Watershed-Scale Sediment Dynamics and Stream Restoration Planning

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Abstract

Salmon recovery initiatives in the Pacific Northwest increasingly emphasize process-based restoration approaches implemented at a watershed scale. To date, effective implementation of these approaches has been limited by our understanding of the watershed-scale sediment processes to inform the planning and project implementation of salmon habitat restoration. In this study, we developed a planning-level sediment budget to evaluate sediment sources, transport, and storage by modifying and applying the Sediment Impact Assessment Methodology (SIAM) framework previously developed by Wallerstein et al. (2006). We applied the approach along a 143-mile stream network draining the 525 mi^2 Upper Grande Ronde River watershed in northeastern Oregon. This modeling-based framework, built on one-dimensional HEC-RAS hydraulic models, allows for direct assessment of restoration strategies and designs on reach to watershed scales. The approach also provides a framework to help answer key questions about recovery timescales with and without restoration, the longitudinal connections (upstream and downstream effects) between these projects, and where and how to maximize the benefits of generally limited coarse (bed material) sediments in the watershed. This paper will discuss the improvements made to the original SIAM framework using an add-on developed with the Python programming language that addresses limitations around bed erosion and bed material sediment transfer. We will also present the key assumptions and application of the model for restoration planning, including highlights about our approach that increased the cost-effectiveness of the improved model framework for watershed-scale applications.

Introduction

Coarse bed material sediment is a key ingredient for success in restoring salmon habitat and is also critical for recovery in incised streams. Therefore, the supply and transport of coarse sediment is a critical consideration in developing informed restoration strategies that align with watershed conditions and processes. The goal of this study was to create a cost-effective and watershed-scale planning tool to assess existing sediment dynamics and system-wide responses to proposed restoration activities. In support of this goal, we developed and implemented a planning-level sediment framework that built upon and refined the previously developed Sediment Impact Assessment Methodology (SIAM, originally developed by Wallerstein et al., 2006).

The original SIAM framework provides an efficient modeling-based sediment budget approach that is well-suited to integrate reach- and watershed-scale variations in sediment supply and transport important for restoration planning and design. The SIAM program was developed at Colorado State University and the University of Nottingham (Wallerstein et al., 2006), under funding from the US Army Corps of Engineers and UK Engineering and Physical Sciences Research Council and with support from engineers at the Engineering Research and Development Center, Vicksburg. It was later added to the hydraulic design packages available in the Hydraulic Engineering Center – River Analysis System (HEC-RAS) (Gibson and Little 2006, Thorne et al. 2011). In the HEC-RAS Program Documentation, SIAM is described as:

> *"a sediment budget tool that compares annualized sediment reach transport capacities to supplies and indicates reaches of overall sediment surplus or deficit. SIAM is a screening level tool to compute rough, relative responses to a range of alternatives, in order to identify the most promising alternatives."*

This study offers a modified version of SIAM, developed in the Python programming language, that increases SIAM's applicability across broader landscapes and stream conditions. Our refinements particularly address some limitations of the original framework for sediment supply-limited streams with mixed bedrock control where bed erosion is slow or limited. We present a case study of the new methodology applied to the Upper Grande Ronde (UGR) River watershed in the Blue Mountains of northeastern Oregon.

Watershed Setting

The Grande Ronde River drains generally north and northeastward through the Blue Mountains towards the town of La Grande Oregon, and then northeast to its confluence with the Snake River at the Washington-Idaho border. The UGR watershed (545 square miles in area), as defined in this study, consists of the drainage area upstream of Hilgard Junction State Park, near river mile [RM] 82. We developed an integrated SIAM model for the mainstem GRR and eight key tributaries (Beaver, Limber Jim, Clear, Sheep, Fly, Meadow, McCoy, and Dark Canyon Creeks), shown in Figure 1.

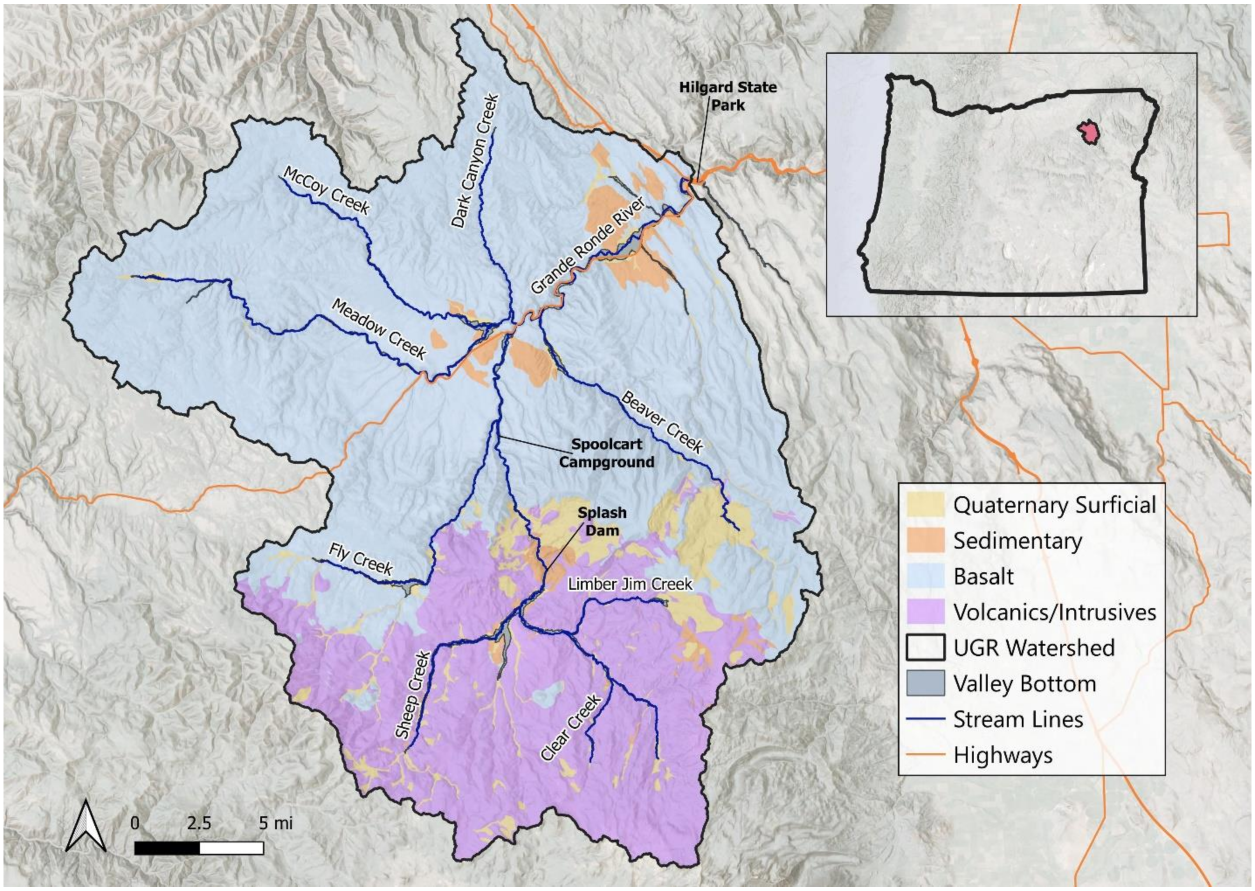

Figure 1: Study area terrain and geologic map with the extent of detailed SIAM modeling represented by the length of named and emboldened streams.

Variation in the bedrock geology has a noted influence on the local terrain and stream network geomorphology. In particular, a distinct geologic transition separates basaltic bedrock in the north from mixed igneous and volcanic rocks to the south. This transition marks a change from lower relief dissected tablelands in the north to higher relief terrain in the south. The geologic transition is also evident in stream longitudinal profiles (Figure 2).

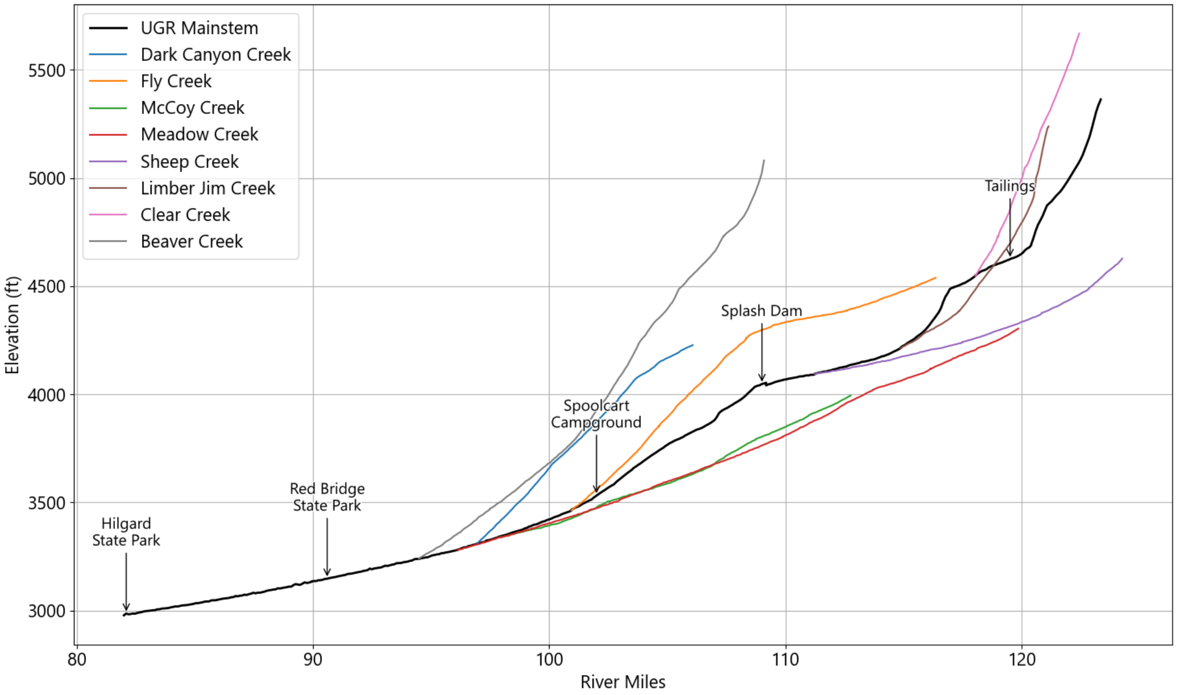

Figure 2: Stream profiles of the mainstem UGR and modeled tributaries. Tributary profiles positioned according to the location of their confluence along the mainstem.

Valley bottoms and floodplains range between meadows to canyons, which vary in their slope, confinement by valley walls, and sediment character. As shown in Figure 3A, meadow reaches feature unconfined valley bottoms with generally lower long-stream gradients and relatively fine bed grain sizes (gravels to small cobbles). In contrast, canyon reaches generally have narrow, confined valley bottoms and relatively steep long-stream gradients with beds dominated by cobbles and boulders (Figure 3B). Exposures of bedrock in the streambed are also relatively common and create notable knickpoints in the longitudinal stream profiles, as observed in Figure 2.

Figure 3: Typical views of (A) a meadow reach (Meadow Creek above McCoy Creek confluence) and (B) a canyon reach (lower Meadow Creek).

Historic and ongoing human impacts also exert a strong influence on the morphology of the modern-day channels. Historic beaver trapping, timber harvest operations, and cattle grazing were all prevalent watershed impacts that drove watershed-wide stream incision and channel simplification. Widespread beaver trapping and log transport via splash dams caused particular bed scour and disconnection from floodplains. From general field observations, it appears the incision occurred historically and is a less active process at present day. Roads and railroads have also interrupted the landscape-scale connectivity and delivery of coarse sediment, especially from hillslopes to streams. Together, we interpret that these effects have led to a landscape with generally increased sediment transport capacity and erosion potential in streams, and reduced inputs of coarse sediment. As a result, a general restoration strategy from a sediment perspective is to restore depositional floodplain settings that were more prevalent historically.

Methods and Model Development

SIAM sediment models are built upon a one-dimensional HEC-RAS hydraulic model and then then sub-divided into reaches that become the basis for computations of sediment mass balance based on the sediment delivered and transported. This requires two core steps:

- Base HEC-RAS hydraulic model development, including model (channel and floodplain) geometry (cross-sections) and reach-scale hydrologic inputs.
- SIAM sediment model development through mapping of sediment reaches with consistent sediment supply and transport characteristics, compilation and input of streambed gradation data, and development of sediment supply inputs defined by annual fluxes and grain size distributions.

Hydraulic Model Development: For the hydraulic model, cross-sections were spaced an average of 150 feet apart and capture terrain from topobathymetric Light Detection and Ranging (LIDAR) terrain data acquired in 2021 (NV5 2021). The mainstem GRR and tributaries were modeled individually, and the results were later integrated outside of HEC-RAS into a watershed-scale sediment model. The model also integrated existing models (Cardno 2014) where available.

Hydrologic inputs were determined at 1-mile intervals via regional regression equations implemented in StreamStats (USGS 2016). The flow profiles used in the models are the 10%, 5%, 1%, 0.5%, 0.25%, 0.1%, and 0.05% annual duration flows, the maximum of which is approximately the 10-year (10% annual exceedance probability) flood. To estimate flows exceeding those covered by regression equations, we developed a simple extrapolation approach based on ratios to the 5% and 10% annual duration flows measured at a series of local USGS gages (Risley, Stonewall, and Haluska 2008).

Sediment Model Development and Refinements to SIAM Framework: The SIAM module calculates “sediment transport potential” from reach-averaged hydraulic model outputs applied to an established sediment transport equation. In this case, we chose the Meyer-Peter-Müller solver for sediment transport based on its applicability to gravel-bedded streams (Meyer-Peter & Müller 1948). The model uses these transport calculations, applied to the local sediment gradation and fluxes delivered from upstream and local sources, to calculate a mass balance and implied quantity of erosion or deposition for a given reach.

Our sediment budget focused on coarse sediment (>2 millimeters [mm]), a relatively scarce and important resource for instream habitats in the UGR watershed. Fine sediments (<2mm) are another equally important component of the watershed sediment budget, but they are more widely available and their transport is seldom limited by the sediment transport capacity of a stream.

During initial testing of SIAM, we found three limitations for a watershed-scale application to supply-limited conditions found in the UGR study area:

1. SIAM assumes no limit to streambed scour in response to computed excess sediment transport capacity. This model condition was considered unrealistic for the UGR stream network based on beds with low erodibility from common bedrock control as well as noted bed armoring in response to historic stream incision. Initial testing revealed that the base SIAM assumption resulted in excessively large downstream sediment transfer rates from steeper reaches (Figure 4).
2. SIAM calculates sediment transport for grain sizes present within the bed of a given reach, as opposed to the sizes delivered to a given reach from upstream and local sources. This simplification results in miscalculation of sediment transport capacity where the grain sizes present in the bed differ from those delivered to a given reach.
3. SIAM requires bed gradations, sediment source gradation, and sediment source fluxes for each reach, which is a manual process that is difficult to scale to large study areas with many reaches.

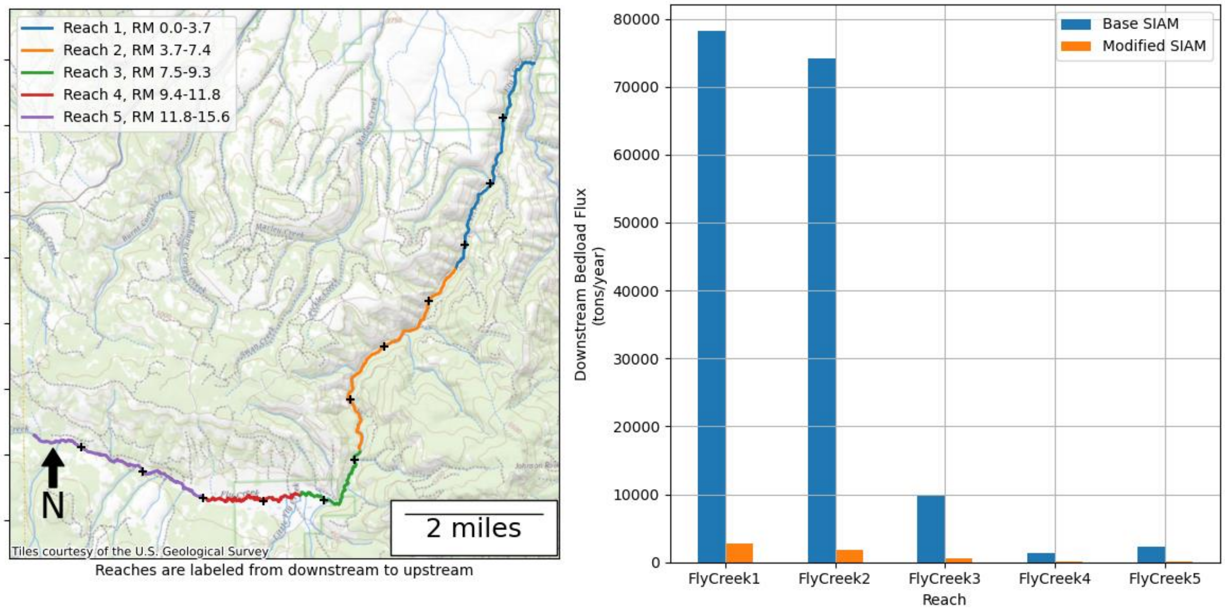

Figure 4: Planform view of Fly Creek (left). And bedload fluxes transported out of each reach from base SIAM and our modified version (right). The lower reaches of Fly Creek (1 & 2) are steep, confined, and have exposed bedrock in the channel. Reaches 3-5 are lower slope and predominately alluvial.

We developed a back-end algorithm to address these issues and improve applicability to our study area. Our Python-based algorithm makes use of SIAM's outputs of sediment transport potential by grain size class, and implements a similar mass-balance framework with revised components addressing the corresponding limitations noted above:

1. An assumed non-erodible bed addresses the known armoring and bedrock control observed throughout the UGR stream network.
2. Sediment transport potential values were applied to the computed grain size distribution reflecting the mixed distribution of upstream and local sources.
3. We use an empirical relationship between basin slope and bed material yield (developed for Western Oregon by O'Connor et al., 2014) to estimate the average annual flux to each reach. This required an automated measurement of contributing watershed area and slope from 30-m digital elevation models on a reach-by-reach basis. We ascribed the same sediment distribution to all sediment inputs, aggregated from over 600 pebble counts collected within the basin.

By focusing on bed material load, we also avoided the need to estimate thresholds between bed and wash load components as required in SIAM through the user-defined "Wash Load Max Class, Diameter" parameter.

The base version SIAM addresses only annual loads of sediment transported into and out of each reach but does not directly address the transit time of sediment through each reach, which is an important consideration in our understanding of restoration response times. We accordingly calculated average transit time amongst all grain size classes transported through each reach, by calculating sediment velocity (U_B) using the continuity equation derived by Einstein (1950) and a calculated mobilized layer thickness (d) on the streambed:

$$d = \frac{q_B}{U_B * \rho_S * (1 - \lambda_P)}$$

Where q_B = bedload transport rate per unit channel width (q_B), ρ_s = sediment density, and λ_P = bed porosity.

The mobilized layer thickness can be approximated as twice the 90th percentile grain size (D_{90}) in the bed (DeVries, 2002), which we calculated for each reach based on the modeled grain size distribution delivered to each reach. The bedload transport rate per unit width (q_B) is the sediment transported out of each reach divided by the top width of the 0.5% exceedance flow (approximately the 1.5-year return interval). Solving for sediment velocity, we then calculated the transit time for an average grain to travel through each reach, based on reach length.

Case Study Results

The model elucidated multiple aspects of watershed-scale sediment dynamics, as described below.

Downstream increases in flux: The model predicts a general trend for fluxes of sediment to increase downstream, especially along the mainstem GRR. In Figure 5, this trend is represented by arrow size in a Sankey diagram that increases in width with distance downstream. Although no field measurements of bed material transport were available, this general pattern meets the expectation that sediment flux increases as a function of contributing drainage area.

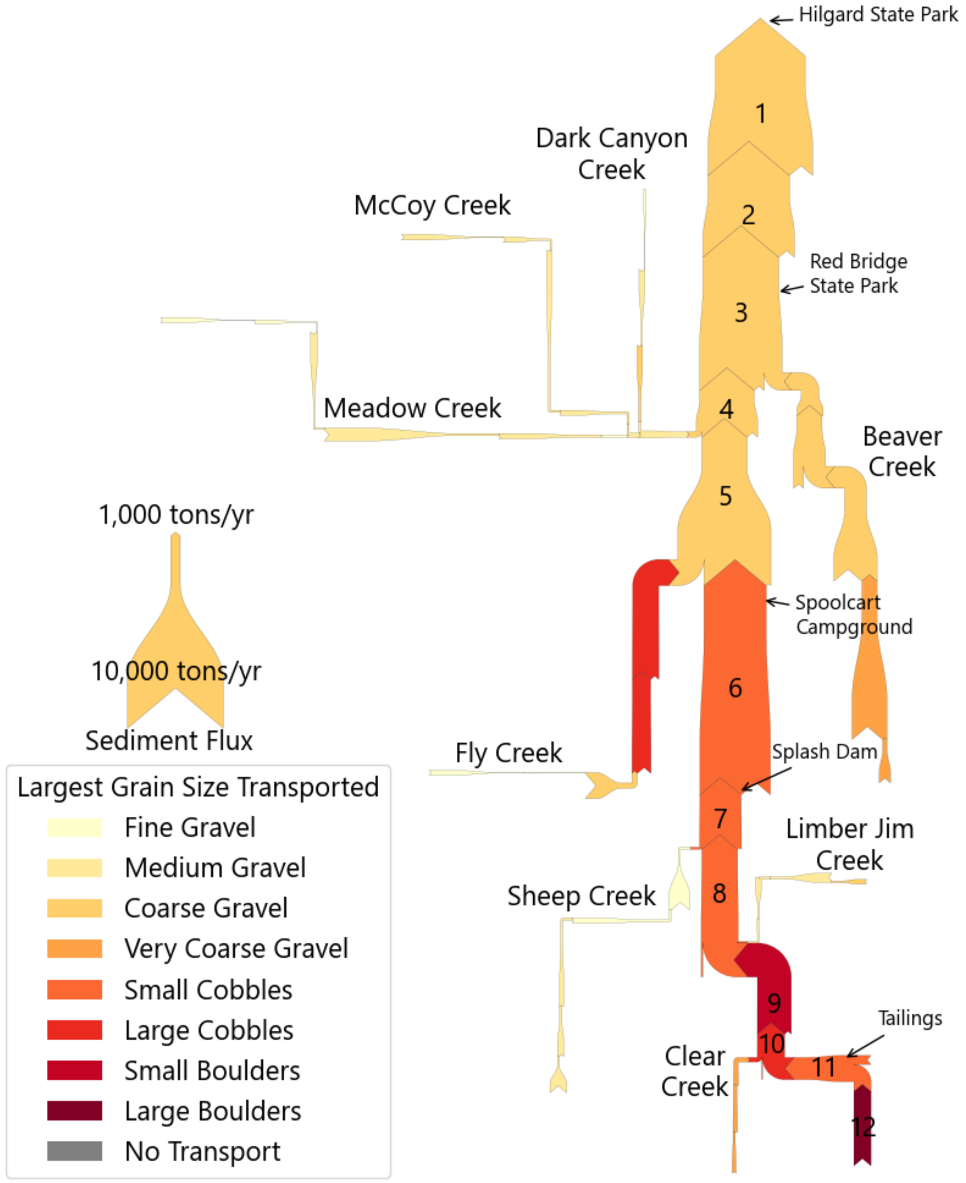

Figure 5: Sankey diagram representing annual bed material flux, colored by modeled sediment transport competence (largest grain transported). Each segment represents a modeled sediment reach, which are scaled lengthwise to reach length, and scaled in width to the flux of coarse sediment entering/exiting a given reach. Modeled tributaries and associated reaches are labeled and organized according to their place in the stream network. Incoming arrows with no upstream segment represent the local supply inputs to each reach.

Downstream fining of sediment: The model predicts a general pattern of grain size fining in a downstream direction. This downstream fining pattern is visible in part through the longitudinal patterns of calculated competence (i.e. modeled largest grain diameter transported) in Figure 5 and Figure 6. These trends in competence reveal that every reach in the mainstem UGR River is capable of transporting coarse gravel (22.6-32 mm) or finer, whereas cobble transport is only predicted to occur upstream of the Fly Creek confluence (Reach 6 and upstream), and boulder transport is predicted in only two reaches near the headwaters (Reaches 9 and 12). The result of this downstream decrease in competence is a size selective downstream fining of grain sizes (Figure 6B). Although the model provides no direct way of predicting grain size distributions on the bed, it does compute the relative size proportions of bed material that is in flux. From these, we estimated the median grain size (D50) of the supplied and retained sediment in each reach, which appear to bracket measured values of D50 (Figure 6C). The general compatibility of modeled and measured D50 values increases confidence in the modeling results.

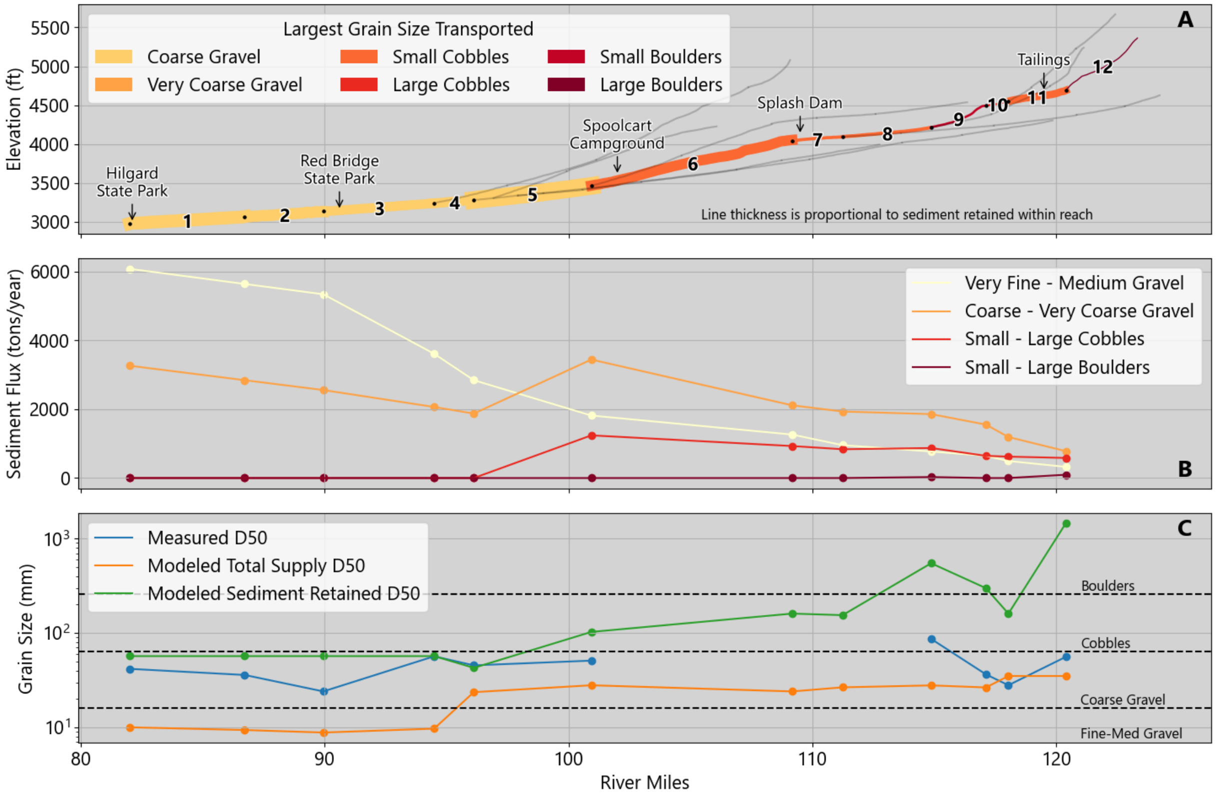

Figure 6: Long-stream profiles of sediment model results for the UGR mainstem. (A) Sediment balances in each sediment reach. Line thickness is proportional to the net amount of sediment retained in a reach. Shading indicates the largest grain size transported through a reach. (B) Sediment flux (transport rate) out of each reach, broken down by bulk grain size classes. (C) Modeled D_{50} compared to the D_{50} measured using pebble counts. Note: pebble counts were not conducted in reaches #7 and #8, which are on private property (Vey Ranch).

Watershed-scale sediment retention: According to the model setup, in a representative year, a total of ~41,000 tons of coarse sediment is supplied to the sediment reaches in the UGR watershed upstream of Hilgard. The model computes that only about a quarter of the coarse sediment supplied to the GRR in the UGR watershed is exported downstream (~9,300 tons per year), with the greater part (~32,000 tons per year, or about 75% of the total supply) being retained in sediment sinks within the UGR watershed drainage network. This result indicates the high capture efficiency of net depositional, meadow reaches. However, potential factors influencing this overall result include potential skew associated with the assumed non-erodible bed in the model and exclusion of very large floods (i.e. those exceeding the 10-yr return interval) in this model study.

The importance of meadow and canyon sequencing: The modeling reveals a general pattern that along-stream sequencing of unconfined meadows and confined canyons influences downstream sediment transport patterns. For example, the presence of a source reach immediately upstream, coupled with a major reduction in sediment transport competence and capacity, makes reach 5 one of the most strongly depositional reaches along the mainstem GRR. In tributaries, SIAM results show that the presence and sequencing of meadows and canyons dictates the delivery ratio of tributary basins to the mainstem, which is the ratio of the quantity of sediment supplied to the mainstem GRR by a tributary to the total quantity of sediment eroded in the tributary watershed (Table 1).

Table 1: Summary of tributary sediment delivery and yield to the mainstem GRR.

Name	Position of Meadow Reach in Tributary	Average Watershed Slope (Indicator of Watershed Yield	Total Local Supply	Total Export	Delivery Ratio	Watershed Yield (tons/square mile)
--	--	(ft/ft)	(tons/yr)	(tons/yr)	(%)	(tons/mi^2/yr)
Beaver	Near mouth	0.25	8,500	1,850	22%	31
Limber Jim	Near mouth and in headwaters	0.21	1,700	150	9%	8
Meadow	Near mouth	0.13	3,200	550	18%	5
Dark Canyon	None	0.18	1,200	225	19%	12
McCoy	Near mouth	0.13	1,700	210	13%	4
Fly	Middle-upper	0.22	5,500	2,700	50%	52
Sheep	Predominately meadows	0.21	4,700	230	5%	4
Clear	None	0.19	800	470	52%	43

Long Sediment Residence Times: Figure 7 displays the calculated transit times in years for the full model domain, revealing a range of reach-transit times on the order of decades to centuries. The overall average speed of coarse sediment moving as bedload is ~130 feet per year, meaning that on average it takes ~40 years for a grain to travel a mile downstream. The average transit time through a sediment reach in the SIAM model is 120 years. Along the GRR mainstem, our calculations reveal that it takes the average grain ~575 years to transit from the headwaters to Hilgard State Park.

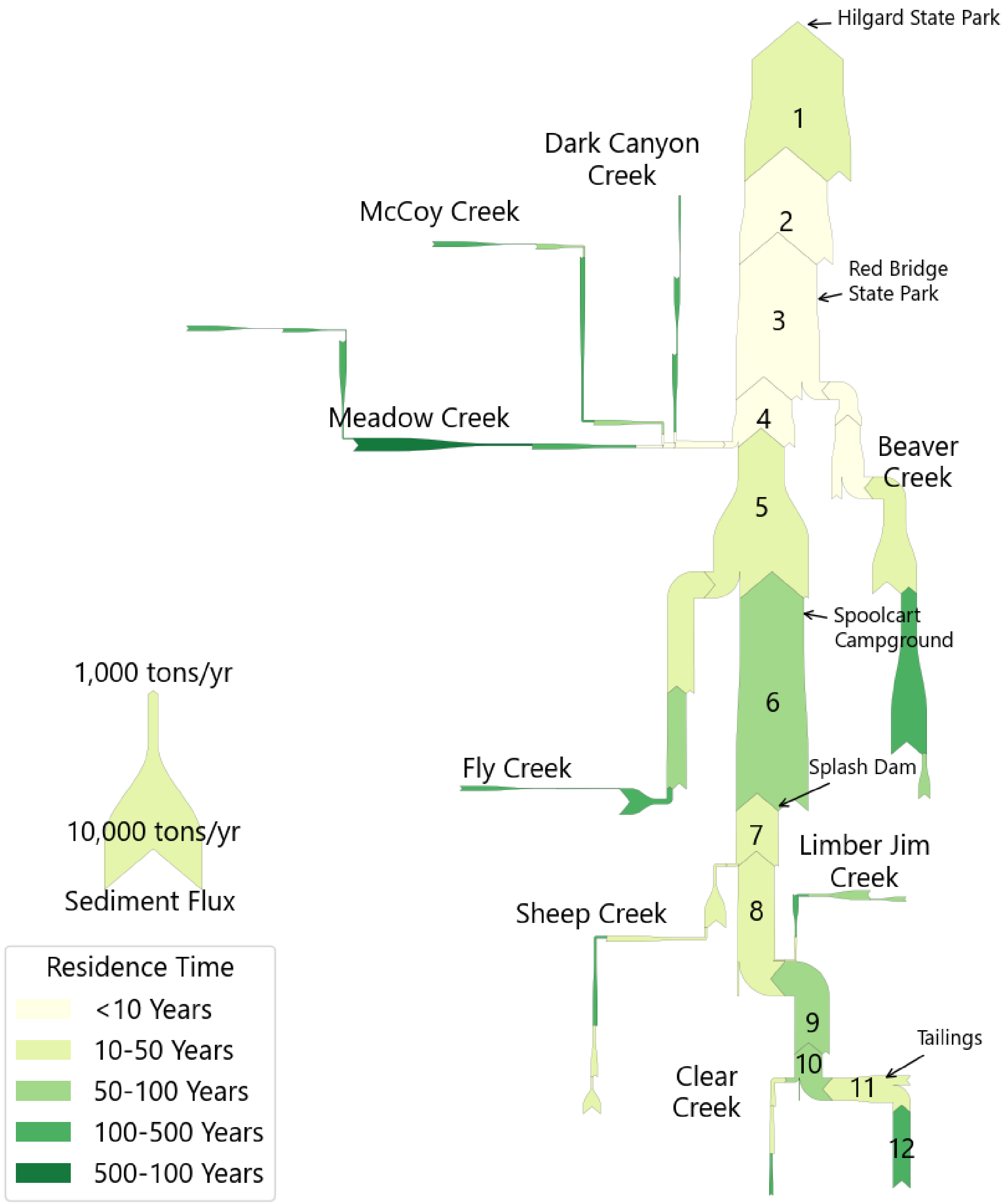

Figure 7: Sankey diagram representing modeled coarse sediment fluxes through the UGR watershed on an annual basis, colored by calculated sediment transit (residence) time through each reach. Each segment represents a modeled sediment reach, which are scaled lengthwise to reach length, and scaled in width to represent the flux of coarse sediment passing through a given reach. Modeled tributaries and associated reaches are labeled and organized according to their position in the stream network. Incoming arrows with no upstream segment represent the local supply inputs to each reach.

Channel Hydraulics and Trapping Efficiency: Figure 8 shows the propensity for deposition as a function of shear stress. Propensity for deposition is presented as trapping efficiency, or the ratio of sediment supply to sediment retention in a reach. Of all modeled reaches, the average shear stress in the channel during the 1.5-year flow never exceeds 4 lbs/ft^2. Reaches with channel slope less than 2% and channel depth less than 2.5 feet at the 1.5-year flow, criteria that roughly corresponds with a shear stress of 1.5 lbs/ft^2, have the highest trapping efficiency. The pattern of high trapping efficiency for channels with shear stress below 1.5 lbs/ft^2 holds true across the basin with few outliers.

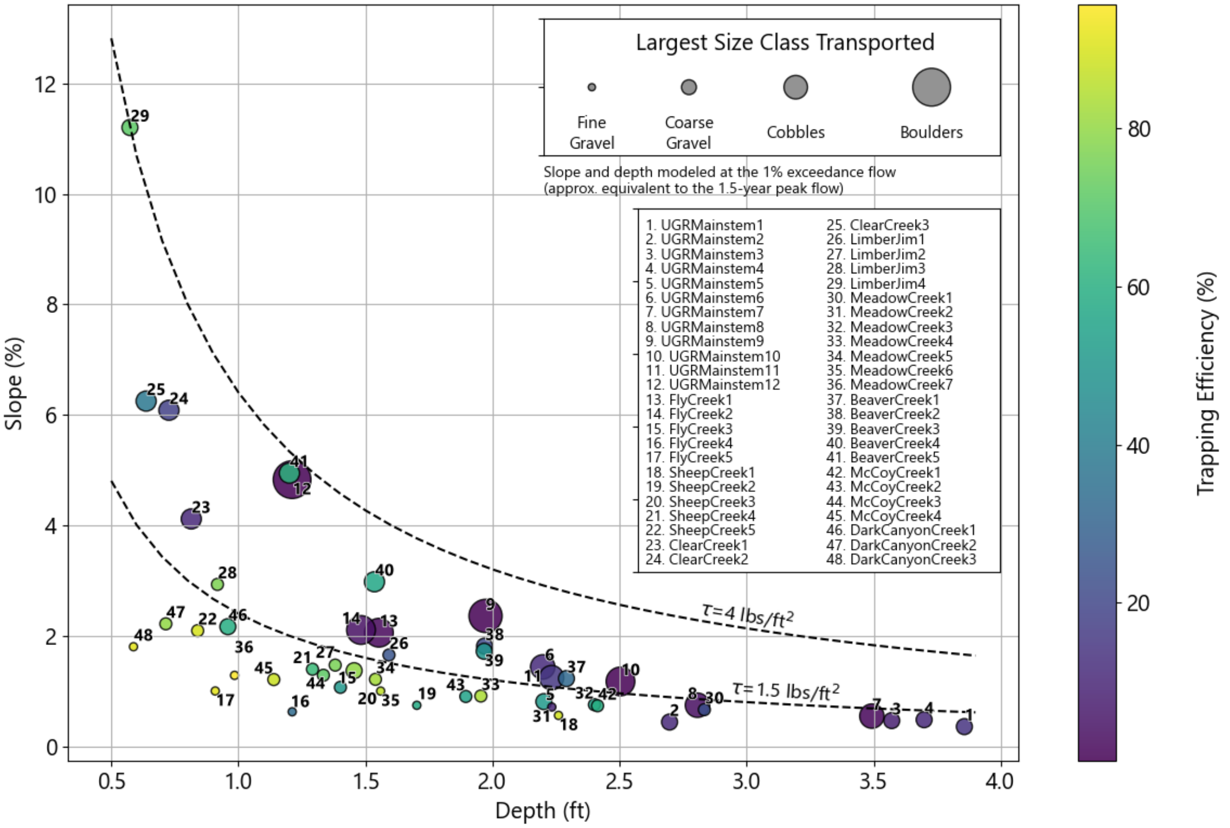

Figure 8: Sediment transport and trapping efficiency as a function of shear stress (namely slope and depth).

Discussion and Implications

River restoration strategies have emphasized process-based approaches for over a decade (Beechie et al., 2010). However, most restoration plans and designs continue to be developed with a limited knowledge of the sedimentological context. In many cases, this fact is driven by limited funding and a general impression of high-cost and high-uncertainty sediment studies. Our enhanced SIAM framework addresses these issues by providing a relatively low-cost approach that can be implemented at a watershed scale. While our UGR model is planning-level in nature and lacks significant validation at this time, it nonetheless provides a realistic picture of relative sediment patterns across a large watershed. The framework and results hold major promise for aligning restoration approaches with watershed sediment context, informing upstream and downstream connections to individual restoration projects, and creating more holistic strategies that address sediment sources and transport.

This paper presents a refined SIAM framework that increases its applicability in gravel-bedded streams with a limitation on coarse sediment supply. Our primary refinement imposed a non-erodible bed to limit excessive predictions of bed erosion. In reality, our refinements represent a compromise and point to a need for a framework that addresses a broader range of stream conditions. We envision a future version that incorporates negative feedbacks to bed erosion from armoring/coarsening (e.g. Shen 1983, Dietrich et al. 1989) and allow the user to impose known bedrock outcrops in the stream profile. Another refinement to include is the effects of comminution and downstream fining (O'Connor et al. 2014). These elements would more explicitly address bed erosion processes and would allow the model framework to simulate bed erosion and incision over a wider range of geomorphic settings.

Conclusion

The main outcome of this study is a modified version of the Sediment Impact Assessment Methodology (SIAM) that is applicable over large watersheds with gravel-bedded and sediment supply limited streams. The modifications address excessive bed erosion, refine mass balance calculations of sediment transport by grain size, and a simplify the sediment/hydrologic inputs for scaling purposes.

The improved SIAM framework, developed in Python, is modular and can accommodate any number of 1D HEC-RAS models organized into a stream network. Geometries, hydraulics, and sediment transport potential are read directly from source files (namely the ".g0x" and ".h0x" files) produced by HEC-RAS. Expanding the model domain is as simple as reading in new 1D models with a pre-built function. This allows for easy application of this framework where 1D models already exist, such as those created for regulatory flood mapping. Hydrologic and sediment inputs are determined automatically from easy to measure basin statistics, all of which can be provided by the USGS's StreamStats API. These improvements increase the scalability, objectivity, and applicability of base SIAM.

Our case study in the Upper Grande Ronde River watershed shows that despite the simplified model inputs, the model simulates realistic watershed patterns of sediment flux, competence, and size gradation. Computed sediment velocities and transit times also provide an output which improves our understanding of the (slow) response times of streams from a sediment perspective. This cost-effective model will inform process-based restoration strategies in the UGR basin and represents an example of how we can better inform and optimize our watershed restoration and planning efforts over even larger watersheds and geographies.

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