THE USE OF TURBIDITY SENSORS FOR MONITORING SEDIMENT LOADS FOLLOWING WILDFIRE

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Abstract: Turbidity sensors (OBS-3 and OBS-5; D & A Instruments) were deployed to monitor sediment loads following a moderate-to-severe burn in the Little Granite Creek watershed near Bondurant, WY. The sensors were installed at the mouth of a burned tributary, in an adjacent reference tributary watershed, and at a longer-term study site on the main stem. Sensors were calibrated using depth-integrated samples taken with DH-48 suspended sediment samplers and from samples obtained using ISCO automated water samplers. The ISCO samplers were later programmed to collect samples once a threshold turbidity value was exceeded. This scheme allowed the collection of more samples during periods in which rapid changes in sediment loads were most likely to occur. Generally, the turbidity sensors characterized the sediment load at all sites very well during periods of snowmelt runoff, with good correspondence between turbidity values and measured suspended sediment concentrations. However, fouling problems were encountered at the 2 sites below the burned area during summer baseflow when slower and warmer water fostered the growth of algae on the sensors. The growth was quite rapid, with detectable fouling occurring within days after cleaning at one site. This likely could have been avoided with more frequent cleaning of the sensor or the use of a device with an automated cleaning wiper. In short, turbidity sensors showed promise as a surrogate for monitoring sediment loads following large-scale disturbance, such as wildfire. However, the results underscore the need for periodic and on-going collection of suspended sediment samples to calibrate the signal from the sensors and to identify shifts in relationships between turbidity and suspended sediment concentration.

INTRODUCTION

Substantial increases in sediment loads commonly occur in channels downstream of areas burned by wildfire. Rapid increases in sediment are typically associated with increases in runoff generated by high intensity rainfall. Such events are often short-lived, but can deliver a tremendous amount of sediment to the aquatic system and potentially to water supply systems further downstream. Monitoring sediment loads in these systems can provide information about sediment transport rates and processes occurring after large scale disturbances, as well as the precipitation intensity required to trigger sedimentation events. However, given the episodic nature of these pulses in sediment and flow, it is often difficult to adequately characterize sediment concentrations using a discrete water sampling scheme. Turbidity sensors, which measure light backscattering from particles suspended in water, have been utilized as a surrogate measure of suspended sediment concentration (SSC) (Kuhnle and Wren 2005). High turbidity generally indicates a high concentration of material, including organic and inorganic sediment. Turbidity sensors that have been programmed to measure on a relatively frequent basis (e.g., 15 minute interval) can provide highly detailed information on sediment transport, particularly when calibrated using periodic grab samples of SSC.

As part of a monitoring program following a wildfire, we deployed turbidity sensors to provide estimates of SSC at Little Granite Creek near Bondurant, WY. The monitoring was conducted in control and burned watersheds during snowmelt runoff and summer baseflow periods. The objectives were to determine 1) if there was a predictable relationship between turbidity and measured suspended sediment concentrations, and 2) whether the sensors worked with sufficient consistency so that they could be used to replace the discrete water collection program. Turbidity values were linked to sediment concentrations measured concurrently and regression relationships were developed. The quality of these statistical relationships and departure over time are discussed. Problems encountered with instrument fouling are also described, as are recommended methods for reducing these difficulties.

WATERSHED DESCRIPTION

Little Granite Creek, an upland contributor to the Snake River system, drains 21.1 miles^2 (54.6 km^2) of the Gros Ventre range near Bondurant, Wyoming, south of Jackson, Wyoming. A sediment sampling program at this site began in 1982 as part of environmental monitoring in conjunction with planned exploration and extraction of fossil fuels in the upper basin. Though the exploratory effort was eventually abandoned, suspended sediment monitoring was continued by the USGS through 1993 (Ryan and Emmett 2002), providing an extensive dataset against which changes in sediment loads due to wildfire could be detected (Ryan et al. 2003). The area is administered by the USFS, Bridger-Teton National Forest, Jackson Ranger District. Over half of the basin is in the Gros Ventre Wilderness Area.

Detailed descriptions of the Little Granite Creek watershed are provided in Ryan and Emmett 2002 and Ryan et al. 2003. Briefly, the two main tributaries of Little Granite Creek are Boulder Creek (8.0 miles^2/20.7 km^2) and the upper basin of Little Granite Creek (7.6 miles^2/19.7 km^2). Approximately 80% of the forested area in Boulder Creek and less than 5% of that in upper Little Granite Creek burned in 2000 (Figure 1). Both basins face south and had similar pre-fire forest cover (Engelmann spruce, subalpine fir, and lodgepole pine) and geology (sedimentary formations of marine origin (Love and Christiansen, 1985)). Flow and rates of sediment transport were monitored at (1) the mouth of Boulder Creek (burned), (2) upper Little Granite Creek (reference), and (3) Little Granite Creek above the confluence with Granite Creek (site of previous work) (Figure 1). Site 3 is approximately 2.5 river miles (4 km) downstream of the burned area. The elevations of the monitoring sites are around 6,500 feet (1981 m.).

Little Granite Creek near Bondurant, Wyoming

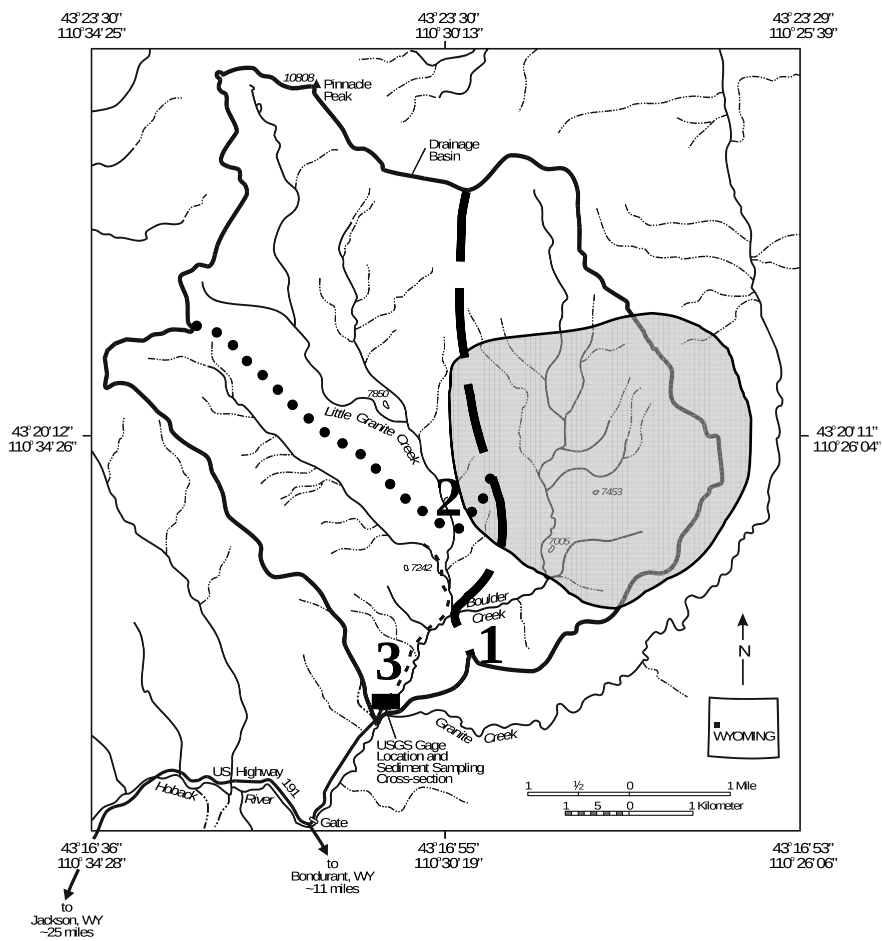

Figure 1 Map of Little Granite Creek watershed. Stipple pattern approximates the area burned by the Boulder Creek fire in 2000. An estimated ¾ of the area burned with moderate to high severity. The dark dashed line delineates the Boulder Creek watershed and the dotted line indicates the limits of the unburned watershed (upper Little Granite Creek). Numbers are described in text. The light dashed line represents an unimproved forest road.

The primary sources of sediment in the watershed come from mass wasting, including active earthflows from unstable hill slopes, and slumping from undercut terraces and road cuts. Baseline concentrations of suspended sediment at high flows are relatively high (between 100 and 1000 mg L^{-1}) because of the underlying marine sedimentary formations (Ryan and Dixon, in review). By comparison, similar measurements in streams in forested areas draining granitic terrain are rarely greater than about 100 mg L^{-1} (Andrews 1984).

METHODS

In 2002, an OBS-5 turbidity sensor (D & A Instruments 2005) was deployed at the Lower Little Granite Creek site, downstream of the burned area (Figure 1, site 3). This device was selected in anticipation of very high sediment loads following wildfire because particle concentration detected by this sensor are greater than those of many other sensors. The sensor was calibrated at the factory using a suspended sediment sample collected from the site in 2001. The device was attached to a metal post that had been driven into the channel bed adjacent to a sampling platform from which water and sediment samples were obtained. The device was adjusted for changing flow depth several times during the runoff season. The internal datalogger was programmed to take a reading and recorded an estimate of SSC once every 5 minutes. These values were later correlated with SSC's measured once every 4 hours by an ISCO automated water sampler (Teledyne ISCO 2005) and with samples taken with a DH-48 depth integrated sampler (Edwards and Glysson, 1998; Federal Interagency Sedimentation Project 2005) on an intermittent basis.

In 2003, OBS-3 turbidity sensors (D & A Instruments 2005) were deployed at each of the 3 sites in Little Granite Creek watershed (Figure 1). These devices were selected because results from the previous year indicated that the range of measured particle concentrations was within the limits established for this device. The sensors were installed on a metal post driven into the channel bottom at each of the monitoring stations. The height of the OBS-3 was manually adjusted during the flow season so that the sensor was seated at about ½ the depth of the flow (± depending on daily flow fluctuations). Data collection and instrument programming were performed using Campbell CR10x dataloggers (Campbell Scientific 2005). At 15-minute intervals, the dataloggers recorded the median of a series of 20 turbidity readings taken in rapid succession. Turbidity values (FTU) from the OBS-3 were calibrated using SSC determined from samples collected intermittently using a DH-48 sampler. Later in the season, automated water samplers were installed and programmed to collect water samples when a threshold turbidity value was exceeded (Eads and Lewis 2002). This sampling scheme permitted the collection of samples only when rapid changes in sediment concentrations were likely to occur, thereby reducing the overall number of samples collected and processed. The turbidity threshold above which collection was initiated varied by site due to differences in load characteristics (expected concentration range, color, etc.) in the burned and reference watersheds.

Stage data were collected at 15-minute intervals in both 2002 and 2003 using Aquarod stage recorders or pressure transducers. Intermittent discharge measurements were made at each of the 3 sites (about 25 per runoff season) and stage-discharge relationships were developed.

RESULTS

Turbidity and Suspended Sediment Measurements – 2002: An overall linear relationship between estimates obtained with the calibrated OBS-5 sensor and concentrations from the automated samplers was observed (Figure 2). However, the relationship differs for low and high ranges of concentrations and is never 1:1. Though not easily discerned at the scale shown, at low concentrations, estimates from the OBS-5 consistently overestimated measured concentrations by about 100 mg L^{-1}. This discrepancy did not appear to be related to fouling of the sensor and may reflect a limit in resolution at the lower end as this particular device is intended for use in flow with higher concentrations of sediment. There was better correspondence between measurements and estimates at higher concentrations (>500 mg L^{-1}) where differences were on the order of 10-40% of the measured values. A notable departure from the general trend was observed for samples following a storm on September 7, 2002 (shown in purple, Figure 2). The values from the OBS-5 over-predicted measured concentrations during this storm by a factor of 4 to 5. The differences for this short period are likely due to changes in the sediment characteristics following the rainstorm and, hence, visual qualities of the stream water. For instance, differences in organic matter content or particle sizes will change the amount of backscattered light received by the sensor, causing erroneous estimates from a pre-calibrated device. While the exact cause of this particular discrepancy is unknown, the results underscore the need for periodic and on-going collection of suspended sediment samples to calibrate the signal from turbidity sensors and to identify shifts in established relationships between turbidity and SSC.

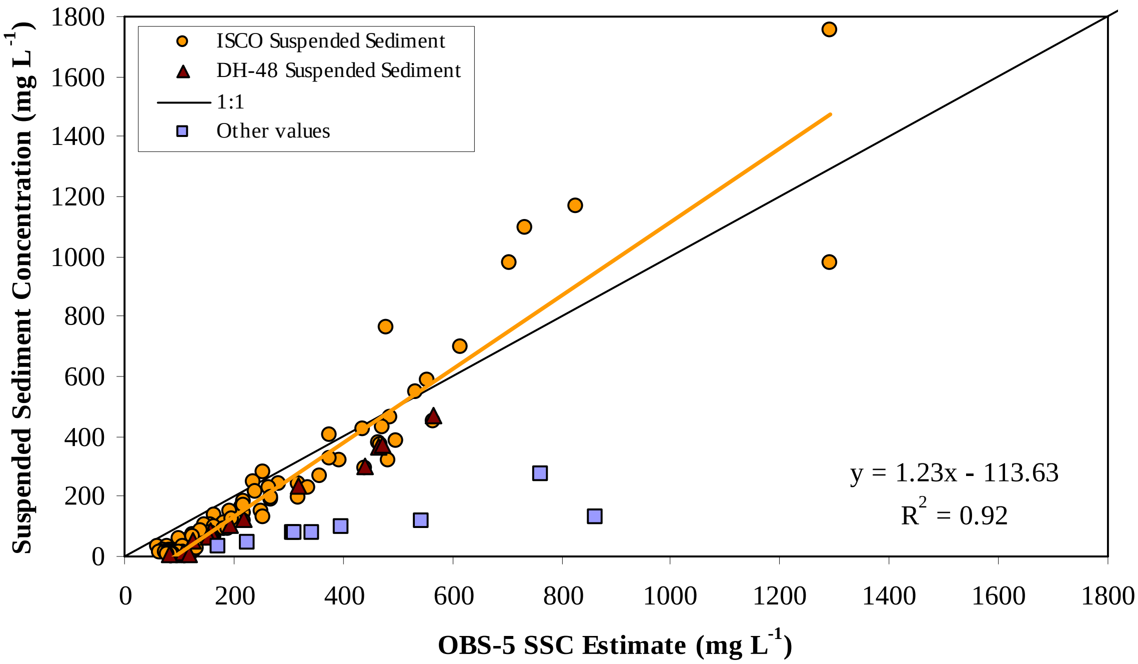

Figure 2 Relationship between estimates of suspended sediment concentration obtained with a (calibrated) OBS-5 turbidity sensor and measurements from ISCO automated samplers (orange circles) at Lower Little Granite Creek. Correspondence between samples obtained with automated and depth-integrated samplers was close to 1:1, as shown by the overlap between orange circles (ISCO) and red triangles (DH-48). This indicates that the flow was well-mixed and no correction factor for the automated sampler was required. Purple squares (excluded from the regression) depict a drift in the relationship between turbidity and ISCO samples following a rain storm in late summer.

Turbidity and Suspended Sediment Measurements – 2003: OBS-3 turbidity sensors were installed on the rising limb of the snowmelt hydrograph in 2003 and removed from the sites in early fall. Similar to that observed in 2002, there were linear relationships between measured (raw) turbidity values and SSC's at all 3 sites (Figure 3), though these relationships often varied over the course of the hydrograph (Figure 3, e.g., Boulder Creek). At Upper Little Granite Creek, the predictive relationship over the duration of the measurement period was quite good as the departure of individual measurements of SSC was relatively small (Figure 4a). The automated sampler was triggered to collect water samples during two storms in late summer and there was close correspondence between measured and predicted SSC during these events. At Lower Little Granite Creek, there was good correspondence from the period of late May to early June (Figure 4b). Shortly thereafter, there was notable departure on the falling limb of the seasonal hydrograph as the sensor became increasingly fouled due to the growth of algae over the lens. This occurred as flows became slower and warmer and the period of ambient light availability increased. Turbidity values returned to expected levels following sensor cleaning, but there continued to be fouling problems during June and July until a regularly scheduled cleaning program could be established. At Lower Little Granite Creek, this was achieved by cleaning the sensor on a weekly basis. At Boulder Creek, a more frequent program was needed. Here, the sensor often became fouled within days after cleaning, providing erroneous turbidity values that are difficult to discriminate from the main record (data not shown). The automated water sampler at Lower Little Granite Creek was triggered to collect samples during 5 higher concentration events, though one (September 12) appears to be a false trigger initiated, in part, by sensor fouling.

Estimates of peak concentrations during snowmelt runoff in 2003 ranged from about 450 to 3,330 mg L^{-1} at Upper Little Granite and 450 to 4,800 mg L^{-1} at the Lower site (Figure 4). This suggests that differences in SSC between the upper and lower sites were not substantial over the early part of the record. For comparison, concentrations in the first post-fire year (2001), measured using a discrete sampling program, ranged from 300 to 1,200 mg L^{-1} at Upper Little Granite and 350 to 5,700 mg L^{-1} at Lower Little Granite during the snowmelt period (Ryan et al. 2003).

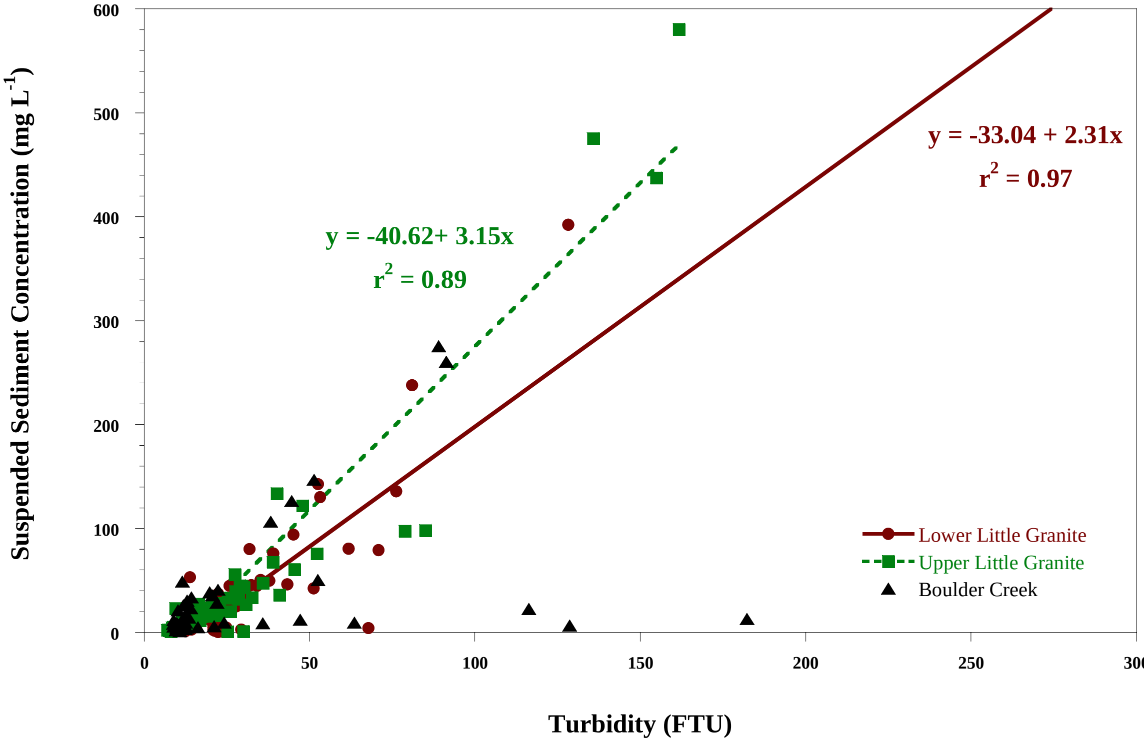

Figure 3 Relationships between turbidity values and measured SSC at 3 sites in Little Granite Creek watershed. Standard error of the residuals at Lower Little Granite was 30.1 and was 33.9 at Upper Little Granite. One additional data point for Lower Little Granite is beyond the limits of this plot, but is included in the regression. No single regression could be determined for the Boulder Creek site as the relationship between turbidity and SSC varied over the measurement period.

Most of the estimates of peak concentrations from the turbidity sensors fall within the range of those measured previously, suggesting that they are realistic values. Higher projected concentrations at Upper Little Granite in 2003 are likely due to the ability to obtain estimates from turbidity sensors during periods that were unsampled by the discrete sampling program. Notably, the peak concentrations from the turbidity record use a reliable statistical relationship, providing increased confidence in the estimate of SSC for these periods. To predict peak concentrations using the discrete data, one would need to establish a relationship between flow and SSC and extrapolate this relationship to higher discharges. Given that the relationship between flow and SSC varies greatly over different parts of the seasonal hydrograph (Ryan and Dixon, in review), this estimate has greater inherent uncertainty than that obtained using turbidity/SSC relationships.

Estimates of SSC obtained during baseflow and summer thunderstorms at Upper and Lower Little Granite were also comparable, though more variability was exhibited in the Lower Little Granite data (Figure 4b). This may be due, in part, to the crossing of more than 1 log cycle, which visually exaggerates small differences in SSC in the 0.1 to 1 range. The difference in ranges may also be an artifact of the model used to estimate concentration from turbidity. SSC estimates for Upper Little Granite ranged from 2 to 8 mg L^{-1} during baseflow and increased up to 200 mg L^{-1} during a single event in early September. SSC estimates for Lower Little Granite ranged from 0.2 to 10 mg L^{-1} and increased up to 120 mg L^{-1} during the same event.

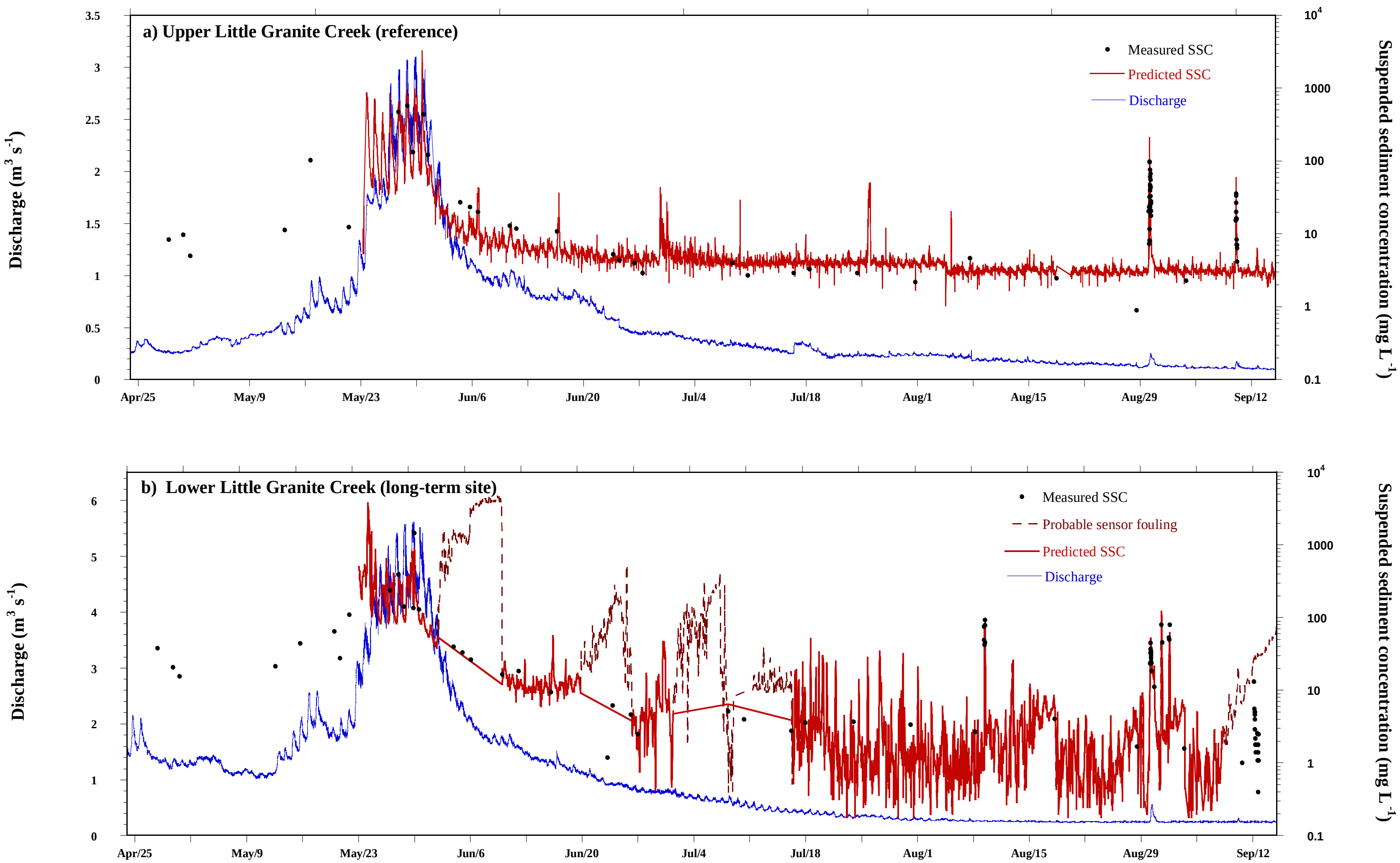

Figure 4 Suspended sediment concentration estimated from values of turbidity from OBS-3 sensors at a) Upper and b) Lower Little Granite Creeks in 2003 (red line). Individual DH-48 samples are shown as black circles and discharge is indicated as a blue line. SSC is plotted on a logarithmic scale to show better the correspondence between predicted and measured values. Though a slightly larger range of values exists for Lower Little Granite during baseflow, this appears exaggerated in (b) where the values cross more than 1 log cycle.

DISCUSSION AND SUMMARY

The purpose of this paper was to report findings on the relationship between measured SSC and turbidity values obtained under reference conditions and at sites below an area recently burned by wildfire. Generally, there was good correspondence between turbidity values and SSC and this relationship could be used to develop time-series data for sediment concentration. Such information can potentially improve the understanding of the timing and magnitude of instream sediment transport relative to changing hydrologic conditions or large-scale sediment inputs following disturbance. It also improves the understanding of the inherently variable nature of sediment concentrations over different ranges of timescale. Moreover, implementing a sampling scheme using a turbidity threshold permits the collection of water samples during periods of higher and more rapidly changing sediment conditions, potentially improving the predictive capabilities of the turbidity/SSC relationship(s). Automating the process allows sample collection during periods often missed by a discrete or intermittent sampling program when travel to a site is impossible or impractical.

As shown here and elsewhere, the use of turbidity sensors show great promise in supplementing a discrete water sampling program. However, in order to derive a meaningful record, it is imperative that the turbidity meters be kept free of debris, either by using an automated wiper for smaller materials (biological fouling) or frequent manual cleaning of the sensor surface (which may be impractical in remote locations). Frequent cleaning will help prevent erroneous measurements of turbidity and false triggering of sample collection due to sensor fouling. Our results also underscore the need for periodic and on-going collection of suspended sediment samples to calibrate the signal from the sensors and to identify shifts in relationships between turbidity and SSC.

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REFERENCES

Andrews, E.D. (1984). “Bed-material entrainment and hydraulic geometry of gravel-bed rivers in Colorado.” Geological Society of America Bulletin, 95, pp. 371-378.

Campbell Scientific (2005). “ CR10X datalogger for measurement and control.” [On-line] Available: http://www.campbellsci.com/cr10x [August 22, 2005].

D and A Instruments (2005). “D and A Instrument Company.” [On-line] Available: http://www.d-a-instruments.com/ [August 22, 2005].

Eads, R., and Lewis, J. (2002). “Continuous turbidity monitoring in streams of Northwestern California.” Turbidity and Other Sediment Surrogates Workshop, April 30 – May 2, 2002, Reno, N. [On-line] Available: http://water.usgs.gov/osw/techniques/TSS/eads.pdf [August 22, 2005].

Edwards, T.K., and Glysson, G.D. (1998). “Field methods for measurement of fluvial sediment.” U.S. Geological Survey, Techniques of Water-Resources Investigations. Book 3, chapter C2.

Federal Interagency Sedimentation Project (2005). “US DH-48 Depth integrating suspended wading type sampler.” [On-line] Available http://fisp.wes.army.mil/Catalog_Page_US_DH-48.htm (August 22, 2005).

Kuhnle, R.A., and Wren, D.G. (2005). “Suspended sediment measurement: data needs, uncertainty, and new technologies.” Proceedings of the Federal Interagency Sediment Monitoring Instrument and Analysis Research Workshop, September 9-11, 2003, Flagstaff, AZ, U.S. Geological Survey Circular 1276, pp. 8-15.

Love, J.D., and Christiansen A.C. (1985). “Geologic Map of Wyoming.” U.S. Geological Survey, prepared in cooperation with the Wyoming Geologic Survey, 3 sheets.

Ryan, S.E., and Dixon, M.K. (in review). “Spatial and temporal variability in stream sediment loads using examples from the Gros Ventre Range, Wyoming, USA.” Gravel Bed Rivers 6, Lienz, Austria, September 5-9, 2005.

Ryan, S.E., Dixon, M.K., Dwire, K.A., and Emmett, W.W. (2003). “Historical and on-going hydrologic and sediment transport research at Little Granite Creek near Bondurant, Wyoming.” Proceedings of the First Interagency Conference on Research in the Watersheds, October 28-30, 2003, Benson, AZ. Agricultural Research Service, pp. 657-662.

Ryan, S.E., and W.W. Emmett. (2002). “The nature of flow and sediment movement at Little Granite Creek near Bondurant, Wyoming.” U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, General Technical Report RMRS-GTR-90. Ogden [Utah].

Teledyne ISCO (2005). “6712 Full-Size Portable Sampler.” [On-line] Available: http://www.isco.com/products/products3.asp?PL=201101010 (August 22, 2005).
