empirical data from a literature review and two numerical models to quantitatively estimate sediment storage across the Colorado River Basin, USA. We use assumed alluvial thickness with floodplains delineated in the GFPLAIN model from 30 m digital elevation models. We use the SWAT+ model based on model-estimated (i) groundwater storage and (ii) sediment storage. Existing studies indicate that sediment stored in floodplains and on low terraces is ~0.3–6 m thick. A first-order approximation of volumetric storage capacity for natural floodplains is ~10^5 m^3 per km. Sediment storage volumes of floodplains are ~10^8–10^{11} m^3 over river lengths of 10^1–10^3 m. For the modeling estimates, we evaluated sediment storage by stream order and by elevation band within the Upper and Lower Colorado River Basins. Comparisons among the outputs cause us to place more confidence in the GFPLAIN and SWAT+ aquifer volume estimates. Each method includes substantial uncertainty and constitutes a first-order approximation. Results suggest using 21 and 130 billion cubic meters as approximate lower and upper bounds for total sediment storage in the Upper Basin and 314 and 482 billion cubic meters as approximate lower and upper bounds for the Lower Basin. The largest proportion of sediment is stored in the montane and steppe zones in the Upper Basin and in the Sonoran zone in the Lower Basin.

KEYWORDS

alluvial volume, floodplain, GFPLAIN, groundwater, SWAT+

1 | INTRODUCTION

1.1 | Catchment-scale sediment storage patterns

River corridors, which include the active channel, surrounding floodplain, and underlying hyporheic zone, are complex landscapes that can attenuate downstream fluxes of water, sediment, and other material via storage over varying lengths of time (Covino, 2017; Harvey & Gooseff, 2015; Wohl, 2016, 2021; Wohl et al., 2018; Wohl & Scott, 2017). Specifically, sediment is stored both on the floodplain because of overbank deposition and floodplain construction (e.g., Nanson, 1986; Nanson & Croke, 1992; Wohl, 2021) and/or on the channel bed and margins through bed aggradation (e.g., Topping et al., 2000), bar building (Wheaton et al., 2013; Wohl & Scott, 2017), and eddy deposition (e.g., Mueller et al., 2014).

Sediment storage is broadly conceptualized at the catchment scale as increasing in magnitude downstream, as channel gradient and stream power decline in the predominantly depositional zone of the catchment (Church, 2002; Schumm, 1977). Upstream portions of the river network are more likely to include steeper, more laterally confined river corridors with greater transport capacity, containing predominantly sediment production and transport regions (Montgomery & Buffington, 1997). However, reach-scale controls, including valley-floor lateral confinement, tributary confluences, and disturbance regime, may complicate or override generalizable catchment-scale trends (e.g., Kuo & Brierley, 2013; Macnab et al., 2006; Rice, 2017; Sutfin & Wohl, 2019). Quantitative estimation of catchment-scale sediment storage patterns thus requires an approach capable of incorporating the various topographic and morphologic parameters that influence storage.

Quantitative perspectives and knowledge of sediment storage inform catchment-scale management. Understanding the spatial distribution and relative magnitudes of storage can help managers anticipate patterns of river response following disturbances that increase sediment supply. Because channel adjustments occur heterogeneously throughout river networks as a function of sediment accumulation locations (Czuba & Foufoula-Georgiou, 2015; Fryirs & Brierley, 2001; Jacobson & Gran, 1999; Nelson & Church, 2012), better delineation of the general distribution of sediment accumulation zones can provide insight into where adjustments and alterations may most readily occur (e.g., Collins et al., 2017; Kemper, Rathburn, et al., 2022; Kemper, Thaxton, et al., 2022; Mukundan et al., 2012). Conversely, zones of substantial sediment storage may represent prime sediment source areas during disturbances that enhance sediment transport capacity (e.g., Hazel et al., 2006; Meade, 1982; Walter & Merritts, 2008).

Knowledge of the spatial arrangement of sediment source and sink zones within a catchment can also inform river restoration. River corridors have been drastically altered worldwide (Peipoch et al., 2015; Tockner & Stanford, 2002), resulting in a reduced ability to modulate downstream fluxes via storage (Wohl, 2021). An increasing focus on process-based restoration (Beechie et al., 2010; Ciotti et al., 2021; García et al., 2021) seeks to restore the dynamic hydrologic, geomorphic, and ecological processes inherent in river corridors, including sediment storage (Bernhardt et al., 2007; Norman et al., 2022; Wohl et al., 2015). This commonly corresponds to an increasing focus on the related concept of natural infrastructure, or the management and restoration of natural areas or elements that facilitate dynamic, natural river processes that provide crucial services such as storage and attenuation of downstream fluxes (Nesshöver et al., 2017; Norman et al., 2022; Skidmore & Wheaton, 2022; van Rees et al., 2022). Both process-based restoration and natural infrastructure support the foundational philosophy to "work with the river" (Brierley & Fryirs, 2022; Fryirs & Brierley, 2021). An improved awareness of the spatial distribution of sediment storage volume can enhance our understanding of the geographic context of process-based restoration projects and natural infrastructure approaches (Wohl et al., 2024) and better inform their placement, design, and focus.

Catchment-scale sediment transport modeling can be used to understand the spatial distribution of sediment storage (e.g., Czuba & Foufoula-Georgiou, 2015; Murphy et al., 2019), but this approach can be computationally intensive. Alternatively, empirical data can be used to estimate sediment volumes using data on the spatial distribution and abundance of river corridor segments based on stream order and floodplain area. Here, we take a hybrid approach: we use empirical data and limited, relatively simple numerical modeling to quantitatively estimate sediment storage across a large river catchment with notably heterogeneous climate, geology, and geomorphology. Our primary objective is to estimate sediment storage across the Colorado River Basin in the western United States, utilizing publicly accessible datasets, published algorithms and scaling relations, and a synthesis of available literature.

1.2 | The Colorado River Basin

Flow in the mainstem Colorado River and many of its tributaries is highly regulated for water storage, transbasin diversions, and hydroelectric power generation, and the catchment is categorized as strongly impacted by flow regulation in the global assessment of Nilsson et al. (2005). Climate projections indicate the potential for increased drought and decreasing precipitation across much of the catchment (e.g., Udall & Overpeck, 2017), even as human population and consumptive water demand continue to grow rapidly in the region (Hung et al., 2022; Richter, 2022). The presence of multiple endangered species (Bottcher et al., 2013), increasing risk of disturbances in the form of wildfire (Dennison et al., 2014), drought (Woodhouse et al., 2016), and floods (McCoy et al., 2022), and expanding resource extraction have led to growing pressure for management that can enhance river and catchment resilience (Anderies et al., 2020; McCluney et al., 2014). Although river resilience can be defined in different contexts, a key component of resilience is how river networks and corridors attenuate disturbance-related downstream fluxes of water and sediment (e.g., Norman et al., 2022; Rathburn et al., 2018). It is in this context that we develop spatially distributed estimates of sediment storage within the Colorado River Basin.

We first review existing knowledge of sediment storage within the Colorado River Basin and how it informs our estimations. We then present our analysis and examine emergent trends and systemic variations. Finally, we discuss the implications of our work for understanding catchment-scale sediment storage and suggested future work. Although we concentrate on the Colorado River Basin to provide context for management approaches within one of the most extensively regulated catchments in the world, this approach to storage estimation can be employed in other river catchments to examine storage volumes and patterns.

2 | STUDY AREA

The Colorado River drains 640,000 km^2 of the western United States and Mexico, flowing from headwaters in the Rocky Mountains of Wyoming and Colorado through the Sonoran Desert to its outlet in the Pacific Ocean at the Gulf of California (Figure 1), although the river now rarely reaches the ocean because of extensive flow withdrawals along its course. The catchment is arid or semiarid, with the mean annual precipitation of 300 mm, although precipitation varies substantially with elevation, from 1500 mm in headwaters to <50 mm at the river's mouth. Both precipitation and stream flow show high interannual variability. Naturally occurring peak annual flow is dominated by spring–summer snowmelt from the Rocky Mountains (Wohl & Lininger, 2022), but precipitation also falls throughout the catchment as winter frontal storms from the North Pacific, dissipating Pacific tropical cyclones, and local convective thunderstorms (Ely et al., 1993) and peak annual flow in highly regulated reaches can vary seasonally with flow manipulations.

From the headwaters in Precambrian-age crystalline lithology in the Rocky Mountains, the river network crosses relatively undeformed, Paleozoic- to Cenozoic-age sedimentary rocks on the Colorado Plateau, and then descends into the alluvial basins and crystalline mountains of the Sonoran Desert and the Basin and Range. Prior to substantial human alteration of the catchment, the Colorado River delivered $\sim 1.00 \times 10^8$ Mg of sediment annually to its delta (Meade et al., 1990). Most of the gravel-size and finer sediment originates from the Colorado Plateau and sediment concentration increases downstream as the river and its tributaries flow from the water-producing Rocky Mountains to the sediment-producing lower, drier terrain of the catchment's interior (Schmidt et al., 2022). Substantial sediment is now trapped and stored behind the 19 large dams (>20 m tall) within the catchment (Graf, 1985). The entire sediment load of the Upper Basin is now trapped behind a series of very large dams on the mainstem and primary tributaries, including Flaming Gorge Dam (completed 1964), Navajo Dam (completed 1962), and Glen Canyon Dam (completed 1963). Dams in the Lower Basin largely preclude any sediment delivery to the delta (Schmidt et al., 2022).

River corridor morphology also varies substantially, from steep, laterally confined headwaters in the mountains, through deep, narrow canyons on the Colorado Plateau, into broad alluvial basins in the

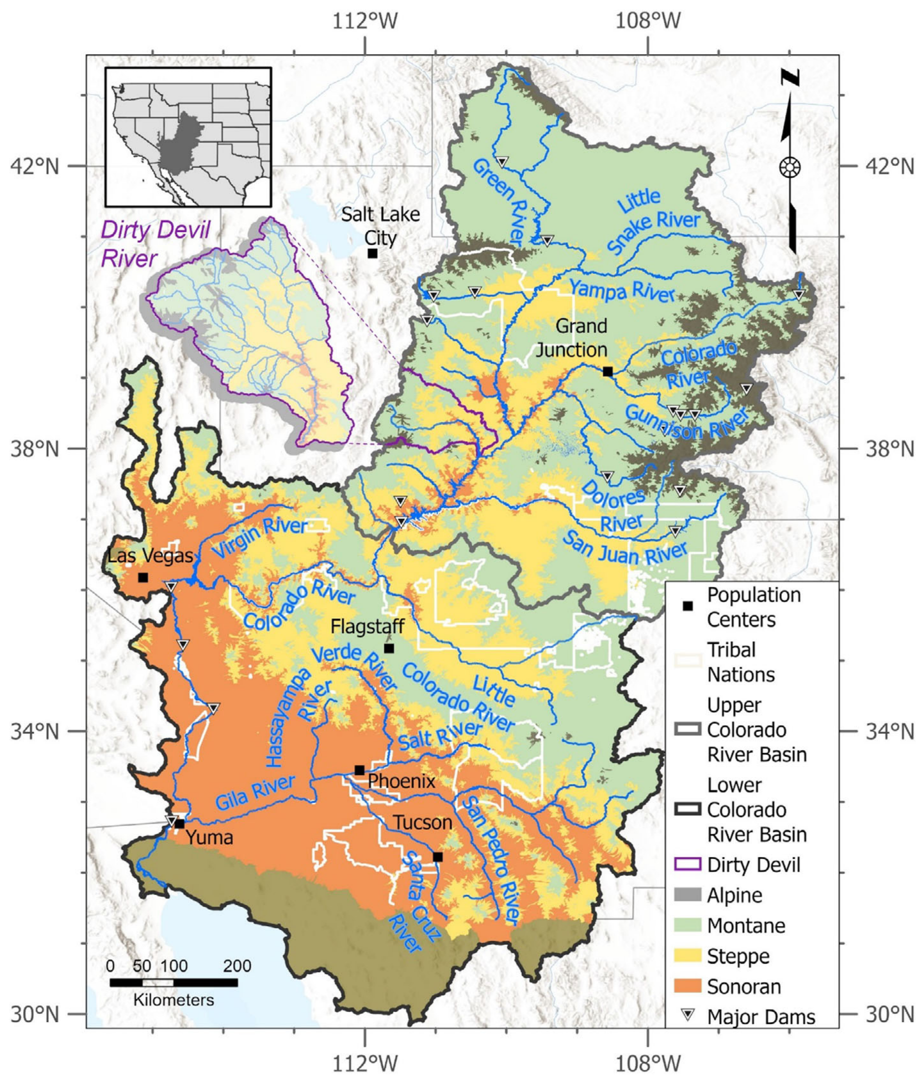

FIGURE 1 The Colorado River Basin with major rivers, elevation bands (alpine, steppe, montane, Sonoran), and delineated sub-basins (Upper and Lower). The southernmost brown portion of the catchment is in Mexico, where hydrography and elevation are not available at equivalent resolution; this portion of the catchment was not included in analyses. Inset shows the Dirty Devil River basin, where sensitivity analysis was performed. [Color figure can be viewed at wileyonlinelibrary.com]

lower catchment. Although many of the larger tributaries in these lower elevation basins were historically perennial, consumptive water use during the 20th and 21st centuries made the rivers ephemeral (Blinn & Poff, 2005; Goodrich et al., 2018; Webb et al., 2014), so that sediment transport now occurs episodically.

The Colorado River catchment is commonly administratively divided into the Upper and Lower Basins (Figure 1), with the dividing point at Lee Ferry, Arizona (Schmidt et al., 2022). The Upper Basin drains ~285,000 km^2 and the Lower Basin ~355,000 km^2.

3 | METHODS

In addition to the Upper and Lower Basins, we distinguished four elevation bands within each basin (Figure 1). The elevation bands are based on internally similar hydrology, topography, climate, and vegetation that influence stream flow and sediment dynamics: (1) the alpine and subalpine (>2840 m above sea level) includes the mountainous headwaters; (2) the montane (2840–1830 m) generally contains the upper reaches of the catchment's major tributary rivers (the Yampa, Upper Green, Gunnison, Upper Colorado, and Big Sandy Rivers); (3) the steppe (1830–1370 m), which includes the Colorado Plateau rivers (Dirty Devil, San Juan, and Little Colorado Rivers); and (4) the Sonoran (<1370 m), with primarily ephemeral and intermittent rivers.

We used three approaches to constrain sediment storage within the Colorado River catchment: (i) review existing published literature summarizing sediment storage; (ii) use the GFPLAIN model to delineate 100-year floodplains from existing digital elevation models (DEMs) and assumed alluvial thickness, as constrained by the literature review; and (iii) use the SWAT+ model to quantitatively estimate sediment storage.

3.1 | Literature review

We conducted a keyword-based literature search of common databases (Google Scholar, Web of Science), with keywords (Table S1) chosen to identify studies that examined sediment storage or storage-related processes within sub-catchments of the Colorado River. The search was non-restrictive in terms of date of publication. Of note, the literature reviewed relied primarily on field-based estimates rather than numerical modeling studies.

3.2 | GFPLAIN modeling

We created a 100-year hydrogeomorphic floodplain model using GFPLAIN at a 30-m resolution (Knox et al., 2022; Nardi et al., 2019) in ArcGIS Pro (ESRI Inc., 2020). The GFPLAIN algorithm uses terrain analysis techniques to extract the stream network from a digital terrain model. Each drainage network cell is assigned the maximum potential flow depth, in this case for the 100-year return interval flood, by adopting a power law based on contributing drainage area as a scaling parameter. The GFPLAIN algorithm produces a gridded floodplain layer by flagging low-lying cells along river corridors. The algorithm recognizes the floodplain extent as formed by those cells draining to the selected channel location that is characterized by elevations that are lower than the corresponding maximum channel flow level. Catchments are initiated at a minimum drainage area of 10 km^2.

We initially created a floodplain shapefile for the Upper Basin and one for the Lower Basin. The floodplain area procedure divides the GFPLAIN floodplain shapefile into polygons of equal areas of 0.01 km^2. The resulting polygons are joined with other existing shapefiles to give them a value for stream order and elevation. The stream order and elevation information are then used to calculate an area sum for each stream order in each elevation band using similar methods as Wohl and Knox (2022). See Figure S1 for GFPLAIN workflow.

The accuracy of this approach is limited by the original methods used to create centerlines and transects, but visual assessment indicated that most floodplain areas are accurately captured. A much larger source of uncertainty results from use of 30-m resolution digital elevation data and 10 km^2 catchment minimum area, which precludes inclusion of first- to third-order streams. Consequently, we used the GFPLAIN output for floodplain area on fourth-order and larger channels. For first- to third-order streams, we used the lengths of first-, second-, and third-order channels in the NHD+ database (the US Geological Survey's National Hydrography Dataset) and a global dataset of channel width (Downing et al., 2012). This dataset has median channel width values of 1.6, 1.9, and 5.5 m, respectively, for first-, second-, and third-order channels. Based on personal field experience with small channels throughout the Colorado River catchment, we doubled channel width to estimate floodplain width for first- and second-order streams (3.2 and 3.8 m, respectively) and tripled channel width (22 m) for third-order streams. These estimated areas were combined with the GFPLAIN data. (We did not use channel width values from the NHD+ database because of missing values for low-order streams. Using the Dirty Devil River catchment within the Colorado River Basin, for example, channel width values are available for only 68% of the stream segments and most of these values are for higher-order stream segments.) Global channel length data suggest that first- and second-order channels constitute 70%–80% of total channel length in any river network (Downing et al., 2012), but comparable estimates for floodplain area are not available at regional or global scales.

Finally, we estimated sediment thickness in relation to stream order and elevation band, as informed by the literature review and by personal field experience in the Colorado River catchment (Table S2). Use of a single value, even with uncertainties, for each stream order within each elevation band reflects a simplification and the resulting sediment volumes should most appropriately be regarded as order-of-magnitude estimates.

We also conducted a sensitivity analysis on the effect of DEM spatial resolution and minimum catchment area. We analyzed the Dirty Devil River Basin (11,329 km^2) in the Upper Colorado River

Basin using both 10 m and 30 m DEMs and a minimum catchment area of 1 km^2 (we note that where 1 m- or sub-meter scale lidar data are available, a similar analysis would require months of computational time).

3.3 | SWAT+ modeling

The soil and water assessment tool (SWAT) is a river-catchment-scale hydrologic model developed to quantify the impact of land management practices and climate on hydrological processes in large, complex river catchments (Arnold et al., 1998). To prepare a SWAT model, the catchment is divided into sub-basins and hydrologic response units (HRUs), with each HRU representing a spatial area that is a unique combination of soil type, land use type, and topographic slope within the catchment. Each HRU is composed of a soil profile with multiple soil layers and an underlying aquifer. The physically distributed model computes fluxes (evapotranspiration, surface runoff, percolation, soil lateral flow recharge, groundwater discharge) for each HRU within the river catchment on a daily time step, then aggregates the outflow fluxes (surface runoff, soil lateral flow, groundwater discharge) to sub-basin outputs based on the spatial fraction of the HRUs, and finally routes sub-basin outputs through a river reach within the channel network.

In this study, we use SWAT+ (Bieger et al., 2017), a revised version of SWAT that uses the same basic algorithms to calculate processes but allows for a more accurate representation of channels and hydrologic connections. Whereas SWAT uses a single channel per sub-basin, SWAT+ can use any number of channels, given their connection information. In addition, we use a new groundwater module for SWAT+, *gwflow* (Bailey et al., 2020), which simulates groundwater storage and flow within unconfined aquifers in a physically based, spatially distributed manner, in contrast to the simplistic linear reservoir approach of SWAT and SWAT+. The *gwflow* module uses a grid cell approach to discretize the unconfined aquifer into discrete aquifer control volumes, with each cell interacting with HRUs and channels through recharge and groundwater-channel exchange. The *gwflow* module is called a subroutine within the SWAT+ code, allowing for efficient exchange of water between the surface, soil, and aquifer systems.

The SWAT+ model of the United States portion of the Colorado River uses the following inputs (spatial resolution in parentheses after each): land use (NLCD; 30 m), soil type (Gridded Soil Survey Geographic; 10 m), topographic elevation (USGS National Elevation Dataset; 10 m), channels and reservoirs (NHDPlus, Moore & Dewald, 2016), cultivated fields (Yan & Roy, 2016), and floodplain. For the *gwflow* module, inputs include aquifer thickness (ground surface to bedrock; 250 m; Figure S2; Shangguan et al., 2017), hydrogeologic unit boundaries and properties (Horton, 2017), and initial groundwater head (Bailey & Alderfer, 2022). For a detailed explanation of SWAT+ model construction and *gwflow* spatial connections, see Bailey et al. (2023). For this study, we used 500-m grid cells for the *gwflow* module. The SWAT+ model is in fact a collection of 134 sub-models, one for each eight-digit catchment within the Colorado River Basin. The models are connected by using the downstream flow from an upstream catchment as inflow into a downstream catchment, for each connected catchment. Model outputs include stream flow for each channel, groundwater head and storage for each grid cell, and maps of groundwater fluxes (surface-subsurface hydrologic exchanges, recharge, groundwater pumping for irrigation). The SWAT+ model for the Colorado River Basin was run for the period 1 January 2000 to 31 December 2015.

In the context of this study, we used two methods to estimate sediment storage from SWAT+ outputs. The first method is based on model-estimated groundwater storage using the average annual groundwater heads from the years 2000 through 2015 and the formula, $storage = specific\ yield{*}area{*}(groundwater\ head - bedrock)$. Groundwater storage is expressed in cubic meters, which can be interpreted as a minimum estimate of the associated volume of the alluvial aquifer. Because this approach uses 500-m grid cells, we did not consider estimates from first- to third-order streams, for which this spatial resolution is too coarse to be accurate.

The second method is based on sediment storage directly estimated by SWAT+. In this method, sediment transport in each channel is a function of erosion and deposition, simulating downcutting and widening of the stream channel throughout the simulation. Erosion or deposition of sediment in the channel can occur depending on the stream power, the exposure of the channel sides and bottom to the erosive force of the stream, and the composition of channel bed and bank sediment. Total sediment generated in a channel equals the sum of suspended sediment load, headcut erosion, bed erosion, and bank erosion. The mass of sediment stored in the channel versus that routed to a downstream channel is directly proportional to the volume of water being stored or routed, based on the comparison of the computed channel routing time to the daily time step (SWAT+ uses a fixed daily time step throughout the simulation). We converted the SWAT+ output for sediment, which is in metric tons, to cubic meters by using the average density of granite (2.65 g/cm^3).

4 | RESULTS

4.1 | Literature review

We identified 31 publications that included information on sediment storage or accumulation rates in the Colorado River Basin. These studies (Figure S3; Table S3) are relatively well-distributed across elevation bands and reveal three primary findings. First, as might be expected, sediment storage is generally greater in wide, alluvial river reaches and these areas can be most effectively targeted for nature-based storage restoration projects. This is explicitly illustrated by inter-reach differences in a few of the reported storage values (e.g., Grams & Schmidt, 2005). Several additional studies that do not make storage estimations include a general discussion of the greater storage potential of wide reaches (e.g., Dean & Topping, 2019; Pearthree, 1993; Topping et al., 2018).

Second, although studies exist that report estimated ages and thicknesses of sediment in the Colorado River catchment, the resulting information is spatially uneven and inconsistent with respect to parameters measured and units reported. Much of the southeastern portion of the Upper Basin and northeastern, southwestern, and far western portions of the Lower Basin remain understudied (Figure S3). In addition, most studies that delineate and describe valley sediment do not estimate total volume in storage. Of note, we did not include any of the robust sand budget work undertaken in Grand and Marble Canyons (e.g., Grams et al., 2019; Topping et al., 2021) in our review, as these studies explicitly focus on the sand fraction of sediment load/storage, whereas we make no such grain-size-based distinction.

Third, we found almost nothing that evaluated sediment storage created by human manipulations designed to mimic natural storage. These types of projects exist, but they are poorly documented in publicly identifiable or accessible records. This problem is not unique to the Colorado River catchment or to nature-based storage: A comprehensive database of river restoration does not exist for the United States as a whole or for any region of the country.

With the important caveats noted earlier, the existing literature indicates that sediment stored in natural floodplains is $\sim 10^1$ m thick, and alluvium deposited both on the present-day floodplain and on low terraces ranges from ~0.3 to 6 m thick. Studies that estimate alluvial volumes indicate that a first-order approximation of volumetric storage capacity for natural floodplains is $\sim 10^6$ m^3 at the reach scale (10^5 when normalized per km). When normalized by time (i.e., per year) and length (i.e., per km), estimates of annual deposition rates range from 10^3 to 10^6 m^3/km/yr. At larger spatial scales, sediment storage volumes of natural floodplains are $\sim 10^8$–10^{11} m^3 over river lengths of 10^1–10^3 m.

4.2 | GFPLAIN modeling

The NHD+ data indicate that the Colorado River catchment reflects global patterns, with first- and second-order streams constituting the great majority of total channel length (Figure S4). The GFPLAIN modeled distribution of floodplain area by stream order and elevation band in the Upper and Lower Basins (Figure 2) suggests that river corridors in the alpine and subalpine zones make only minor contributions to total floodplain area in the Colorado River catchment. The Upper Basin has the greatest floodplain area in fourth-order rivers of the montane zone and fourth- to sixth-order rivers in the steppe zone. The Lower Basin has the greatest floodplain area in fourth- and fifth-order rivers in the Sonoran zone.

The estimated sediment storage in the Upper and Lower Basins as calculated from the GFPLAIN floodplain area and assumed sediment thicknesses (Figure 3, Table S4) indicates that more sediment is stored in the Lower Basin, which likely reflects the presence of the large alluvial basins, such as those underlying major metropolitan areas including Phoenix, Tucson, and Las Vegas. Within the Upper Basin, the steppe elevation band includes the greatest existing sediment storage, primarily in fourth- to seventh-order streams. Within the Lower Basin, the Sonoran elevation band has by far the greatest sediment storage, primarily in fourth- to ninth-order streams.

The sensitivity analysis using 10 m DEMs and a 1 km^2 catchment threshold for the Dirty Devil River Basin (Figure 4; Table S5) indicates that the main analysis underestimates total floodplain area and associated sediment storage, as expected. The total floodplain area estimated using the finer spatial resolution analysis is 118% of the floodplain area estimated using the main analysis (30 m DEM and

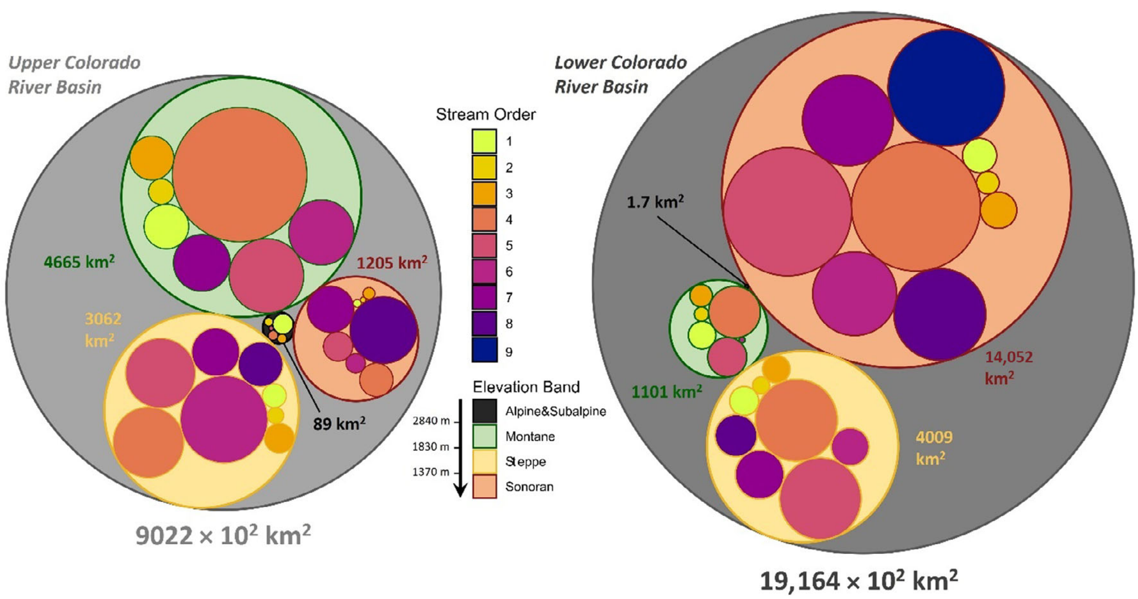

FIGURE 2 Distribution of floodplain area by stream order in the Upper and Lower Colorado River Basins. The numbers reflect the total floodplain area in each category of stream order and elevation band. Note that the inner circles indicating the distribution of floodplain area by stream order are scaled proportionally to the total floodplain area in each band. [Color figure can be viewed at wileyonlinelibrary.com]

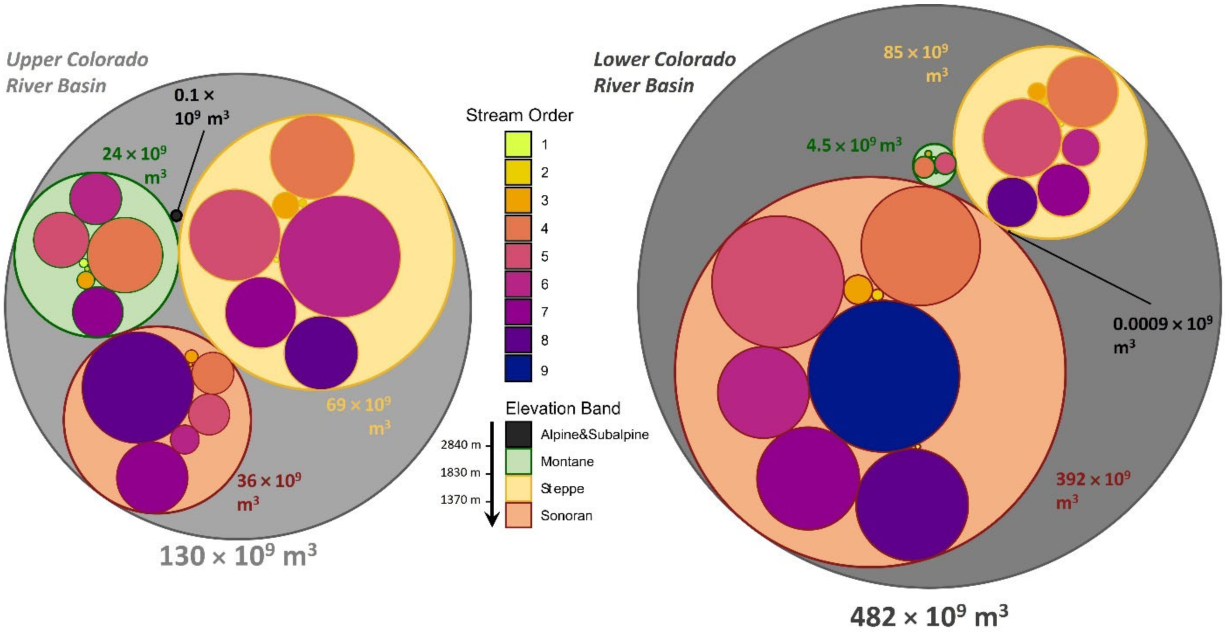

FIGURE 3 Illustration of current sediment storage by stream order and elevation band with the Upper and Lower Colorado River Basin, as estimated from GFPLAIN and assumed sediment thickness values. [Color figure can be viewed at wileyonlinelibrary.com]

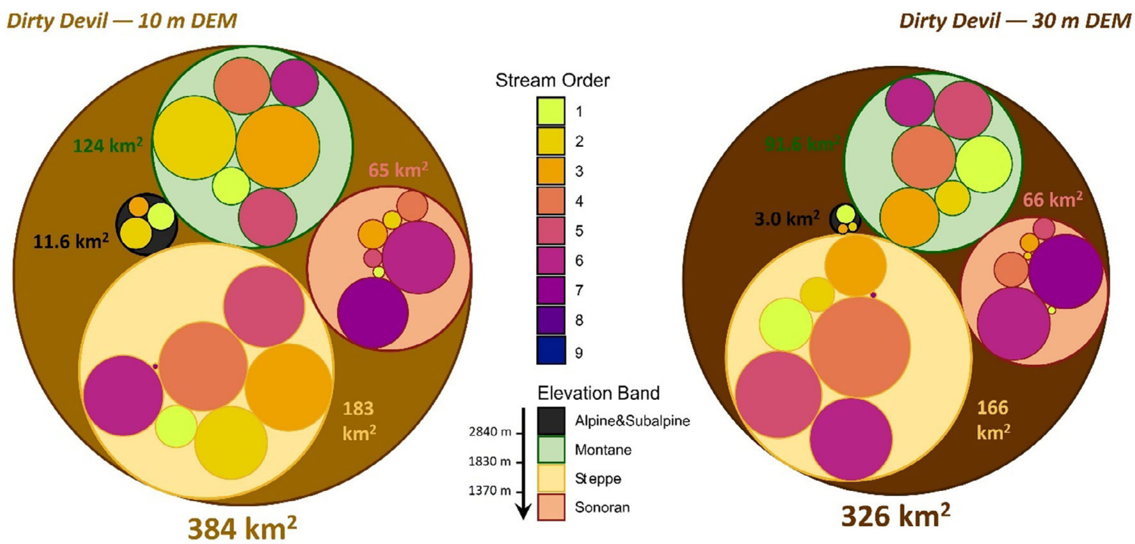

FIGURE 4 Differences in estimation of floodplain area by stream order and elevation band in the Dirty Devil River Basin of the Upper Colorado River based on 10 m (left) and 30 m (right) digital elevation models (DEMs)s, both using 1 km^2 catchment minimum area. [Color figure can be viewed at wileyonlinelibrary.com]

10 km^2 catchment threshold). The greatest differences between the analyses appear in the alpine/subalpine and montane zones.

4.3 | SWAT+ modeling

As noted in the Methods, estimated sediment storage can be obtained from SWAT+ modeling via either groundwater storage (Figure 5) or directly estimated values (Figure 6). The aquifer volumes suggest nearly 15 times as much total sediment storage in the Lower Basin relative to the Upper Basin. The montane and steppe zones store nearly equal sediment volumes in the Upper Basin, with the greatest storage along fourth-order montane streams and sixth- order steppe streams. The Sonoran zone stores most of the sediment in the Lower Basin, with sediment distributed primarily between fourth- and sixth-order streams.

The directly estimated values suggest twice as much sediment storage in the Lower Basin relative to the Upper Basin. The montane

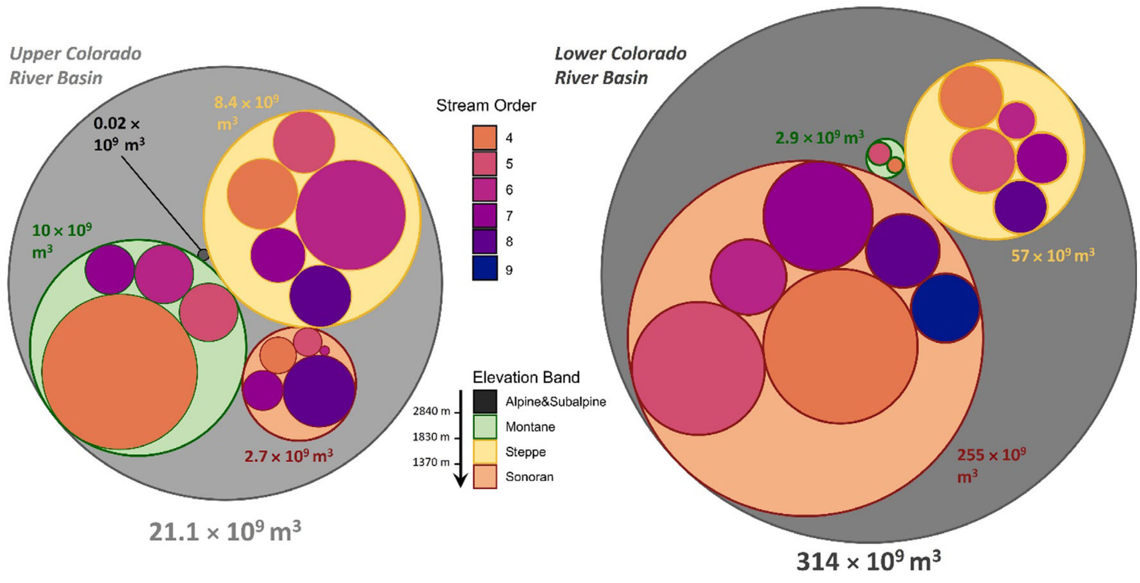

FIGURE 5 Illustration of current sediment storage by stream order and elevation band within the Upper and Lower Colorado River Basin, as estimated from SWAT+ aquifer volume. Note that first- to third-order streams are not included because of the spatial resolution used in this portion of the SWAT+ model. [Color figure can be viewed at wileyonlinelibrary.com]

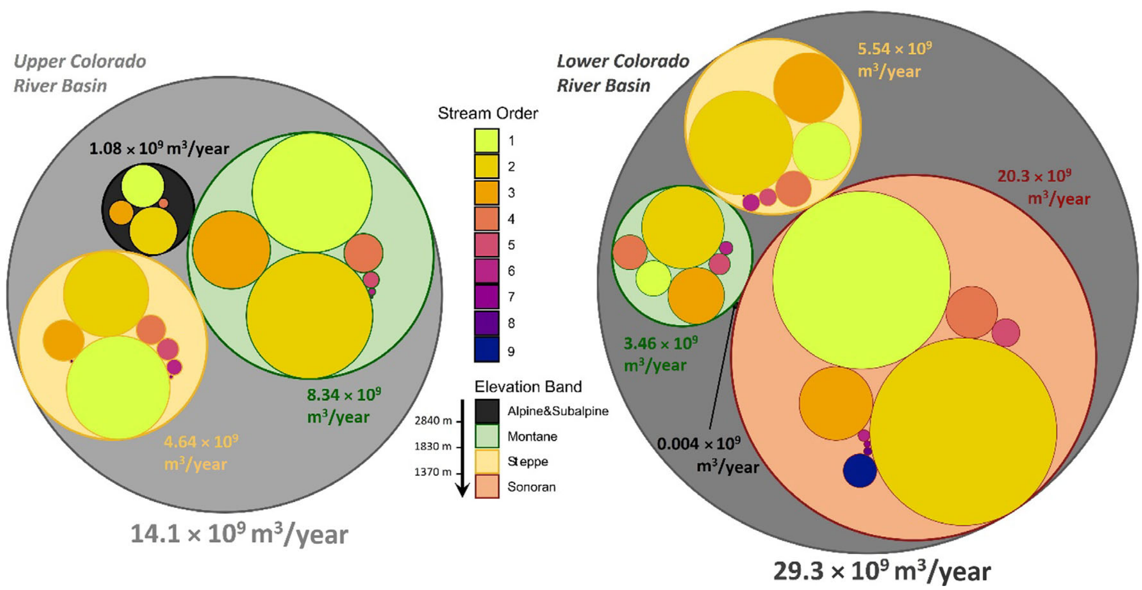

FIGURE 6 Current sediment storage by stream order and elevation within the Upper and Lower Colorado River Basin, as estimated from SWAT+ direct calculations. [Color figure can be viewed at wileyonlinelibrary.com]

and steppe zones store most of the sediment in the Upper Basin, with the montane zone storing roughly twice as much as the steppe zone. First- and second-order channels store much of the sediment in the montane and steppe zones in the Upper Basin and in the Sonoran zone in the Lower Basin.

Figure 7 provides a comparison of all three methods of estimating sediment storage. In the Upper Basin, the GFPLAIN method results in six times greater estimated sediment storage than the SWAT+ aquifer method and nine times greater sediment than the directly calculated SWAT+ values. The SWAT+ aquifer estimate for the Upper Basin is nearly twice that of the directly estimated sediment, which is interesting given that the directly estimated values include first- to third-order channels and the aquifer volume does not. The GFPLAIN estimates also indicate most of the sediment stored in the steppe zone, whereas both SWAT+ estimates have sediment more equally distributed between the montane and steppe zones.

In the Lower Basin, GFPLAIN and SWAT+ aquifer create more closely matched total sediment volumes, with most of the sediment in the Sonoran zone along fourth- and fifth-order streams. GFPLAIN suggests that sediment is more evenly distributed among fourth- to

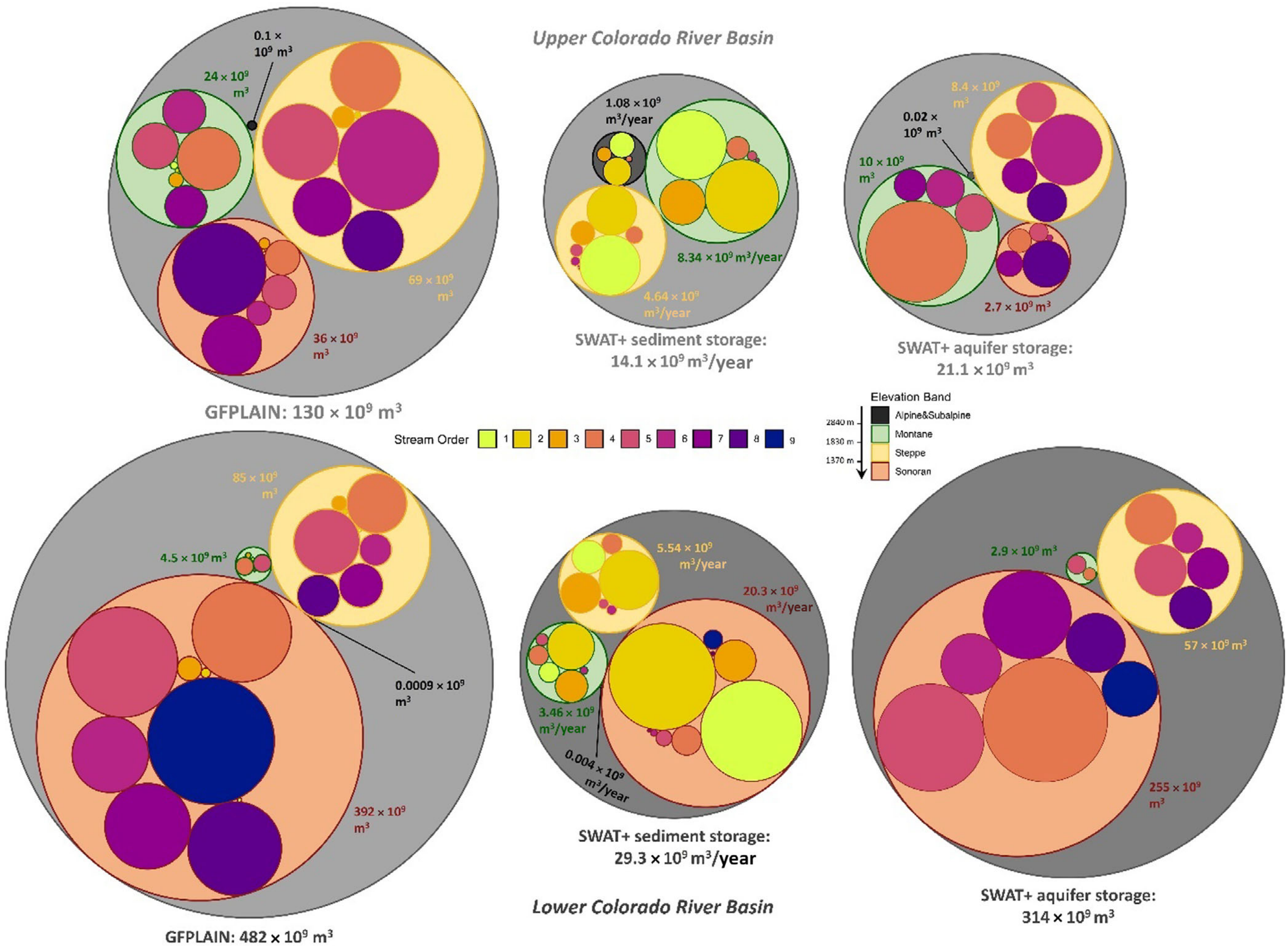

FIGURE 7 Estimated current sediment storage in the Upper and Lower Colorado River Basins using three different approaches. [Color figure can be viewed at wileyonlinelibrary.com]

eighth-order streams, whereas SWAT+ aquifer has sediment primarily in fourth- and fifth-order streams. The SWAT+ direct calculations suggest substantially lower total sediment volume than either of the other methods but match the other methods in suggesting sediment storage primarily in the Sonoran zone.

5 | DISCUSSION

5.1 | Literature review

The literature review of sediment storage in the Colorado River catchment revealed substantial gaps in knowledge for anything beyond first-order approximation of storage distribution (Figure S4). Particularly noteworthy is the absence of scaling relations for valley-fill depth in relation to stream order or drainage area. Although the geographic coverage of sediment studies is fairly extensive, the distribution of studies that explicitly examine storage volumes (e.g., Godfrey et al., 2008) is more uneven, especially within the higher (alpine and subalpine) elevations of the Upper Basin and montane regions of the Lower Basin (Arp & Cooper, 2004).

There are also notable inconsistencies across the Colorado River Basin in both the metrics measured and the units in which they are reported. These inconsistencies preclude a more precise synthesis and regionally robust quantitative understanding of sediment storage. Many studies report raw values rather than normalized by space (per length, area, etc.) or time (per year). Some studies report mass, some volume, and some thicknesses. Although reported data can be transformed to normalize values or achieve unit equivalency, this may misrepresent trends or findings. Future work that expressly quantifies sediment volumes in units normalized by floodplain area will facilitate metanalysis, as will studies that quantify mass of sediment and report bulk density of the sediment. The regionally representative equation derived by Graf (1987) for cumulative volume of sediment stored as a function of drainage area (Equation 1) may have substantial potential for consistent approximations of stored sediment volume, and future work could productively compare this established relation to surveyed sediment volumes. Graf (1987) suggests that cumulative volume of sediment stored in each area can be related by the following equation:

$$U = aA_d^{\,b} \quad (1)$$

where U is cumulative volume sediment stored, A_d is drainage area, and a and b are empirically derived coefficients that will presumably vary with climate, lithology, relief, and land cover. We were unable to find any published values of a and b for the Colorado River catchment.

The estimation of sediment storage relative to drainage area based on GFPLAIN results is very time-consuming because of the need to generate values for drainage area at an enormous number of sites in a catchment the size of the Colorado River Basin. However, we used the Dirty Devil River Basin as a test case for this analysis, estimating drainage area and upstream sediment storage for every NHDHR reach in the basin that includes an appreciable floodplain. This results in ~5500 data points. We removed floodplain volumes with <1 m^3 of sediment storage because these results were likely noise. The coefficients on the relation between sediment volume and drainage area (Figure 8) are within the range documented by Graf (1987), suggesting that the estimates for sediment storage that we derived from various techniques in this paper are within a reasonable range.

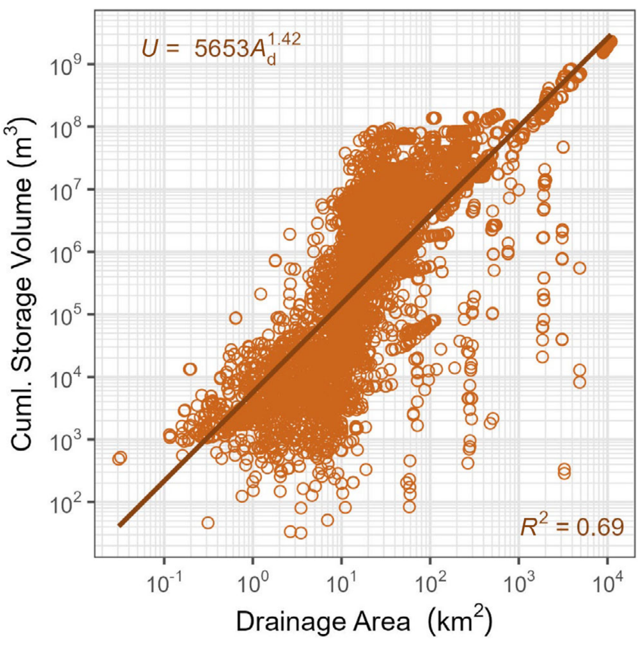

FIGURE 8 Estimated relations between cumulative volume of sediment stored and drainage area based on sediment volume data from GFPLAIN modeling and drainage area derived from the National Hydrography Dataset. In the regression equation, U is cumulative volume of sediment storage and A_d is drainage area. [Color figure can be viewed at wileyonlinelibrary.com]

5.2 | Sediment storage estimates using GFPLAIN and SWAT+

As described in the Methods, we estimated floodplain area for the first- and second-order channels that are not captured in the 30-m resolution data used in the GFPLAIN modeling. This resulted in a notable increase in floodplain area from third- to fourth-order channels (Figure 2; Table S4). This disappeared, however, in the sensitivity analysis using 10 m DEMs (Figure 4), suggesting that it is the result of our methods rather than actual trends in floodplain area.

Perhaps the most interesting results are the comparison of three different methods of estimating sediment storage for the Upper Colorado River Basin in Figure 7 (see also Table S6). The Upper Basin total estimates from the two SWAT+ methods are relatively similar and the Lower Basin total estimates from GFPLAIN and SWAT+ aquifer volume are relatively similar. The lower values for SWAT+ direct estimates relative to SWAT+ aquifer volume are surprising, given the inclusion of first- to third-order channels in the direct estimates but not in the aquifer-based estimates. The SWAT+ direct estimations indicate more storage in first- and second-order channels than the other methods, which is likely an artifact of this calculation method. Previous studies have reported overestimation of simulated sediment storage by SWAT (Bonumá et al., 2014; Dakhlalla & Parajuli, 2019; Yuan & Forshay, 2019). The differences with respect to stream order, and the substantial differences in total estimate relative to the other methods in the Lower Basin, cause us to place more confidence in the GFPLAIN and SWAT+ aquifer volume estimates.

As noted earlier, each of the methods that we used includes substantial uncertainty and is best considered a first-order approximation. Considering this, and the scatter in the estimates from different approaches, it seems appropriate to use 21 and 130 billion cubic meters as approximate lower and upper bounds for total sediment storage in the Upper Colorado River Basin and 314 and 482 billion cubic meters as approximate lower and upper bounds for the Lower Basin. The largest proportion of sediment is stored in the montane and steppe zones in the Upper Basin and in the Sonoran zone in the Lower Basin.

To provide some context for these numbers, Lake Powell (the reservoir with Glen Canyon Dam) accumulated an estimated 1.07 billion cubic meters of sediment from 1963 to 1986 (Ferrari, 1988). On a global scale, estimated riverine sediment fluxes to the oceans prior to intensive human alteration of land cover and river networks were circa 15.5 billion metric tons per year (Syvitski et al., 2005). Assuming an average sediment density of 1.7 g/cm^3, this equates to roughly 9.12 billion cubic meters. Our results suggest that a single large river catchment with relatively moderate sediment yields by global standards (Walling & Webb, 1996) can store a substantial volume of sediment relative to estimated global annual fluxes.

It is important to note that the estimates of sediment storage presented here reflect sediment dynamics—weathering of bedrock sediment and movement into river corridors for subsequent transport and storage—operating over timespans of 10^3–10^6 years. Although the volumes of sediment stored in reservoirs such as Lake Powell significantly impact river corridors downstream from these reservoirs, the volume of sediment stored is relatively small compared to sediment storage throughout the entire Colorado River Basin, which includes large alluvial basins in which sediment thicknesses can reach thousands of meters (Figure S2).

Sediment dynamics, including storage, will undoubtedly change across the Colorado River Basin as climate continues to change. Quaternary alluvial sequences indicate substantial changes in sediment mobilization versus storage in sub-catchments within the Colorado River Basin during past episodes of changing climate (e.g., Hereford, 1984, 2002) and the drylands prevalent across the Colorado River Basin experience alternating episodes of channel incision and aggradation even in the absence of substantial climate change (e.g., Gellis et al., 1991). Future climate changes will thus likely result in altered spatial distributions of sediment storage at sub-catchment scales. As long as the major dams in the Colorado River Basin remain in place and effectively trap all entering sediment, however, climate change is not likely to substantially alter catchment-wide magnitudes of sediment storage over the next few decades.

6 | CONCLUSIONS

The results presented here reveal at least two key points. First, the cumulative effect of small channels (1st-3rd order) remains poorly constrained because of the lack of spatially consistent, high-resolution topographic data that would support floodplain mapping along these streams. Second, the lack of consistent field measurements limits our ability to develop general estimates of how floodplain sediment storage varies with drainage area or stream order.

River management designed to enhance or minimize sediment storage is typically undertaken at the local scale as a function of considerations such as site access, budget, and feasibility of intervention based on physical characteristics of the river corridor and on societal or community acceptance of management. However, increasing recognition of the importance of catchment-scale planning suggests that the type of analysis undertaken here might be used to prioritize and coordinate multiple local-scale projects, especially those designed to enhance sediment stability and retention during disturbances. The uncertainty in this type of analysis might be reduced if undertaken at smaller spatial scales (e.g., sub-catchments within the Colorado River Basin) using higher resolution spatial data and more field-based data for validation of estimates such as alluvial sediment thickness. Overall, we hope the approach and results of this study provide context for future research targeted at better constraining the magnitudes and spatial distribution of sediment storage in the Colorado River Basin and other catchments, as well as for sediment management within the Colorado River Basin.

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DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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