SIAM, SEDIMENT IMPACT ANALYSIS METHODS, FOR EVALUATING SEDIMENTATION CAUSES AND EFFECTS

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INTRODUCTION

River restoration succeeds best when accounting for system interactions and restoring processes. Sedimentation effects can undermine, bury, or leave restoration efforts stranded. Traditional means of evaluating sediment impacts include sediment continuity analysis and mobile boundary hydraulic modeling. Sediment Impact Analysis Methods (SIAM) provides a framework for combining morphological, hydrologic, and hydraulic information. The results develop a quantitative picture of sediment movement through a watershed that are more detailed than a qualitative geomorphic evaluation, yet require less effort than a numeric mobile boundary model.

SIAM represents a network as a series of homogeneous reaches and defines the connectivity between reaches to create a geomorphic aware sediment linkage model from a sediment continuity perspective. The results map potential short- and long-term imbalances and instabilities in a channel network and provide the first step in identifying sediment related problem areas and designing or refining remediation. The procedures allow for a rapid assessment of dynamic equilibrium in channel networks to improve efforts to target the source of problems and develop solutions from a systems approach.

The following paragraphs describe the theory behind the SIAM model and then validate and compare against numerical models of Hickahala Creek, Mississippi and hypothetical mobile boundary numerical simulations. The SIAM techniques facilitate incorporating sediment movement into stream rehabilitation and management.

COMPUTATIONAL METHODS

Input Records: Constructing a SIAM model requires developing records to describe the bed material gradation, sediment characteristics, hydrology, hydraulics, transport potential, and local sediment sources of a dendritic network. The input records describe the driving sedimentation parameter for a regime static in space and time. Hydrology, hydraulics, and transport potential describe the magnitude, duration, and hydraulics, and theoretical transport capacity of a flow event. Bed material describes the composition of the channel boundary. Sediment characteristics describe how flow events interact with the channel boundary including cohesive scour, armored reaches, and the threshold between wash load and bed material load. Local sources describe sediment supply from features outside of the modeled reaches such as gullies, net bank failure, surface erosion, or augmentation.

Hydrology consists of flows and durations representing the range of events under a particular flow regime. SIAM acts independently from the methods used to generate input and can scale from coarse to very detailed definitions. A project may begin with a coarse survey and regional estimates and then fill in specific measurements where available. By separating the development of input records from the synthesis, the model retains the flexibility to vary techniques and procedures as the state-of-the-art improves or studies expand a database.

Local Sediment Accounting: SIAM models the movement of sediment through a watershed by dividing the range of grain classes into wash load or bed material load transport modes. A reach in SIAM contains a wash material reservoir and a channel material reservoir. Wash material passes through a reach without interacting with or modifying the channel boundary. A change anywhere upstream impacts all downstream reaches in connected grain classes. Channel material interacts with the channel bed and banks to impact the physical structure of the channel. A change to the channel material budget can only immediately impact the reach directly downstream. Impacting reaches farther downstream requires adjustment to the channel boundaries and may take many years to exert an impact. Grain classes can transition back and forth between reservoirs as the material moves to downstream reaches. A transition from wash material to channel material severs the connection to upstream wash load reservoirs. **Figure 1** shows the conceptual framework for a reach in the SIAM model.

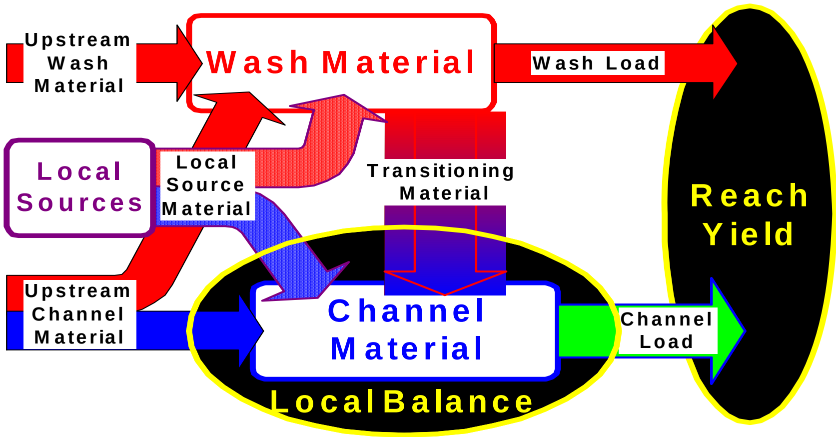

Figure 1 SIAM Reach Level Conceptual Framework.

Material enters a reservoir through upstream channels or local sediment sources. Local sources include material supplied to a reach from outside of the channel bed or upstream of the model boundary. Sources include inflows to the reaches at the upstream boundary of the model, bank failures, surface erosion, gravel mining, gully formation, and all other forms of external sediment production. Local sediment source records do not include material hydraulically supplied between modeled reaches through entrainment or bed scour. All material supplied to the wash reservoir must either transition to the channel reservoir or pass downstream. Material leaves the channel reservoir according to the channel load. Channel load entering a downstream reach either passes into the wash material reservoir or the channel material reservoir depending on the wash load threshold. Supply of material to the channel reservoir does not need to equal the channel load. When supply exceeds the load, a positive local balance occurs. When load exceeds supply a negative local balance occurs. SIAM tracks the individual supply constituents to identify causality. A large wash load may originate from gully formation high up in the basin or the cumulative effect of agriculture. Local accounting only links wash load impacts. Identifying impacts to or from channel load requires network accounting. Effects require adjustment to channel boundaries.

Network Accounting: The computation routines do not adjust channel boundaries, update sediment sources, or account for time dependent effects. Sediment supplies represent regime averaged properties, and average results over a regime to provide balances showing trends in a system, but not intermediate or final states. Network impacts from channel reservoir imbalances are computed through extrapolating trends in the channel reservoir according to geomorphic principles of channel response. A reach that cannot transport the supply of material is aggrading and will evolve to increase transport capacity. A reach transporting more than the supply of sediment is degrading and will evolve to reduce the sediment transport rate. For a single reach in a network otherwise at equilibrium, the evolution results in a permanent change to the upstream base level and a transitory change to the downstream sediment supply. An aggrading reach adjusts in order to increase transport capacity by either increasing slope, reducing width, and/or fining of boundary material. An aggrading reach will increase the base level of upstream reaches and temporarily reduce the supply to downstream reaches with no net change in transport capacity. A degrading reach must adjust to reduce transport capacity through a combination of reduction of slope, increase in width, or coarsening boundary material. The base level of upstream reaches lowers and the downstream reaches experience increased sediment supply with no net change in transport capacity. **Figure 2** shows an example adjustment.

The imbalanced reach acts as a pivot with upstream reaches moving one direction and downstream reaches moving the opposite. Multiple aggrading and degrading reaches create interference to attenuate or amplify geomorphic change. Reaches do not always adjust equally. Stream power and applied energy provide a means of distributing the change throughout a network. Reaches, which respond more to changes in sediment supply and transport capacity, will absorb more of the adjustment than less responsive reaches. The pivot point within a reach moves upstream or downstream depending on the responsiveness of the connected reaches.

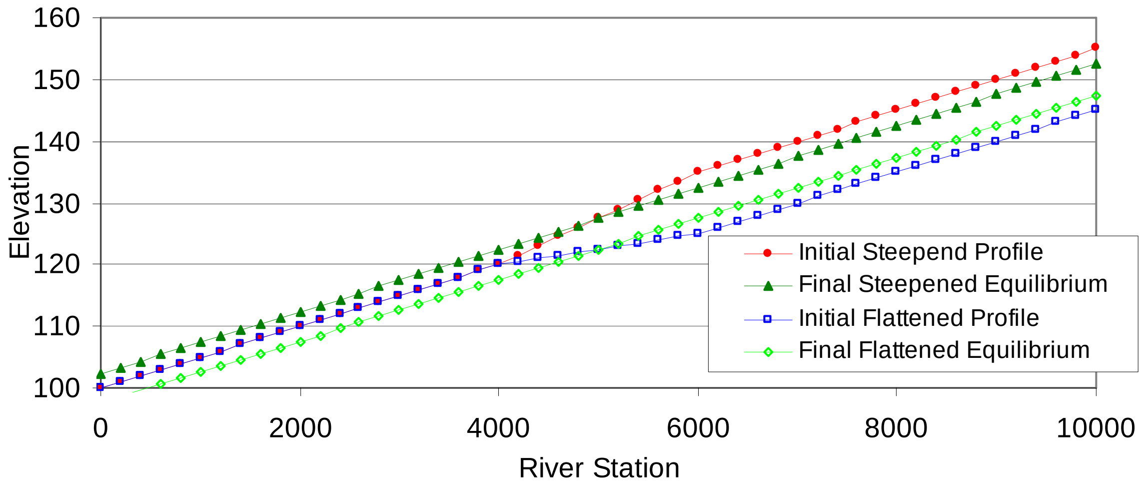

Figure 2 Adjustment Progressions of Aggrading and Degrading Reaches.

<u>Applied Energy and Responsiveness:</u> Bagnold (1966) postulated a link between stream power and sediment transport. His research suggested stream power provided an integrative parameter for relating sediment transport to channel hydraulics with an efficiency term defining the fraction of the total stream power expended in sediment transport. Other researchers use similar energy methods for total load (Yang 1973 and Parthenaides 1977). Equation 1 shows stream power in terms of shear stress and the hydraulic components of shear stress.

$$\Omega_T = \tau \cdot v \cdot P = \left(\gamma \cdot R \cdot S_f\right) \cdot v \cdot P \tag{1}$$

Where,

Ω_T = total stream power;
τ = shear stress;
P = wetted perimeter;
γ = unit weight of water;
R = hydraulic radius;
S_f = friction slope; and
v = average flow velocity.

The sediment load is related to the relative weight of sediment and the fraction of the total power expended in sediment transport. Bagnold defined an efficiency term as a linear function of the ratio between channel velocity and mean particle diameter. Using fall velocity as a surrogate for particle diameter, Equation 2 shows the hydraulic parameters controlling sediment transport rates.

$$Q_s \approx \Omega_A = \sum\left(e_b \cdot \Omega_T\right) = \sum\left(\gamma \cdot \left(\frac{v}{\omega}\right) \cdot \left(R \cdot S_f \cdot V \cdot P\right)\right) \tag{2}$$

Where,

Q_s = sediment load in mass or volume per time;
Ω_A = power expended in sediment transport over a flow event, applied power;
e_b = efficiency coefficient $\approx \left(\frac{v}{\omega}\right)$; and
ω = particle fall velocity in water.

Applied stream power represents a flux of force per time for a single flow event. The sediment load is also a flux, but of mass (or volume) per time. Geomorphic change occurs due to net transfer of material, yield, from a channel boundary. SIAM applies the stream power to a reach control volume. Application of the duration of an event to the stream power over the reach length results in work done on the channel boundary. Equation 3 applies the stream power over the longitudinal length of a channel for the duration of a flow event to derive an applied work term, Π_A.

$$Y_s \approx \Pi_A = \sum(\Omega_A \cdot t \cdot X) \tag{3}$$

Where,

Y_s = sediment yield;
Π_A = applied work;
t = duration of a flow event; and
X = longitudinal length of the channel.

Applied energy provides a measure of the resistance to adjustment due to changes in sediment load. Reaches requiring large changes in the amount of work required for altering sediment yields will respond more than a reach requiring small changes. The responsiveness is defined by the slope of the work versus yield curve, Equation 4.

$$\Psi = \frac{d}{dY_s}\Pi_A = \frac{d}{d\sum(Q_s \cdot t)}\sum(\Omega_A \cdot t \cdot X) \approx \frac{d}{dQ_s}\sum(\Omega_A \cdot X) \tag{4}$$

Where Ψ = response parameter.

Responsiveness measures the change in sediment transport capacity with a change in applied stream power, which represents the inverse of the slope of the sediment transport rating curve as a function of stream power. Half of imbalance moves upstream of the pivot point and half of the imbalance moves downstream. The stress from the imbalance on each side of the pivot point must be evenly distributed to maintain equilibrium. The imbalanced reach adjusts to accommodate some of the imbalance. The effect appears as a shift in the pivot point. The location of the pivot point depends on the ratio of responsiveness of the surrounding reaches. Estimates of the pivot point location neglect the internal responsiveness of the pivoting reach and bias the position towards predicting lower amounts of response in reaches relatively shorter than other reaches in the network. **Figure 3** shows an example of pivot movement and the impact on the network balance.

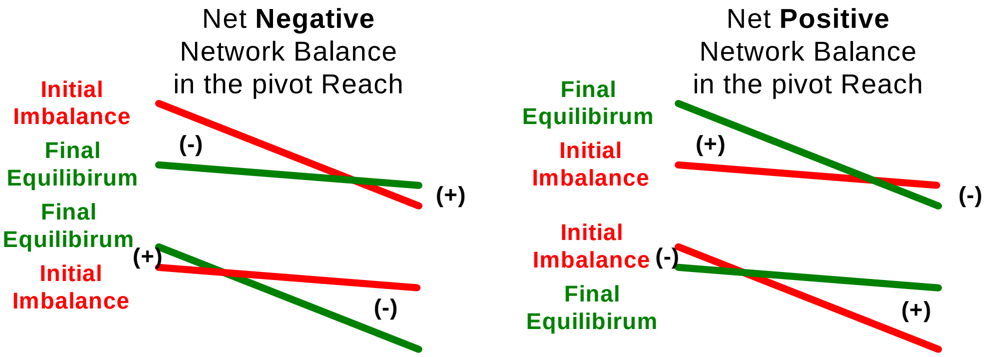

Figure 3 Pivot Reach Absorption of Network Balance Effects.

VALIDATION AND APPLICATION

<u>Hickahala Creek, Mississippi, Demonstration Basin:</u> Historic agricultural practices in the Hickahala Creek Basin (230 mi^2) in North Central Mississippi increased sediment yields and exacerbated flooding. Channelization in the 1960's initiated incision and widening and continued deposition in the lower reaches. A rehabilitation plan implemented grade control, bank stabilization, drop pipes, land treatment, and detention ponds. These actions stabilized the watershed and halted the downstream deposition. Geomorphic studies, numerical simulations, and rehabilitation plans performed by Simons, Li and Associates, SLA, (1987a, b, and c) identified sediment sources and hydraulics in the Hickahala Basin as well as locations of geologic controls and the sediment budget. Channel boundaries consist of bedrock, erodible cohesive clays, silts, sands, and fine gravel. Armoring was not found to be significant. A SIAM model was developed for the Hickahala Basin consisting of 84 reaches spanning 15 tributaries nested to a 4th order for the purpose of validating the computational techniques.

Local Accounting on Hickahala Creek: The SLA investigations integrated field observations, sediment transport, and numerical modeling to classify reaches as under capacity (aggrading, positive local balance) or over capacity (degrading, negative local balance). SIAM results agreed in 25 cases and disagreed in 5 cases. The SIAM model broke the reaches into smaller lengths. Subsuming reaches to the SLA designation reconciled 1 case and inclusion of additional tributaries accounted for 3 cases. Sufficient information on SLA input was not available to determine the discrepancy in the last case.

Applied Energy Relationships on Hickahala Creek: Modeled reaches in the Hickahala Basin represent cohesive and sand bed channels with small gravel in a range of stages of adjustment processes. The channel evolution model of Schumm, Harvey, and Watson (1984) lists five stages of adjustment including initial imbalance, incision, widening, deposition, and equilibrium. The hypothetical regime was developed by adjusting flow-duration subject to passing an equivalent volume. The hypothetical regime curve was compared to the computed existing work and yield estimates. **Figure 4** shows example comparisons with yield in tonnes per year on the vertical axis and applied work in N-m on the horizontal axis.

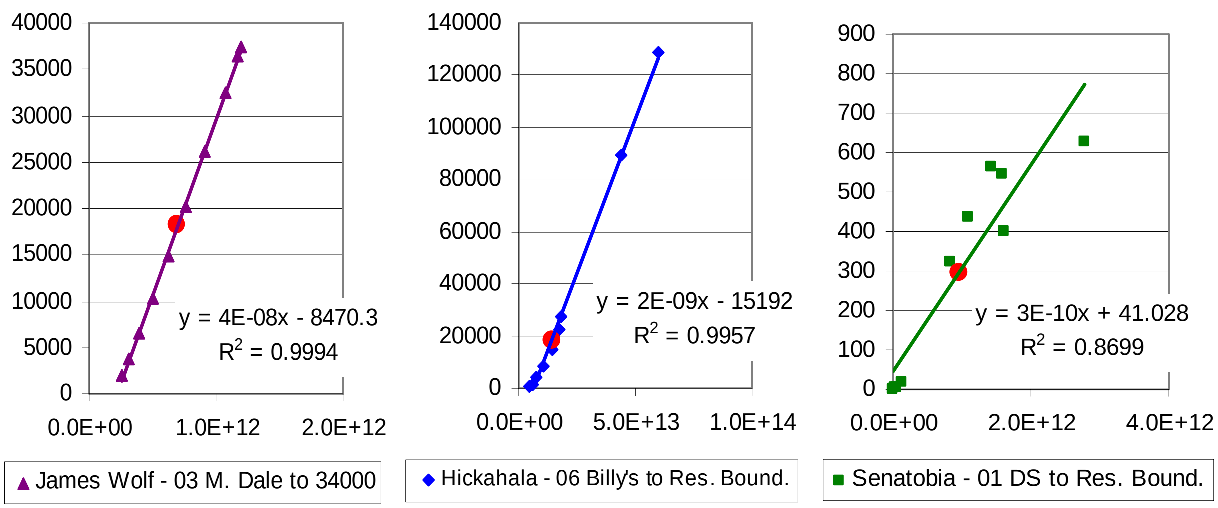

Figure 4 Example Existing and Hypothetical Regime Work Comparison.

R^2 values averaged 0.95 with a standard deviation of the residuals averaging 14% when normalized to the existing regime yield. The loosest fits occur in areas controlled by backwater from the reservoir at the basin outlet. Fits outside of the reservoir resulted in R^2 values around 0.99 and standard deviations on the residuals of 12 percent. Statistics on the difference between the existing computed sediment yields compared to the hypothetical regime relationship showed 93 percent of the data within 2 percent of the prediction curve. The spread of channel evolution stages validates applied work for predicting sediment yield from reaches based on discharge conditions for channels in a variety of adjustment phases. Hickahala creek represents a rainfall driven system with flashy floods and long periods of lower flows. For snow melt driven basins with rain on snow events, the fewer unsteady and transient sediment impacts might improve the correlation. However, the shift to coarser material is subject to all the additional uncertainties in gravel and cobble transport relationships and represents a shortcoming in the ability to predict sediment movement.

Channel geometry changes applied work through the hydraulic radius, wetted perimeter, and friction slope. Velocity is dependent. Two of the three parameters operate independently while the cross section shape (rectangular, trapezoidal, ovoid, and irregular, etc) fixes the third. Either a designer selects a channel shape or the shape forms though interaction with the bed and bank material. Either case is external. Slope and perimeter were selected for comparison. The geomorphic evaluation of Hickahala provided partial hydraulics for the 1968 channelization plan under the 2 year recurrence discharge. Comparing yield to the hypothetical regime curve provided comparisons for adjustments to channel geometry. Normal depth and rectangular geometries were assumed. The duration was assumed equal to the time required to pass the entire annual volume. Only reaches outside of the reservoir boundary were included resulting in 11 test cases due to the inability to completely determine hydraulics under backwater influence from the given information. **Figure 5** shows some example comparisons with yield in tonnes per year on the vertical axis and applied work in N-m on the horizontal axis.

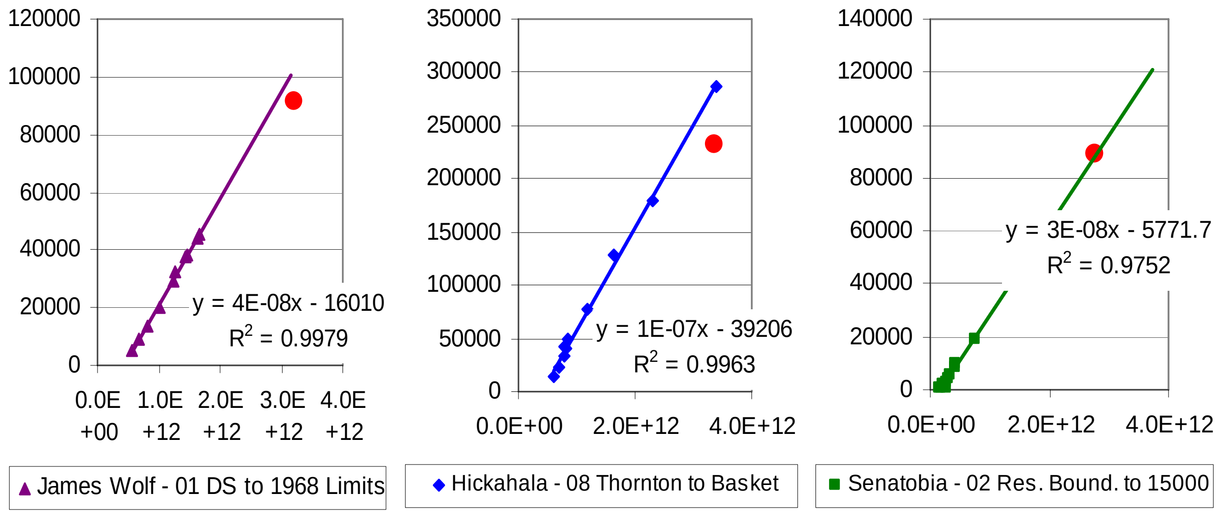

Figure 5 Example Historic Geometry Applied Work versus Hypothetical Regime.

Comparing the channelized work and yield results to the hypothetical regime curve showed an average error of 10 percent with a standard deviation of 100 percent for the errors. The largest error occurs under backwater and invalidates the normal depth assumption. Excluding the largest error reduces the standard deviation to 30 percent. Other inaccuracies include the general assumption of normal depth and the duration estimate using a representative discharge. In several cases, comparing to the 1968 plan required extrapolating the hypothetical regime curve. The order of magnitude agreement was considered adequate to not refute the applied work theory. Due to the limitations of empirical evaluation, universality cannot be demonstrated outside of the range of conditions provided by the Hickahala Creek channelization plans. Repeated surveys throughout channel evolution for a variety of systems would be required for more conclusive empirical confidence in the application to other basins.

Mobile Boundary Example Models **Figure 6** shows an example numerical boundary run with degrading reaches and a comparison to network balances. Comparison of SIAM to mobile boundary numerical simulation used GSTAR 1D. Relative adjustments under mobile boundary modeling were compared to the routed SIAM stresses. The GSTAR 1D model shows greater changes in the shorter sections. SIAM trend results agree with the GSTAR 1D simulation in direction. Magnitudes cannot be directly compared, but relative differences provide a means of understanding. Of the total 4.93 ft adjustment difference on each side of the pivot, the shortest reach (maximum change) comprised 71 percent. In the SIAM simulation, the shortest reach (maximum change) showed a 65 percent difference. The estimate of the pivot point location in SIAM uses the upstream and downstream reaches only and neglects additional weight from adjustment in the pivot reach. Accounting for the shift in the pivot reach would increase the difference and change SIAM results in the direction of the GSTAR 1D simulation.

Cases of GSTAR 1D and SIAM models were compared combining fixed and free boundaries, upstream and downstream shifts of the imbalanced reach, multiple imbalanced reaches of different directions and magnitudes, different grain diameters, and changes in width. Grain sorting and mixing changed the sediment transport rates resulting in geometries generally deviating from SIAM in magnitude, but matching in direction.

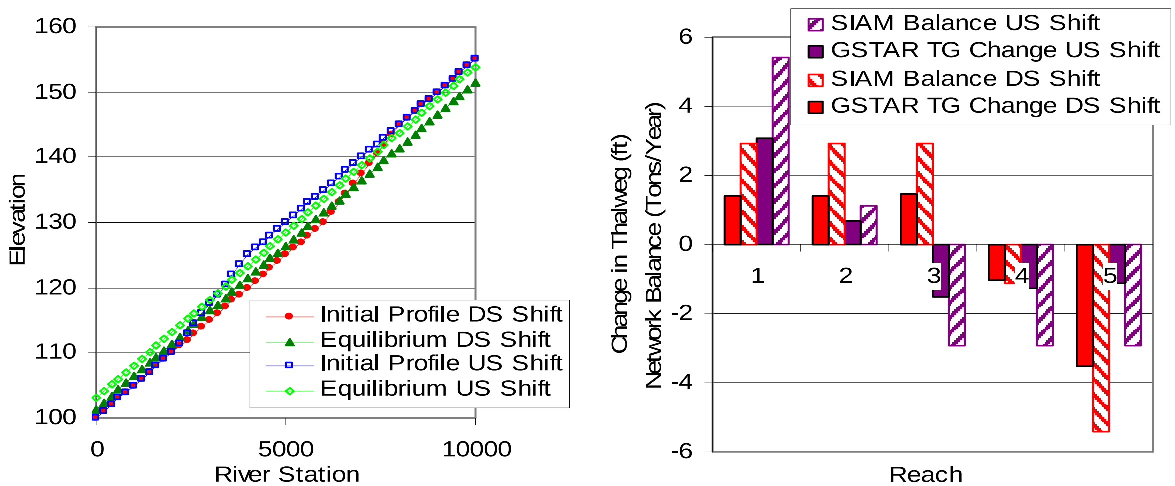

Figure 6 Comparison of SIAM Results to Mobile Boundary Modeling.

Additional SIAM Information on Hickahala Creek: The SIAM model of Hickahala Creek included several results not present in the geomorphic report including a relative breakdown of which sediment features provided the majority of the input to both sediment yield and geomorphic adjustment. For the purpose of identifying total sediment yield, wash load comprised the bulk of the material passing the outlet. **Figure 7** shows an example breakdown of the wash load.

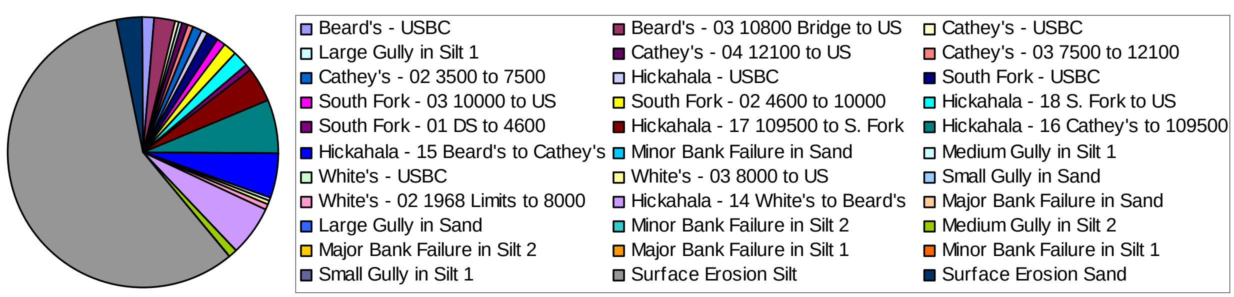

Figure 7 Wash Load Composition Entering Hickahala Creek at the Reservoir Boundary.

Wash material primarily originates from surface erosion in silty material. Secondary contributions include erosion of cohesive material in the upper reaches of the basin. Halting upstream degradation would reduce the wash load 21 percent. For the same reach, the most significant sources of channel material occurred through bank erosion in sandy material with 85 percent occurring in major sites and 14 percent occurring in minor sites. The results would suggest bank protection to reduce long term deposition in the reservoir.

DISCUSSION

A sediment continuity analysis compares the supply and transport capacity on a reach by reach basis. The wash load and local balance routines in the SIAM model improves upon the methodology by considering transport mode in linking reaches. Dividing sediment movement into wash and bed material transport modes differentiates between short-term yield effects and long-term geomorphic change. Targeting wash load can result in solutions with immediate improvements. Efforts impacting the structural component require longer time frames. Transitions between wash and channel reservoirs may isolate portions of the watershed from impacting goals at the outlet. In some cases a structural problem (aggradation or degradation) may result from transitioning material. Identifying transition material linkages can suggest immediately realizable benefits. The additional amount of effort in applying SIAM over a sediment continuity analysis is the specification of a wash load threshold.

The applied energy methods in SIAM provide a means of estimating the impact on sediment transport to changes in the hydraulic conditions including geometry, slope, discharge, and duration. The hypothetical regime curve provides a means of estimating how adjustments to the governing parameters can change yield. Alternately, a target yield can be obtained by adjusting the parameters to achieve the desired outcome. SIAM provides an estimate for a starting point. A mobile boundary numerical or physical model can verify and fine tune the procedure.

Applied energy also provides a means to route the impact of changes in one portion of the network to other reaches. Comparison in uniform grain sizes showed close agreement. The lack of an exact pivoting point location introduces error, but none of the hypothetical test cases found differences large enough to impact the direction of change. An exact evaluation requires a mobile boundary model. Comparisons of SIAM to GSTAR 1D under conditions of grain sorting showed larger deviations in the relative magnitude than the uniform gradation but generally agreed on direction. SIAM grain sorting requires interpretation of the results beyond the scope of this paper.

Advantages of the SIAM model include ease of setup and operation. Hydraulics and sediment transport are developed outside of the computational framework and may use a diverse array of techniques including regime relationships, regional hydrology, or other simplifications to fill in sparse data sets. Quality of the results is subject to the accuracy of the input. Time step and section spacing are present in SIAM computations. SIAM will always return a result, but quality depends on the appropriateness of the model. Numerical simulations for the simple 5 reach, 50 cross section comparisons took on average 1 hour. The Hickahala Creek model ran in 1 minute on a 1.6 GHz processor. An equivalent model within GSTAR 1D might take 1 or more days. The quick results allow consideration of multiple scenarios. When using sparse data sets, multiple scenarios can identify the sensitivity. SIAM returns less information on final channel geometry than a mobile boundary model. SIAM reports magnitude and direction of trends while a mobile boundary model reports states. Ultimate conditions remain unknown in SIAM. SIAM will not result in a final water surface profile and does not output the results from grain sorting. In a numerical model, the connection between sediment sources and impact becomes obscured. SIAM tracks the linkages in both wash and channel material load resulting in targeted recommendations for rehabilitation.

CONCLUSIONS

The SIAM model contributes to stream assessment and rehabilitation by facilitating the integration of sediment continuity. Considering sediment balances reduce the likelihood of system scour or deposition shortening the useful life of a project. By locating potential instabilities, detailed field investigative efforts can target the most crucial areas. Source tracking allows planners to focus mitigation efforts to the areas causing the most problems. In considering the transition from wash material to bed material load, immediate benefits may be realized through grain size specific design practices. The simplified formulation of continuity reduces some of the difficulties and data requirements present in numerical modeling efforts at a cost of less information. Future work on the SIAM model includes improvements to incorporate grain sorting and application to more systems including the Sacramento River, CA, Methow Basin, WA, and Rio Grande River, NM.

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