How many measurements are required to construct an accurate sand budget in a large river? Insights from analyses of signal and noise

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Opening the discussion:

What is the general purpose in creating a sand budget? What is the motivation in creating a sand budget in Eastern Grand Canyon?
Why do a sand budget in Grand Canyon?

- Major goal by resource management to rebuild sandbars from 1963 flood releases
- Sand bars are used by river recreationists and support riparian ecosystems
- Want to scale duration of controlled floods from Glen Canyon dam with estimated sand supply

Introduction - Relating sediment transport to morphological change

- **Flux-based** ($\Delta S_f$) – measurements of sediment influx ($I$) and efflux ($E$) are summed over the time period and difference computes the mass balance. Generally quantified as units of mass.

\[
I - E = \Delta S_f
\]  

- **Morphological-based** ($\Delta S_m$) – difference between measurements of bed elevations made over the same river segment at the beginning ($z_1$) and end ($z_2$) of the measurement period over an area ($a$) summed across the river segment of interest. Generally quantified as units of volume.

\[
\Delta S_m = \sum a(z_2 - z_1)
\]  

In a closed sediment budget, flux and morphology-based measures are related where $\gamma$ is porosity and $\rho$ is density:

\[
\Delta S_f = \Delta S_m (1 - \gamma) \rho
\]  

units: $M = L^3 (1 - 1) * \frac{M}{L^3}$
What are some problems that may arise when creating a sand budget? What are possible uncertainties associated with calculating a sand budget?

Think spatially and temporally

Quantifying Uncertainty

Uncertainties in flux or morphological change may be large (of similar magnitude) as the computed mass balance

• Random Errors
  • uniformly distributed across a dataset (spatially and temporally)
  • for sediment budgets over large spatial or temporal scales, may be inconsequential as they average out

• Systematic Errors (bias)
  • may affect all or part of a dataset (not spatially or temporally uniform)
  • can have a large impact on a sediment budget because they are additive
  • Result from
    • Measurement uncertainty – What are some examples of measurement uncertainties?
    • Sampling uncertainty – what are some examples of sampling uncertainties?

• Signal-to-noise ratio (SNR) – ratio of magnitude of variable of interest to the magnitude of potential systematic temporal and spatial uncertainties of measurements and incomplete sampling
In this case: \( \text{SNR} = \frac{\Delta S}{\sum \text{measurement uncertainty} + \text{sampling uncertainty}} \)
What is the main problem the paper aims to address? What are the 3 main objectives in solving this problem?

**Problem:**
Sediment budgets over long segments (>100 channel widths) or time periods (>2 years) may produce indeterminate results due large and/or additive uncertainties
- Small signals relative to
  - spatial and temporal accumulation of measurement uncertainty
  - inadequate sampling frequency or spatial coverage

**Paper Objectives:**
- Present a closed fluvial sand budget that is at the segment-scale (>100 channel widths) from subdaily measurements of sand flux and spatially extensive changes in bed morphology
- Present an approach for evaluating measurement- and sampling-related systematic uncertainty
- Illustrate the dual impact of measurement and sampling uncertainties on segment-scale sand budget estimates computed from either sand flux or morphological change measurements
Study Area

- time period: May 2009 - May 2012
- 50 km segment
- GLCA Dam governing flow conditions
- Paria River - primary source of fine sediment
- Eddies are most important for sand storage
- 203 individual eddies (200 m² - 26,000 m²)

Measurement and Computation of Flux-based Sand Budget

\[
\Delta S_f = I_{susp} + I_{bed} + I_{trib} - E_{susp} - E_{bed}
\]  

Influx @ 50 km
- \(I_{susp}\) = cumulative suspended-sand load
- \(I_{bed}\) = estimate for cumulative bedload flux
- \(I_{trib}\) = estimated sum of sand inputs from ungagged trib. (between Rkm 50 and Rkm 100)

Efflux @ 100 km:
- \(E_{susp}\) = cumulative suspended-sand load
- \(E_{bed}\) = estimated cumulative bedload flux

(14% +/- 50%) of the measured increase in cumulative silt/clay loads between Rkm 50 and Rkm 100, based on episodic measurements of sand concentrations in tributary flows)
Measurement and Computation of Flux-based Sand Budget

Random measurement errors of flux assumed to be zero over 3-year study period

**+/-5% Uncertainty in the mainstem sand loads** - estimated as the maximum probable bias: the maximum likely systematic error that may be temporally or spatially persistent and potentially affect the sand budget (based off of repeat measurements of the SSC in the area)

\[
\Delta S_{UB} = \frac{\Delta S_{UB}}{\Delta S_{LB}} = \frac{(I_{susp} + I_{bed})(1 + U_I) + I_{trib}(1 + U_{trib})}{(E_{susp} + E_{bed})(1 + U_I)}
\]

\[
\Delta S_{LB} = \frac{\Delta S_{LB}}{\Delta S_{LB}} = \frac{(I_{susp} + I_{bed})(1 - U_I) + I_{trib}(1 - U_{trib})}{(E_{susp} + E_{bed})(1 - U_I)}
\]

\[
\Delta S_{LB} = \text{Lower bound of sand budget} \\
\text{Mainstem load } U_I = 0.05, \text{ tributary inputs } U_{trib} = 0.50
\]

\[
\Delta S_{UB} = \text{Upper bound of sand budget}
\]

\[
\Delta S_{LB} = (I_{susp} + I_{bed})(0.95) + I_{trib}(0.50) - (E_{susp} + E_{bed})(1.05) \\
\Delta S_{UB} = (I_{susp} + I_{bed})(1.05) + I_{trib}(0.50) - (E_{susp} + E_{bed})(0.95)
\]

**Signal to Noise Ratio (SNR) of Flux-based Sand Budget**

- boundary between low and high SNR is usually 2 (3 dB)
- ratio of mean to standard deviation

\[
\text{SNR}_{fs} = \frac{\Delta S_{UB}}{\sigma \Delta S_{fl}}
\]

\[
\text{SNR}_{fm} = \frac{\Delta S_{UB}}{\sigma \Delta S_{fm}}
\]

**SNR}_{fs} is based on the flux-based budget and subsampling the dataset (depends on frequently of measurements)**

**SNR}_{fm} is based on measurement noise (here, Upper Bound, which is symmetric to Lower Bound)**
Data collection for the Morphological Sand Budget

Channel and bank morphology measured in May 2009 and May 2012 using optical total station and sonar

- Depositional settings grouped into:
  - Active Deposits
  - Inactive Deposits
- 71% of active deposits mapped
  - 50% of total area mapped
- Bed classified as sand, gravel, or rock

How did they differentiate between an active and inactive deposit for this location?

<table>
<thead>
<tr>
<th>Table 1. Depositional settings in study area and proportion of each setting that was mapped and included in digital elevation model</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Depositional Setting</strong></td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>Active channel and fine-grained deposits</td>
</tr>
<tr>
<td>Channel within eddy</td>
</tr>
<tr>
<td>Pools in channel</td>
</tr>
<tr>
<td>Sandbars in eddies</td>
</tr>
<tr>
<td>Sandbars along channel margins</td>
</tr>
<tr>
<td><strong>Subtotal - Active</strong></td>
</tr>
<tr>
<td>Inactive channel and coarse-grained deposits</td>
</tr>
<tr>
<td>Channel in rapids and riffles</td>
</tr>
<tr>
<td>Sandbars in eddies above CF stage</td>
</tr>
<tr>
<td>Sandbars along channel margins above CF stage</td>
</tr>
<tr>
<td>Gravel bars</td>
</tr>
<tr>
<td><strong>Subtotal - Inactive</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>
Computation of uncertainty in morphological sand budget

- Computed erosion, deposition, net volume change, and uncertainty by depositional setting from cell-by-cell differences in elevation between surveys
- Uncertainty caused by:
  - $\delta_m =$ measurement bias; $\delta_c =$ compositional bias; $\delta_s =$ sampling bias

\[
\delta_m = U_{mb}/A_{mb} + U_{ts}/A_{topo} + U_{sb}/A_{sb}
\]

$U_{mb} =$ maximum estimated systematic error mapped by multibeam sonar (0.06 m)
$U_{ts} =$ maximum probable systematic uncertainty mapped by total station (0.04 m)
$U_{sb} =$ maximum probable systematic uncertainty mapped by singlebeam sonar (0.12 m)
$A_{mb}/A_{topo}/A_{sb} =$ area mapped by multibeam sonar/total station/singlebeam sonar

- $\delta_c =$ maximum probable uncertainty based on bed composition (where volumetric change was measured possibly due to movement of sand but bed was never classified as sand)

Total uncertainty in morphological budget (no extrapolation):

\[
\delta_T = \sqrt{\delta_m^2 + \delta_c^2}
\]

Signal to Noise Ratio of Morphological Sand Budget (SNR) : Sampling Uncertainty

- Examine effect of changing spatial coverage on computed morphological budget
- Provide estimate of uncertainty associated with extrapolating the morphological budget to unmapped areas
- Morphological changes subsampled into 408 segments, incrementally decreasing the number of samples (100% to 0.2%)

$z(\bar{bar}) =$ area-weighted average elevation change,
$\Delta V_i =$ volume change in each subsampled segment
$A_s =$ area of subsampled segments
$A_m =$ constant total area of original set of measurements
$\Delta S_{ms} =$ estimated sediment budget for the sample

After repeating 100 times...

$\text{SNR}_{ms} =$ sampling uncertainty from morphological measurements
$\Delta S_m =$ mean value for each subsample size
$\sigma_{\Delta ms} =$ standard deviation for each subsample size
Signal to Noise Ratio of Morphological Sand Budget (SNR) : Measurement Uncertainty

\[ \text{SNR}_{mm} = \text{morphological measurement uncertainty} \]
\[ \Delta S_m = \text{measured morphological sand budget} \]
\[ \Sigma \delta_m = \text{constant sum of uncertainty in all segments} \]

\[ \text{SNR}_{mT} = \text{total uncertainty from morphological measurements} \]
\[ \sigma_{\Delta m} = \text{standard deviation for each subsample size} \]

Note
Estimates of measurement uncertainty in both morphological and flux-based sand budgets are estimates of the maximum probable systematic uncertainty (bias) for spatially and temporally aggregated budgets because systematic errors do not have an expected value.

Estimates of sampling uncertainty can only be addressed by stochastic simulation, in which case the standard deviation of the resulting distribution is the most appropriate measure of variability.

Extrapolation of morphological sand budget

Estimating changes in sand volumes for areas not measured

\[ \Delta S_{mEx} = \text{extrapolated morphological sand budget} \]
\[ \Delta S_m = \text{measured morphological sand budget} \]
\[ z_{\text{bar}} = \text{Area-weighted mean change in sand elevation where measurements were made} \]
\[ A_T = \text{total area of active deposits} \]
\[ A_m = \text{area where measurements of active deposits were made} \]
\[ \delta_s = \text{estimated uncertainty in extrapolated portion of sand budget} \]
\[ \sigma_{\Delta m} = \text{standard deviation from SNR computed for percentage of the study area where morphological measures were collected} \]

What does this relationship assume?
Results: Temporal Sand Budget

- When did the major temporal change occur in the sand mass balance, why?

- Why would the extrapolation of the morphological budget be in better agreement with the flux based budget?
Results: Spatial Sand Budget from morphological measurements

- What does the morphological budget tell us that the flux based budget does not?
- What part of the channel experienced the largest amounts deposition and erosion? What was the net effect? How much spatial variability is there?
- What part of the channel sees the overall largest net changes?
- Why are eddies the focus of such change?

Net elevation change in entire area = -0.08 m

Results: Accumulated change in sand storage spatially

- How did they make this graph?
- Describe the spatial pattern of net erosion/deposition along the length of the study area for each channel locations.
- Is change spatially consistent downstream vs across the channel width?
Results: Morphologic change and Bed Classification

Point 1: There was greater proportion of erosion from exposed sandbars than from elsewhere in eddies, where net deposition occurred. Why is this of interest?

Point 2: Most morphological change in sand occurred in persistent patches of sand -- Why are the patches of sand persistent?

Results: Change in Bed Cover

How did the proportion of bed covered by sand change by feature? In what feature was there significant change?

Table III. Bed-sediment classification transition probability matrices. Cells shaded gray indicate those transitions where morphologic change was considered sand

<table>
<thead>
<tr>
<th>Eddy</th>
<th>2009 No data</th>
<th>2009 Not sand</th>
<th>2009 Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>No data</td>
<td>0.83</td>
<td>0.04</td>
<td>0.13</td>
</tr>
<tr>
<td>Not sand</td>
<td>0.11</td>
<td>0.42</td>
<td>0.47</td>
</tr>
<tr>
<td>Sand</td>
<td>0.21</td>
<td>0.16</td>
<td>0.63</td>
</tr>
<tr>
<td>Channel</td>
<td>2012</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No data</td>
<td>0.54</td>
<td>0.13</td>
<td>0.32</td>
</tr>
<tr>
<td>Not sand</td>
<td>0.04</td>
<td>0.70</td>
<td>0.26</td>
</tr>
<tr>
<td>Sand</td>
<td>0.06</td>
<td>0.18</td>
<td>0.77</td>
</tr>
</tbody>
</table>

How did the proportion of bed covered by sand change by feature? In what feature was there significant change?

Table II. Morphological sand budget

<table>
<thead>
<tr>
<th>Depositional setting</th>
<th>Area mapped (m^2)</th>
<th>Percent with texture class</th>
<th>Percent sand</th>
<th>Deposition (m^3)</th>
<th>Erosion (m^3)</th>
<th>Net change in sand (m^3)</th>
<th>Measurement uncertainty (m^3)</th>
<th>Bed composition uncertainty (m^3)</th>
<th>Total uncertainty (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed sandbar</td>
<td>125,800</td>
<td>na</td>
<td>100%</td>
<td>21,300</td>
<td>-48,700</td>
<td>3,850</td>
<td>6,300</td>
<td>7,100</td>
<td>19,700</td>
</tr>
<tr>
<td>Eddy</td>
<td>603,900</td>
<td>64%</td>
<td>83%</td>
<td>251,100</td>
<td>-240,900</td>
<td>20,200</td>
<td>45,300</td>
<td>7,700</td>
<td>49,950</td>
</tr>
<tr>
<td>Channel adjacent eddy</td>
<td>1,141,700</td>
<td>91%</td>
<td>74%</td>
<td>122,400</td>
<td>-351,600</td>
<td>-229,200</td>
<td>54,900</td>
<td>42,500</td>
<td>71,400</td>
</tr>
<tr>
<td>Other Channel</td>
<td>1,080,700</td>
<td>80%</td>
<td>88%</td>
<td>70,400</td>
<td>-120,100</td>
<td>-52,700</td>
<td>60,200</td>
<td>4,600</td>
<td>74,142</td>
</tr>
<tr>
<td>Total</td>
<td>2,967,100</td>
<td>77%</td>
<td>86%</td>
<td>465,400</td>
<td>-761,100</td>
<td>-293,500</td>
<td>182,700</td>
<td>54,900</td>
<td>190,770</td>
</tr>
</tbody>
</table>
Results: Flux Based Signal to Noise

- Increasing the sample interval causes the SNRs to decay exponentially
  - What sampling interval do we need to accomplish an SNR_{ft} > 1 (black line)?
  - What about for an SNR_{ft} > 2 (pink dashes)?

- Measurement and subsampling uncertainties are of similar magnitude
  - What happens if we neglect one of these sources of uncertainty?

Results/Discussion: Signal to Noise for Morphology measurements

- SNR decreases as more of the study area is mapped (A)
- Measurement noise is larger than spatial variability in erosion and deposition
- At least 50% of study area must be sampled to determine sand budget with SNR > 1 (black line)
- Can’t reach an SNR > 2 even with increase of area mapped
  - Constant measurement uncertainty (SNR=1.4) is the limiting factor
Major Conclusions:

What the sand budget tells us about Grand Canyon
- Agreement between the two independent measures (within uncertainty) provides verification that the negative signal is correct
  - Addition of extrapolated morphological budget resulted in improved agreement
- Most of sand evacuation happened during 7 month period of high dam release
  - Evacuation was concentrated in specific geomorphic locations that occupied 12% of the study
  - Eddies are the most active but pools and scour holes in main channel experienced most erosion
- Evacuation only changed elevation of sand sources not location of sand sources -- hydraulically forced; sand reservoirs

What the SNR analysis tells us:
- Noise generated by undersampling > noise contributed by measurement error (to a degree)
- Difficult to achieve a SNR >1 for a large river and "long" time period
  - In this study, low SNR is dictated by large noise and small signal acting in concert
  - Floods from the Paria River comprise approximately 90% of the annual sand supply for this reach and inputs can range significantly; How did the net magnitude of sand evacuation from the study reach compare to average annual inputs from the Paria River during the study period? To erosion in 1965?
- Uncertainty of only a few centimeters in morphological measurements accumulate to very large volumes across large regions of interest

Take-Away for future studies:
- Consideration of sampling frequency and spatial extent to improve understanding of the accuracy of a sediment budget and for detection of significant channel change should be applied in the design of both short and long-term studies

Discussion - Final Thoughts

Because the relations between sample density and noise presented in this study are based on high-resolution data collected in a particular setting, values for required minimum sample interval or minimum proportion of study reach that must be measured are specific to this study. ...Nevertheless, temporally-variable sediment flux is not uncommon...spatially-variable sedimentation is also common