USER-INTERACTIVE SEDIMENT BUDGETS IN A BROWSER: A WEB APPLICATION FOR RIVER SCIENCE AND MANAGEMENT

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Abstract: Decision-support tools providing accurate, near-real-time data and user-friendly interactive visualizations are of critical value to resource managers tasked with planning and carrying out management programs in their domain. Creating a system to continuously aggregate datasets and recompute derived values is difficult and error-prone when attempted by hand. To address this need for river managers in support of sediment budgeting, we have created a web-based, open source suite of tools and processes that 1) continually aggregate data of interest, 2) recompute derived values based upon latest available data, and 3) update visualizations on-demand, providing simple front-end tools available to resource managers and the public. For the first time, engineers and scientists can access these tools freely over the web to assist them with planning and adaptive management decisions.

INTRODUCTION

Fine sediment (sand, silt, and clay) forms the template for riverine ecosystems in many rivers with naturally large sediment loads in the western United States. By disrupting the natural transport of fine sediment, the construction of dams and subsequent regulation of flows has dramatically affected the aquatic and riparian ecosystems in many western rivers (Schmidt and Wilcock, 2008). Depending on the locations of the sources of water and sediment in a watershed relative to the location of a dam, and depending on how that dam is managed, the reaches downstream from a dam may undergo sediment evacuation or accumulation (Topping et al., 2000a,b; Grams et al., 2007; Dean and Schmidt, 2011). Substantial changes in the mass balance of sediment downstream from a dam may have important environmental consequences that may require flow remediation (e.g., U.S. Department of the Interior, 2012). The development of environmental flows for ecosystem management in rivers with naturally high sediment loads that are perturbed by upstream water development thus requires the ability to manage sediment. The preferred scientific tool for such management is the sediment budget (e.g., Erwin et al., 2012; Grams et al., 2013).

Accurate sediment budgets require differencing accurate measurements of the amount of sediment entering and leaving a river reach (e.g., Topping et al., 2010). In rivers dominated by suspended-sediment transport, the amount of sediment entering or leaving a reach is determined through integration of the product of water discharge and suspended-sediment concentration (Porterfield, 1972). Both discharge and sediment concentrations are subject to potential biases that accumulate over time. Uncertainty in a sediment budget cannot be accurately quantified without propagating the biases through the calculations (Topping et al., 2000a, 2010).

To assist river science and management in Grand Canyon National Park, Big Bend National Park, Dinosaur National Monument, and Canyonlands National Park (Figure 1), the U.S. Geological Survey's (USGS)

Grand Canyon Monitoring and Research Center (GCMRC) in partnership with the USGS Center for Integrated Data Analytics (CIDA) have designed and built a database and web application for serving, and operating on, time-series measurements of those key water discharge and suspended-sediment concentration values. This web application is the Discharge, Sediment, and Water Quality Monitoring web application, hereinafter referred to as the "GCMRC web application."

Figure 1 The current geographic scope for the GCMRC web application.

The GCMRC web application consists broadly of two subparts: the GCMRC Data And Workflow System (GDAWS) data warehouse (including its associated data collection and computation processes, and the services that provide that data on request); and the web application itself, which consists of back-end services that perform real-time computation on datasets, and a highly capable browser-based client presented to the user in their web browser.

The GCMRC web application is a decisive advance in the state of the art for sediment budget work. The benefits, however, are differently distributed between administrative, scientific, and technological areas of interest.

Administrative benefits: In terms of budgets and operations, the GCMRC web application’s most important characteristic is its 100 percent open source implementation. This resolves to both short-term and long-term cost containment advantages. In brief: nobody is paying for licenses; more importantly, nobody’s hands are tied by restrictive covenants, nondisclosure agreements, et cetera; more important still, open source projects are future- proofed against withdrawal of licensing permissions (unlike proprietary software whose terms and conditions may change); and perhaps most important, open source technologies have an inherent network effect (software with obvious value is supported and thrives) that reduces concerns about ongoing staffing for extension and maintenance.

Another significant administrative benefit of the GCMRC web application is its standards-based nature. The programming code powering the application consists of well-documented and accepted protocols and methods to deliver and visualize information. This is not a single purpose solution that is useful only in Grand Canyon, Big Bend, Dinosaur, and Canyonlands. It is readily adaptable, at no licensing cost and reasonable scope of project effort, to sediment-budgeting requirements in other reaches on other rivers. The custom programming code and open source frameworks supporting the application are provided as public domain software via the USGS GitHub instance online at https://github.com/USGS-CIDA. While the software currently serves river science and management within the scope of the GCMRC project areas, the same code base and architecture could be used to support data integration, data services and online applications and visualizations in other domains.

Scientific benefits: The scientifically interesting aspects of the GCMRC web application are 1) the unprecedented combination of sediment/streamflow data and computation in a single real-time-capable application, and 2) the flexibly expanding suite of visualization and analysis capabilities of the client.

GDAWS handles unit-value time-series of gage height, discharge, water-quality, and sediment-transport data. These data are available for download using the same services that provide data to the web client.

In addition to building user-interactive tools for visualizing these data within a web browser, we continue to design tools for operating on multiple datasets. The first of these is a user-interactive tool that constructs sediment budgets (with propagated uncertainty) for various river reaches in these national parks.

The user-interactive sediment budgets calculated and displayed by the application are always improving in accuracy as they incorporate the latest data. Calculations performed behind the scenes are recomputed with a constant flow of near-real-time data, providing increasingly accurate outputs, allowing management decisions to be made using the most complete and accurate data.

Technological benefits: It is worth noting that GDAWS is, from a technological standpoint, fairly standard (data warehouse design, implementation, and provisioning are well-understood disciplines; there was no need to reinvent them). The interesting technological accomplishments embodied in the GCMRC web application are the clean division between service and client responsibilities, and the implementation of powerful clientside visualization and analysis without recourse to any proprietary software libraries whatsoever. The most interesting aspect of the GCMRC web application from a software developer's point of view is probably the use of clientside open source libraries to achieve remarkable visualization and real-time analysis, and overcoming the challenges of delivering attractive, responsive visualizations built on real-time data as requested by the user in their browser.

DATA AND METHODS

For the sediment budgeting application presented here, the main data types for this project include 1) continuous time-series data and 2) discrete episodically collected suspended- and bed-sediment data. These data, whether collected via automated sensors or human observations, or computed post-collection, are maintained in a single database. The web application is directly driven by that database; integrity and provenance of the data are thus easily confirmed.

The continuous time-series data are typically spaced at 15-minute intervals and include gage height, discharge, water temperature, specific conductance, dissolved oxygen, turbidity, and acoustic measurements of suspended-silt-and-clay concentration, suspended-sand concentration, and suspended-sand median grain size (Griffiths et al., 2012, 2014; Topping et al., 2003, 2007, 2015; Voichick, 2008; Voichick and Topping, 2010, 2014; Voichick and Wright, 2007).

The discrete sample data include equal-discharge-increment (EDI), equal-width-increment (EWI), single-vertical, and calibrated-pump suspended-sediment measurements, and bed-sediment measurements (Edwards and Glysson, 1999).

All of these data are collected using standard USGS methods and other peer-reviewed methods. 95-percent-confidence-level field and laboratory-processing errors for the EDI and EWI measurements are calculated using the methods of Topping et al. (2010, 2011); similar errors for the calibrated-pump measurements are calculated using unpublished analyses based on the methods of Topping et al. (2011). These errors are depicted in the user-interactive plots in the GCMRC web application.

In order to construct the visualization and modeling capabilities displayed within the GCMRC web application, the different datasets are aggregated, and derived-values calculations are performed and stored on new incoming data. The flow of this process is depicted in Figure 2.

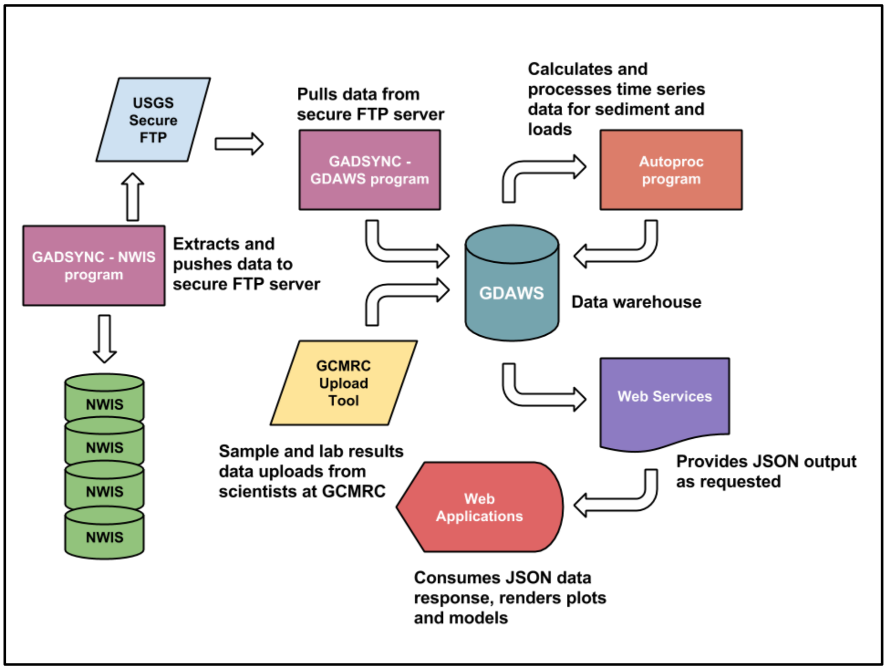

Figure 2 Data flow diagram depicting the movement of data from raw form to client-side visualization.

- GDAWS is a single database organized with the star schema typical in data warehousing. It is implemented on an Oracle database server.
- Time-series data about our stations of interest from the U.S. Geological Survey's National Water Information System (NWIS) database (USGS NWIS, 2014) are extracted twice daily and placed on a secure USGS File Transfer Protocol (FTP) site by a Python program called GADSYNC-NWIS.
- Twice daily, a C# program called GADSYNC-GDAWS retrieves the data placed on the secure FTP site, lightly processes them, and inserts their data into GDAWS. Time-series data not included in NWIS, and discrete sample data, are manually uploaded into GDAWS periodically using a custom web application (the GCMRC Upload Tool) that extracts, transforms and loads the comma-separated data values. To date, the data warehouse contains over 92 million time-series measurements from 57 sites throughout the aforementioned networks. The discrete sample data are critical for calibrating and verifying the acoustic suspended-sediment data and for calculating sediment loads.
- A C# program called Autoproc runs daily, calculating both instantaneous and cumulative sediment loads from the aggregated discharge, acoustic suspended-sediment time-series, and discrete suspended-sediment-sample information in GDAWS. Autoproc extracts data from the GDAWS database, processes parameter values based on the latest time-series data, and re-inserts the newly calculated values back into the database.

Computation of concentrations: major rivers: On the Little Snake, Yampa, Green, and Colorado rivers, and the Rio Grande, suspended-sediment concentrations and grain-size distributions are measured using a combination of 15-minute acoustic data and episodic discrete EDI, EWI, and calibrated-pump sample measurements. The discrete sample measurements are used to both calibrate the acoustic data and then subsequently the acoustic calibrations using the methods of Topping et al. (2007, 2015).

Computation of concentrations: major tributaries: On major tributary rivers where the suspended-sediment concentrations exceed the upper limit where acoustic measurements are possible, suspended-sediment concentrations are computed using a two-step process. First, suspended-silt-and-clay and suspended-sand concentrations are estimated using either physically based model curves (Topping, 1997) or statistically based curves (Topping et al., 2010). Second, these initial sediment-concentration estimates are adjusted to agree with EDI, EWI, single-vertical, and calibrated-pump measured sediment-concentrations as samples get processed through the laboratory, a time-consuming process (Topping et al., 2010). As more samples are incorporated, and the initial estimates become bona fide measurements of suspended-sediment concentration, the uncertainties applied to the tributary suspended-sediment data decrease in the web application.

Computation of concentrations: minor tributaries: The suspended-sediment concentrations in smaller, less important tributary streams are determined using a combination of measurements (Griffiths et al., 2010, 2014, 2015) and indirect estimates (Topping et al., 2010). The uncertainties assigned to the sediment loads in these streams are much larger (typically 50 to 100 percent), but because the loads in these streams are much smaller than the loads in either the mainstem rivers or major tributaries, these large uncertainties do not generally affect the sediment-budget results.

Computation of sediment loads: Sediment loads are calculated using 15-minute discharge and suspended-sediment-concentration data using the method of Porterfield (1972). Because sand, and silt and clay serve different physical and ecological purposes, sand loads and silt and clay loads are calculated independently. This approach allows construction of separate user-interactive mass-balance sand budgets and silt and clay budgets in the GCMRC web application. Construction of these mass-balance sediment budgets require sediment loads to be known on the mainstem rivers, major tributaries, and lesser tributaries, all with assigned uncertainties that are propagated through the budgets.

Computation of mass-balance sediment budgets: The mass-balance sediment budgets for each river reach are calculated using the methods described in Topping et al. (2010) and Grams et al. (2013).

Computed uncertainty: Uncertainties are applied to all sediment loads used in these budgets. The default uncertainties in the web application are chosen such that they represent the largest potential persistent bias in the computed loads at each site. The user can modify these default uncertainties to explore their effect on the uncertainties in the sediment budgets. These bias-type uncertainties result largely from instrumentation bias and include the greatest likely persistent bias in both the discharge of water and the suspended-sediment concentration, and are constrained by consistent measured differences in either discharge or sediment concentration at adjacent cross sections (Topping et al., 2010). Because no difference in either water discharge or sediment concentration occur between these closely spaced cross sections, the differences in the measurements between these cross sections represent biases (generally < 5 percent) in how acoustic-Doppler current profilers, current meters, and suspended-sediment samplers perform in slightly different cross sections. As there is no way to independently know which measurement in which cross section is correct, there is no way to know the “true” value. Thus, uncertainties that represent the greatest likely magnitude of these persistent differences are assigned to each load value. Because these uncertainties are biases, they accumulate over time, resulting in mass-balance sediment budgets in the GCMRC web application with uncertainty that gets larger over time.

Service/browser interaction in handling of computed data: To serve the aggregated and calculated sediment data for use in the front end application, the system organizes requested data into JavaScript Object Notation (JSON) responses. In order to allow the user to adjust the above-described load uncertainties in real-time on their computer, the browser requires all the data be delivered as separate pieces in the JSON response. Usually, the required data are two to five 15-minute time series that need to be transferred to the browser, which can be roughly a million values for an example span of six years. However, in order to accommodate the spectrum of browser memory capacities and variety of internet connection speeds, the application filters the plotted data to windowed local minimums and maximums on requests of periods of that length. The number of values that make it to the browser for the six-year example would therefore be reduced to a few hundred thousand. Because the application attempts to serve the truest visual representation of the data, it is set up to scale the windowed filtering based on the amount of data the user requests.

THE GCMRC DISCHARGE/QW/SEDIMENT WEB APPLICATION: USER EXPERIENCE

When the GCMRC web application at http://www.gcmrc.gov/discharge_qw_sediment/ is visited, the user has a choice of selecting between the monitoring networks for the four national parks, and selecting whether to visit the gateway web page to the time-series data at the monitoring stations or the gateway web page for the user-interactive sediment budgets. These gateway web pages provide a map and list of either the monitoring stations or the sediment-budget reaches.

The map views are supported by an open source mapping library called OpenLayers (http://openlayers.org/). Interactive sediment budget geographic feature layers are represented as shapefile data stored in an open source geospatial server called GeoServer (http://geoserver.org/). GeoServer allows for the management and support of standards-compliant services which can be consumed by many standards-supporting mapping frameworks. The GCMRC web application pulls data from GeoServer into the OpenLayers maps using the Open Geospatial Consortium's (OGC) Web Mapping Service (WMS) Standard (Open Geospatial Consortium, 2006); see also http://docs.geoserver.org/latest/en/user/services/wms/reference.html).

If the user navigates in the GCMRC web application to the monitoring station gateway and selects a specific monitoring station, a new page appears with a photograph of the river at the station, an overview map, and the list of parameters available to plot and download for that station. Within the parameter explorer on this station page, a user may select one or more classes of data (e.g., gage height, discharge amount, or water temperature) and select a date range across which the parameter values are graphed or downloaded. Once the server has returned the JSON response called by the browser and the user's request, dynamic charts consume the response contents and display returned data. To power the dynamic graphs, a JavaScript, open source graphing and charting library called Dygraphs (http://www.dygraphs.com/) is employed (see example Figure 3). Once the graphs are produced in the browser, the user can further refine the time-series displayed by adjusting its related slider to a specific time period, or get more details by hovering over the display to highlight and call out specific point in time values. The download function on each station page allows downloading of any of the time-series data with time stamps in any user-defined format. This function also allows downloading of the full laboratory-processed suspended- and bed-sediment datasets (including all ancillary data fields).

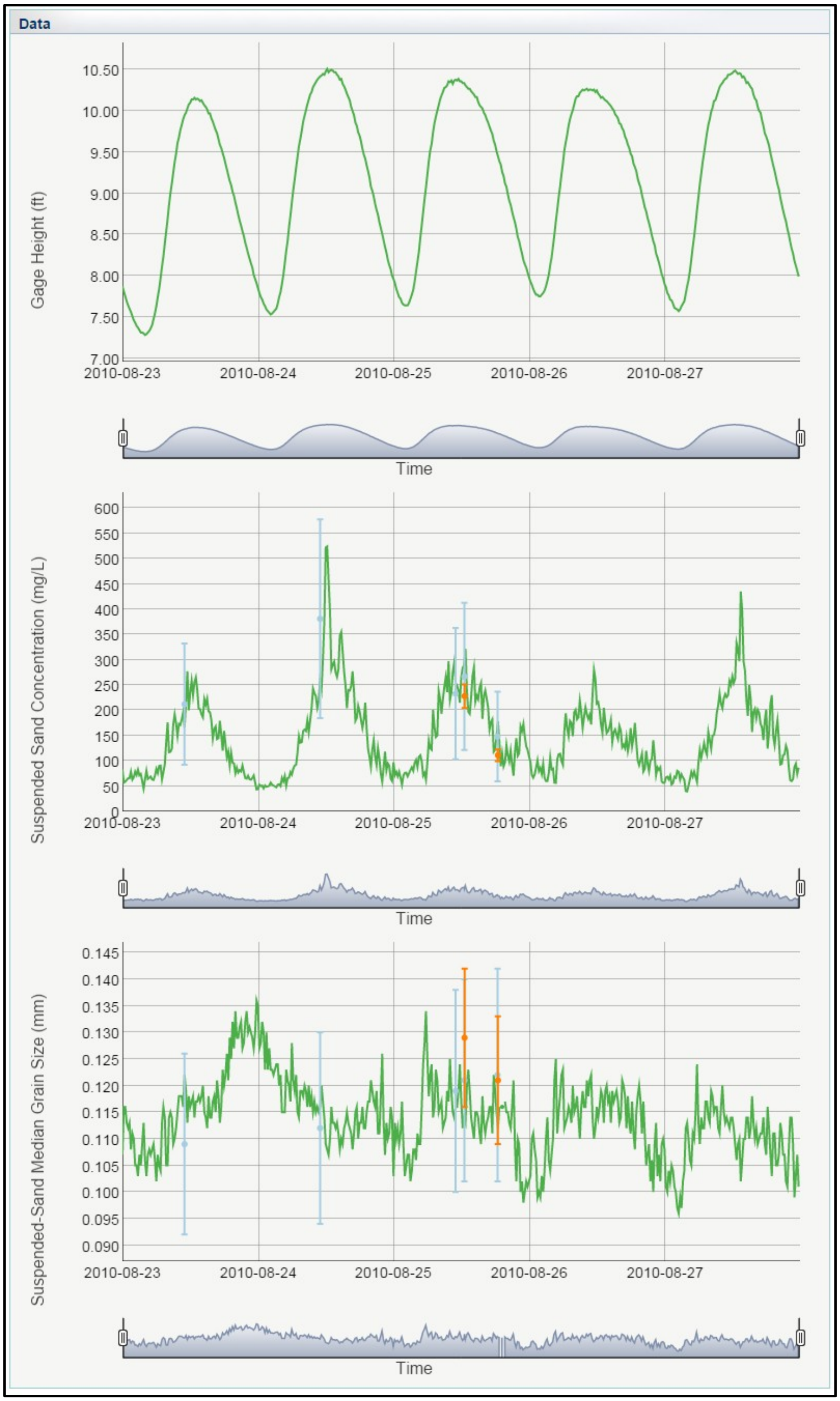

Figure 3 Example of plots of discharge, suspended-sand concentration, and suspended-sand median grain size at the Colorado River near Grand Canyon, AZ, 09402500 gaging station. Acoustic measurements of suspended-sand concentration and median grain size are depicted in green in the lower two plots. Orange points are EDI measurements, light blue points are calibrated-pump measurements. Error bars are 95%-confidence-level errors.

In addition to exploring specific stations' stacked parameter plots, scientists and managers can enter the sediment-budget gateway web pages and select a reach for construction of a mass-balance sediment budget. For any selected reach, the user has the option of setting the time period, modifying the uncertainties (i.e., possible persistent biases) in the various sediment-load time-series used to construct the budget, and modifying the bedload coefficient used to account for bedload in the river, in addition to the measured suspended-sediment load. For all reaches, default values of the possible persistent biases and bedload coefficients based on the best-available scientific information (e.g., Rubin et al., 2001) are pre-selected. An example of a mass-balance sand budget is provided in Figure 4.

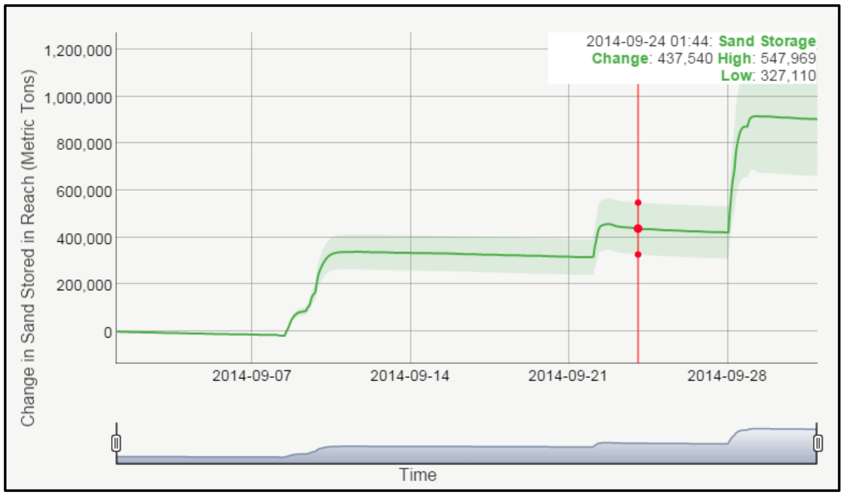

Figure 4 Example of Dygraphs plot of sand storage in the Upper Marble Canyon reach in Grand Canyon National Park.

The zero-bias value is plotted as the solid green line; the green shaded region indicates the region of uncertainty about the zero-bias value. Moving the red slider across the budget allows the user to see the zero-bias, upper, and lower bounds (given the chosen uncertainties) of the change in sediment mass for the selected time period. The ability of modifying the uncertainties in the loads is important because it allows river managers to evaluate "how well the sediment budgets need to be known" in their decision-making process.

RESULTS AND DISCUSSION

When viewing data, a user needs more than mere numerical accuracy. Meaningful conceptual and spatial presentations are essential for grasping the meaning of data. This is particularly crucial in decision-support uses of datasets. The GCMRC web application allows the user, whether a scientist, manager, or member of the lay public, easy access to user-interactive visualizations of discharge, water quality, and sediment data.

The advantage of open web applications—that they require no tools beyond a modern web browser for access and use—needs no elaboration. The GCMRC web application is built with open source components running against a standard relational database interface, making the cost of enhancements and extensions predictable and moderate. The use of web services to provide the data on request allows external users to integrate GDAWS data into other applications or models. The combination of open web services and the open browser application client allows the user easy, verifiable, and clearly comprehensible access to complicated datasets at essentially no cost.

An unprecedented resource: The user-interactive sediment-budgeting tools provided in the GCMRC web application are unique in the world. We have, for the first time, made well-established sediment-budgeting methods available on demand.

Using this tool, river scientists and managers can create a new sediment budget for a selected river reach for any time period of interest (limited only by data availability) with different levels of uncertainty within a matter of minutes. Prior to the development of this tool, the construction of a mass-balance sediment budget was a tedious process that required hours of data downloading, manual data entry, data manipulation, and mathematical operations (all the time running the risks of mistakes because these procedures were not automated in a repeatable workflow). This work was primarily done only by scientists and then presented to managers. Now, managers and members of the lay public can create sediment budgets on their own, on demand, and in real-time using the most up-to-date data available.

The real thing: The GCMRC web application is a working system in production use by multiple teams and programs. It is not a temporary proof of concept. The user-interactive sediment-budgeting tools are being used by river managers and science teams in multiple programs.

First and foremost, these tools are being used on a monthly basis by engineers in the Bureau of Reclamation working within the Glen Canyon Dam Adaptive Management Program (GCDAMP) to plan and implement the release of controlled floods from Glen Canyon Dam to rebuild sandbar habitat in Grand Canyon National Park when downstream sand conditions warrant (U.S. Department of the Interior, 2012). The sediment-budgeting tools are also being used in GCDAMP to evaluate the sediment response to these controlled floods and to evaluate the effects of hydropower operations at Glen Canyon Dam on the sand resources in multiple reaches of the Colorado River in Grand Canyon National Park and Lake Mead National Recreation Area. National Park Service managers also employ the sediment-budgeting tool to seasonally evaluate the effects of flows released from Flaming Gorge Dam on the Green River in combination with natural flood flows from the Yampa River on the sediment resources in Dinosaur National Monument (e.g., Mueller et al., 2014a,b). Finally, the sediment-budgeting tool is being used by scientists to evaluate the effects of upstream Mexican dam releases and local tributary floods on channel and floodplain evolution in the Rio Grande in Big Bend National Park (Dean et al., 2015).

Still generating useful new capabilities: Additional user-interactive functions are being developed for the GCMRC web application over the next few years to continue to improve access to managers and the lay public of tools previously only available to scientists. Some of these may prove as powerful as the sediment-budgeting tools described in this paper. Chief among these new additions will be the development of a duration-curve tool that will allow the user to plot the time equaled or exceeded for any parameter served via the GCMRC web application.

More information about the loosely coupled architecture described and all of the open source components developed for the GCMRC web application are available in a USGS-supported GitHub repository (https://github.com/USGS-CIDA). Anyone interested in expanding the work is welcome to fork the main repository and contribute their own ideas and working code to the project.

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