Technical Note: False low turbidity readings during high suspended-sediment concentrations

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Abstract. Turbidity, a measure of water clarity, is monitored for a variety of purposes including: 1) to help determine whether water is safe to drink; 2) to establish background conditions of lakes and rivers and detect pollution caused by construction projects and storm water discharge; and 3) to establish connections with aquatic biological properties, such as primary production and predator-prey interactions. Turbidity is normally measured with an optical probe that detects light scattered from particles in the water. Probes have defined upper limits of the range of turbidity that they can measure. The general assumption is that when turbidity exceeds this upper limit, the values of turbidity will be constant, i.e., the probe is "pegged"; however, this assumption is not necessarily valid. In cases where turbidity greatly exceeds the upper measurement limit, turbidity probes can falsely report incorrectly low values of turbidity that appear to be within the limits of the probe. In rivers with limited variation in the physical properties of the suspended sediment, an increase in suspended-sediment concentration will initially cause a linear increase in turbidity. When the suspended-sediment concentration in these rivers causes turbidity levels that exceed the upper measurement limit of a probe, turbidity probes do not necessarily "peg" at a constant value. Data from the Colorado River in Grand Canyon, Arizona, USA and a laboratory experiment both demonstrate that when turbidity exceeds instrument-pegged conditions, increasing suspended-sediment concentration (and thus increasing turbidity) may cause optical probes to record decreasing "false" turbidity values that appear to be within the valid measurement range of the probe. Therefore, under high turbidity conditions, other surrogate measurements of turbidity (e.g., acoustic-attenuation measurements or suspended-sediment samples) are necessary to correct these low false turbidity measurements and accurately measure turbidity.

1 Introduction

Turbidity, a measure of the scattering and absorption of light in water, is dependent on the characteristics of the particles that are scattering the light, specifically concentration, grain size, grain shape, refractive index, and color (Sadar, 1998; Downing, 2006). For example, clay-sized particles result in much greater turbidity than an equal concentration of sand-size particles (Davies-Colley et al., 1993; Gippel, 1989). Although turbidity is commonly used to monitor change in water clarity, it is not an absolute measure of water clarity in part because it is an instrument-specific measurement. The design components of a

turbidity instrument that affect the range of measurements are the light source, the detector(s), the optical geometry, which includes the path length of the light, and the angle of the detector(s) from the incident light path (Hach et al., 1985; ASTM International, 2011).

5 A commonly used turbidity probe on multi-parameter water-quality instruments is a nephelometric turbidity probe with a single light source and single detector oriented 90 degrees from the incident light path (Fig. 1). Along with turbidity, additional parameters frequently measured from the same water quality instrument include temperature, specific conductance, and dissolved oxygen. These water-quality instruments are particularly useful for detecting variation from typical conditions in rivers and lakes. For example, such instruments have been used for drinking water protection by being deployed upstream of
10 water treatment plants to monitor for high-turbidity runoff events during storms (U.S. Environmental Protection Agency, 2016). The instruments can be set up to trigger alarms when turbidity or other water-quality parameters exceed permitted thresholds, allowing operators to shut down drinking water intakes to protect filtration systems. The water quality instruments have also been used to monitor and regulate turbidity caused by construction and dredging projects in and around natural bodies of water. Turbidity data in the Colorado River are primarily used by biologists to relate to primary production and
15 interactions between native endangered fish and predatory non-native fish competing for limited resources (Hall et al., 2015; Wellard Kelley et al., 2013; Ward et al., 2016; Yard et al., 2011).

With a constant composition and grain-size distribution of suspended sediment, turbidity measured from a single detector instrument increases linearly with increasing suspended-sediment concentration (Fig. 2). At higher suspended-sediment
20 concentrations, turbidity plateaus at the maximum recording level when the detector becomes saturated with light. In some cases, at still higher suspended-sediment concentrations, the recorded turbidity may decrease as light penetration into the sample diminishes (i.e. a negative response, Fig. 2; ASTM International, 2011). This negative response (i.e., incorrectly low turbidity) is characterized by a high percentage of the light being absorbed by the suspended sediment and less light reaching the detector, resulting in progressively lower turbidity readings with increasing sediment concentration. These incorrectly low
25 turbidity readings at high suspended-sediment concentration will hereafter be referred to as false low turbidity. Turbidity measured in the Colorado River in Grand Canyon, Arizona, USA occasionally records as false low turbidity. Without other measures of turbidity, these false low turbidity readings can be confused with similar correct turbidity values recorded during the linear portion of Figure 2 at much lower suspended-sediment concentration.

30 This study describes both field and laboratory conditions that lead to false low turbidity readings. Recognition of false low turbidity is important because the high turbidity conditions that give rise to such measurements could inadvertently result in environmental harm as well as expensive equipment damage. For example, when turbidity is being monitored on a river below a construction site, false low turbidity would underrepresent a high sediment load which may be considered an environmental contaminant. Additionally, the undetected high sediment load could damage, for example, a drinking water filtration system.

2 Methods

2.1 Field sites

Six gaging stations have been established in the study area in the Colorado River in Grand Canyon National Park, Arizona, USA (Fig. 3) to monitor suspended-sediment load as well as water-quality parameters, specifically water temperature, specific

5 conductance, dissolved oxygen, and turbidity. These water-quality parameters are measured using YSI Incorporated (YSI) multi-parameter sondes with turbidity measured using YSI 6136 turbidity probes (the use of firm, trade, and brand names is for identification purposes only and does not constitute endorsement by the USGS). Changes in turbidity of the Colorado River in the study area are primarily caused by changes in suspended-silt-and-clay concentration (Voichick and Topping, 2014). Owing to the large range in silt and clay concentration possible in this river, optical turbidity probes exhibit pegged and false

10 low turbidity on many days per year. Acoustic attenuation is used as a surrogate measure of suspended-silt-and-clay concentration and turbidity in the study area under such pegged and false low turbidity conditions because this method has been shown to provide accurate measurements of silt and clay concentrations (Topping et al., 2007; Voichick and Topping, 2014; Topping and Wright, 2016). Acoustical data and data from the water-quality instruments are collected concurrently every 15 minutes at all stations in the study area. Physical suspended-sediment samples are collected episodically to verify the

15 acoustical and turbidity measurements.

2.2 Laboratory experiment

The largest sources of silt and clay in the study area are the Little Colorado River and the Paria River (Topping et al., 2000, Voichick and Topping, 2014). The sediment used to create high-turbidity conditions in the laboratory was collected from the bank of the Little Colorado River approximately 1 kilometer upstream from its confluence with the Colorado River (Fig. 3).

20 The sediment was passed through a 63 µm sieve to isolate the silt-and-clay-size fraction. Only silt-and-clay-sized sediment was used in the experiment because: 1) silt and clay causes almost all of the turbidity in the study area (Voichick and Topping, 2014), and 2) by eliminating sand, it was much easier to keep the sediment in suspension to achieve accurate turbidity measurements. In addition, silt-and-clay concentration was measured at the gaging stations from suspended-sediment samples and from acoustical measurements (concurrently with turbidity), allowing for comparison of laboratory and field results. The

25 silt and clay was completely dried in an oven (at 105 degrees Celsius for 12 hours), weighed, mechanically disaggregated, and added in stages to a measured volume of water to calculate concentration. The sediment was kept in suspension with an electric stirrer and turbidity was recorded after readings stabilized using the same model of instrument that was present in the study area (YSI 6136 turbidity probe). Sediment concentration, in mg/L, and the corresponding turbidity value in Formazin Nephelometeric Units (FNU) were recorded.

3 Results

3.1 Field data

Between storm-driven tributary floods, the Colorado River in the study area is relatively clear, with turbidity less than 15 FNU for 50 percent of the time (averaged over all stations, Voichick and Topping, 2014). Turbidity was elevated to the probe's

5 maximum recording level (Figs. 2 and 4) from less than 1 percent of the time at the furthest upstream station to 7 percent of the time at the furthest downstream station (over a period of 5 to 8 years depending on the station, Voichick and Topping, 2014). False low turbidity was recorded during 5 percent of the tributary flooding events when actual turbidity was at or above the probes maximum recording level (Figs. 2 and 4). Consistent with the laboratory experiment, false low turbidity was recorded in all cases during the highest sediment concentrations of a flooding event, with the lowest false low turbidity recorded

10 at the peak sediment concentration (Fig. 5). The lowest silt-and-clay concentrations during the false low turbidity readings ranged from 17,000 mg/L to 27,000 mg/L, averaging 21,200 mg/L (Fig. 5). However, 50 percent of flooding events with silt-and-clay concentrations greater than 20,000 mg/L showed no false low turbidity at the highest silt-and-clay concentrations (i.e. turbidity remained "pegged" at the maximum recording level).

3.2 Laboratory experiment

15 At lower silt-and-clay concentration, the laboratory experiment showed a linear increase in turbidity with increasing silt-and-clay concentration (Fig. 4). Starting at approximately 3,000 mg/L silt-and-clay concentration, turbidity pegged and recorded at the maximum recording level until false low turbidity was initially recorded at approximately 38,000 mg/L after which measured turbidity incorrectly decreased nonlinearly with increasing silt-and-clay concentration.

4 Discussion and conclusions

20 Data from the Colorado River in the Grand Canyon study area agree with laboratory results showing that when deploying a turbidity probe with a single, 90 degree oriented, detector, false low turbidity is possible at high suspended-sediment concentrations (Figs. 2, 4, and 5). The working range of a turbidity probe is the linear portion of the response curve, when turbidity increases linearly with increasing sediment concentration (assuming constant sediment characteristics, Figs. 2 and 4). This is generally stated as a particular range of turbidity values. For the turbidity probe used in the Grand Canyon study area,

25 the working range defined by the manufacturer is 0 to 1000 FNU. Importantly, the laboratory experiment and field data from the Grand Canyon study area showed that many of the false low turbidity readings were reporting within the apparent working range of the turbidity probe. Thus, these readings could unknowingly be interpreted as correct (and relatively low) turbidity even though they represent some of the highest suspended-sediment concentrations (and thus some of the highest values of turbidity) seen at the particular site, significantly higher than the working range of the turbidity probe. In the Grand Canyon

30 study area, acoustic attenuation is used to estimate turbidity above the working range of the probe, based on the linear relation

between turbidity and acoustic attenuation (Voichick and Topping, 2014). In the example shown in Figure 5, the actual turbidity based on concurrent acoustical data was up to 60 times greater than the probe's false low turbidity readings.

Whereas turbidity readings at the maximum recording level of the probe are easily recognized, false low turbidity could be confused with similar turbidity recorded at much lower sediment concentrations. The sediment concentration at which false low turbidity occurs will depend on the characteristics of the sediment, particularly the grain-size distribution, as well as the properties of the instrument, such as path length and detector angle. In the Colorado River study area, there were a large range of silt-and-clay concentration threshold values when false low turbidity occurred (from 17,000 to 27,000 mg/L); this was likely due to variation in silt-and-clay grain-size distribution as well as other sediment characteristics, perhaps due to differing sediment sources (Voichick and Topping, 2014).

In some rivers, including the Colorado River in Grand Canyon, suspended-sediment concentration is not related to discharge because most or all of the suspended sediment is contributed from tributaries with little discharge compared to the mainstem river. In these rivers, discharge cannot be used to estimate suspended-sediment concentration. Thus, false low turbidity is often difficult to recognize without an alternative method of measuring turbidity, such as acoustically or by collecting and analysing physical suspended-sediment samples. The consequences of not recognizing false low turbidity are: 1) underestimating turbidity, and 2) missing the timing and distribution of the peak sediment concentration of a flooding event. In the example shown in Figure 5, false low turbidity occurred during approximately 70 percent of the suspended-sediment load of the flooding event. Additionally, because false low turbidity occurs only during the highest suspended-sediment concentrations, false low turbidity occurs during floods with the largest sediment loads. Without additional evidence, a period of false low turbidity (Fig. 5) would likely be incorrectly interpreted as a period of real low turbidity between two flooding events instead of the period of true maximum turbidity and suspended-sediment concentration during a single large flooding event. Without knowing that false low turbidity does not represent the true turbidity, water could, for example, mistakenly be drawn into a water treatment plant and cause damage to the filtration system. If associated with the monitoring of a construction or dredging project, false low turbidity could result in regulators being unaware of environmental damage caused by the actual, much-higher turbidity. In cases where turbidity is monitored to link water clarity with biological processes such as primary production or fish behavior, false low turbidity could result in an incorrect interpretation of these data relations.

Our results suggest that when low turbidity readings are bracketed by pegged turbidity readings, false low turbidity should be suspected. Data showing this pattern should be verified using surrogate measures of turbidity, such as acoustic attenuation or suspended-sediment concentration, especially if suspended-sediment concentration is known or suspected to be particularly high (e.g. greater than several thousand mg/L).

5 Competing interests

The authors declare that they have no conflict of interest.

6 Data availability

Gaging-station data can be accessed, plotted, and downloaded
5 at: https://www.gcmrc.gov/discharge_qw_sediment/ or https://cida.usgs.gov/gcmrc/discharge_qw_sediment/. Data associated
with the suspended-sediment laboratory experiment are available from the USGS ScienceBase-Catalog
at: https://doi.org/10.5066/F72N516S.

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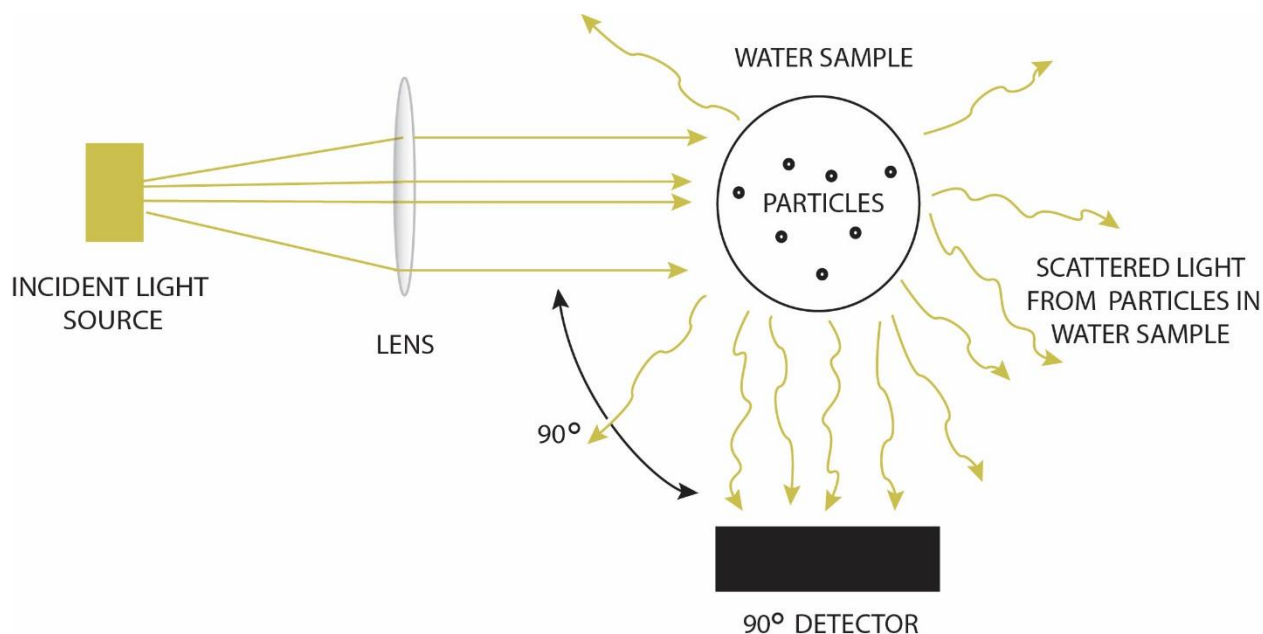
Figure 1: Diagram showing the design components of a nephelometric turbidity instrument: the light source, the detector, and the optical geometry. The diagram shows a single detector oriented 90 degrees from the incident light path, which was used in the Colorado River study described in this paper (modified from Sadar, 2009).
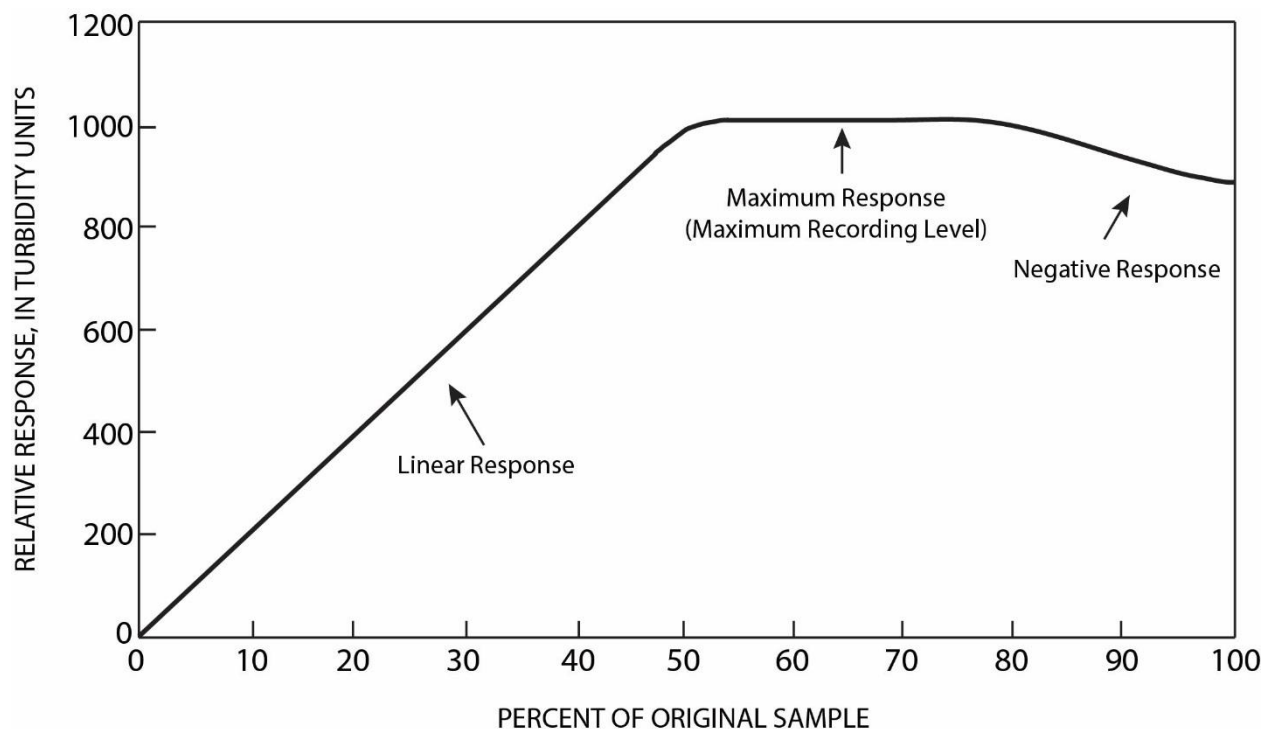
Figure 2: Generic response curve of a single detector turbidity instrument showing three turbidity responses. The turbidity response is dependent on the characteristics of the turbidity instrument as well as the concentration of material in the sample, such as sediment (modified from ASTM, 2011).
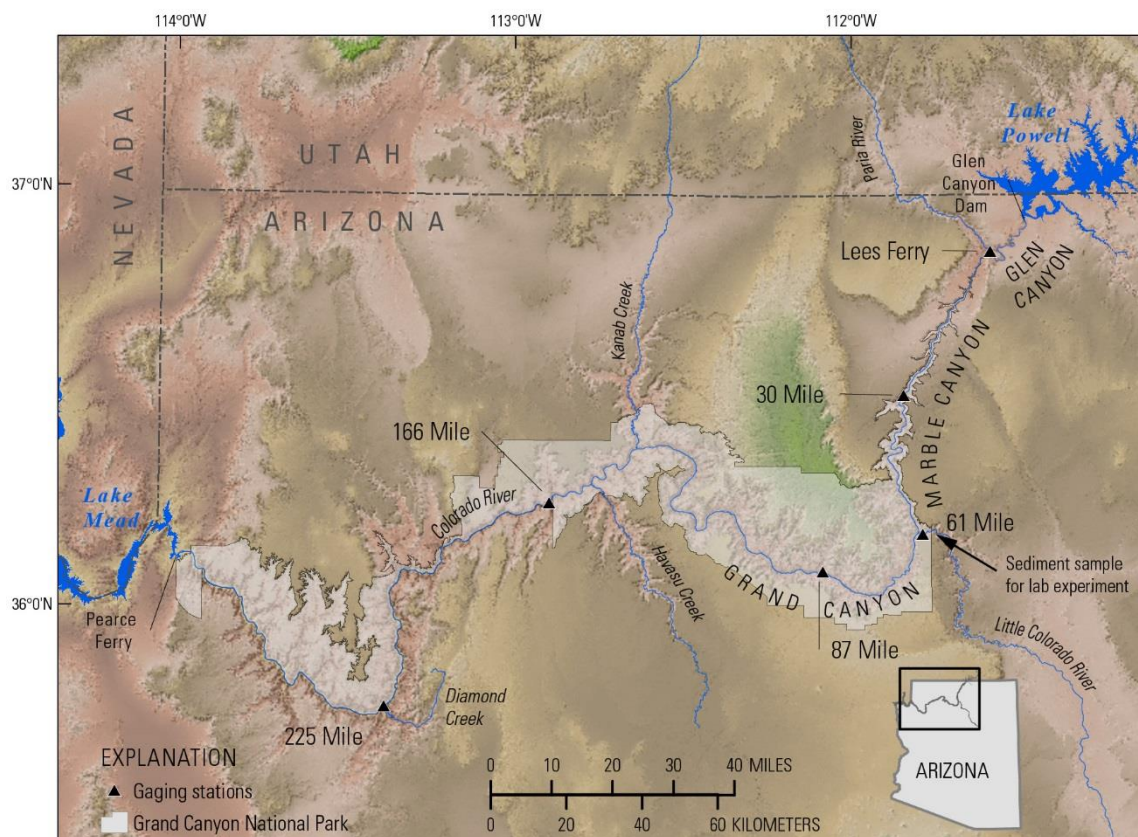
Figure 3: Map of northwestern Arizona, showing the study area in Grand Canyon, major tributaries, and the location of the gaging stations. Gaging stations at which turbidity, suspended sediment and other water-quality data were collected are: Colorado River at Lees Ferry, AZ, 09380000 (abbreviated as Lees Ferry); Colorado River near river mile 30, 09383050 (abbreviated as 30 Mile); Colorado River above Little Colorado River near Desert View, AZ, 09383100 (abbreviated as 61 Mile); Colorado River near Grand Canyon, AZ, 09402500 (abbreviated as 87 Mile); Colorado River above National Canyon near Supai, AZ, 09404120 (abbreviated as 166 Mile); and Colorado River above Diamond Creek near Peach Springs, AZ, 09404200 (abbreviated as 225 Mile).
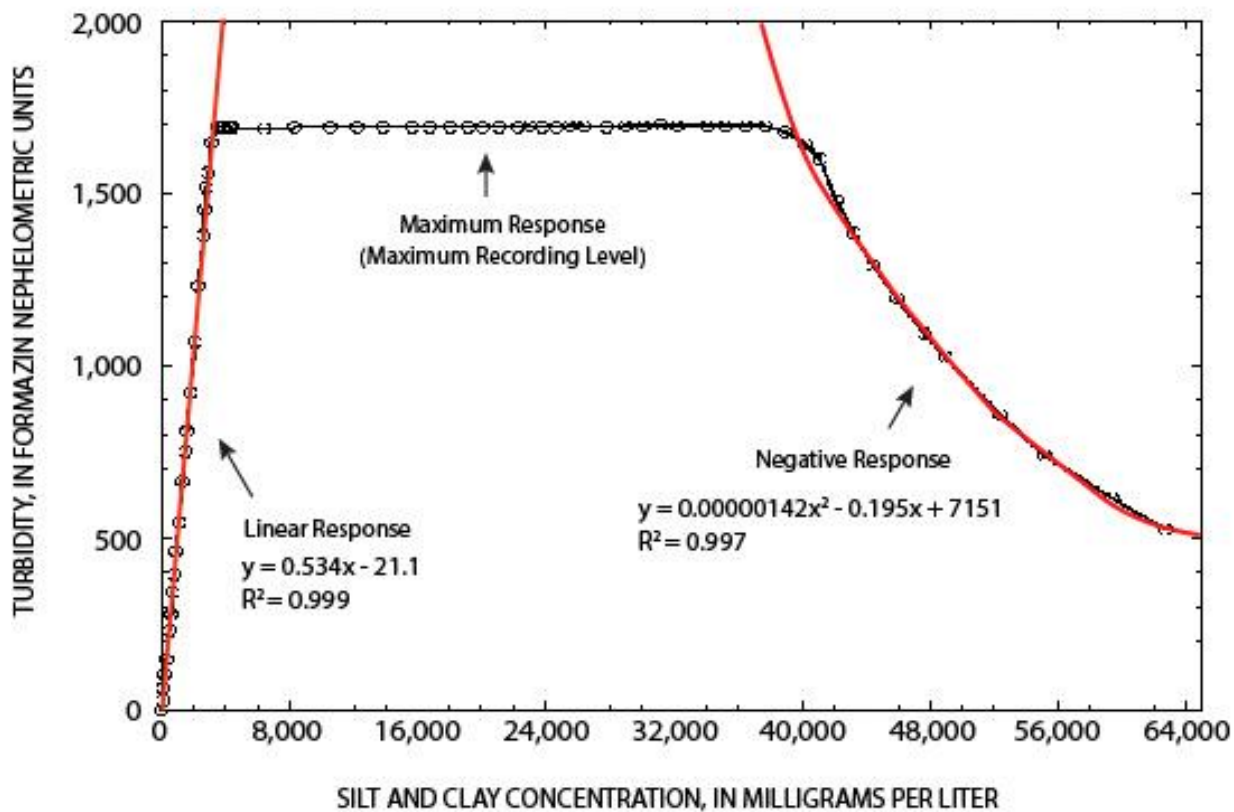
Figure 4: Graph showing the relation between silt-and-clay concentration and turbidity during a laboratory experiment. The silt and clay was obtained from the Little Colorado River (Fig. 3) and turbidity was measured using a YSI Incorporated model 6136 probe. The fitted curves for the linear and negative response portions of the graph are shown in red.
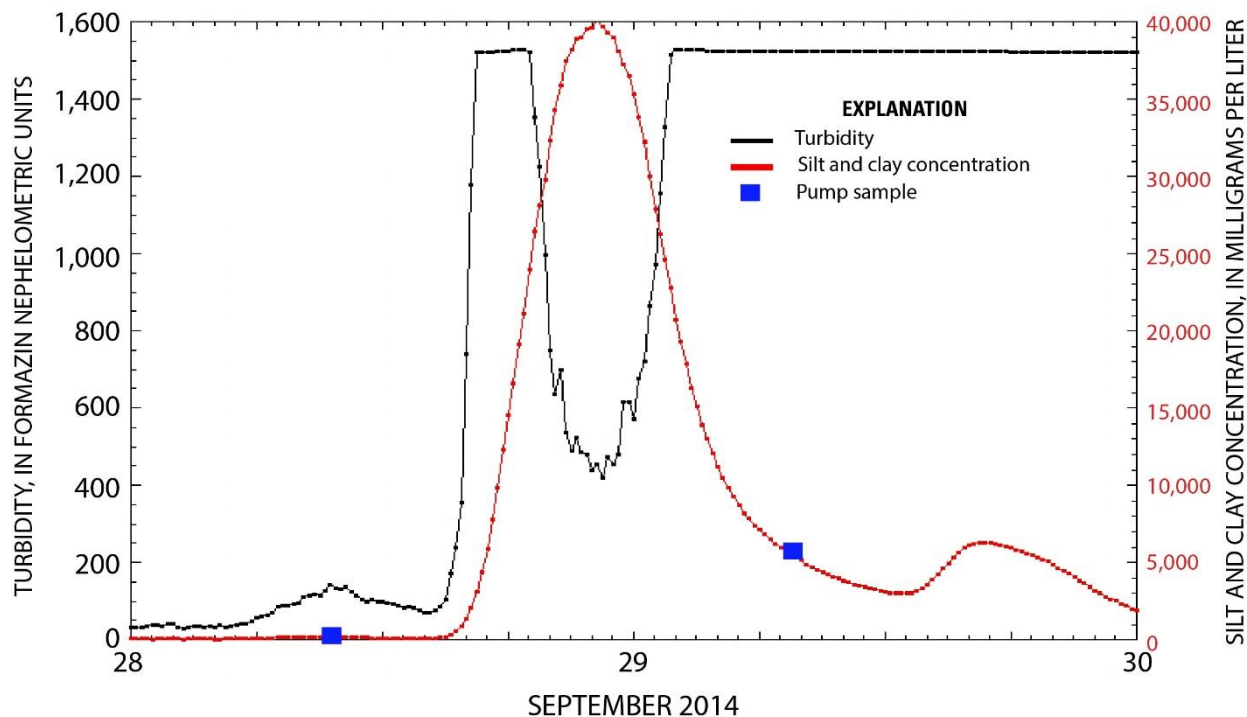
Figure 5: Graph of turbidity (shown in black) and silt-and-clay concentration measured with a 1MHz acoustic-Doppler instrument (shown in red, pump sample silt and clay concentration shown in blue) at the Colorado River near river mile 30 gaging station (Fig. 3) from September 28 to 30, 2014. Turbidity changed from a linear response to increasing silt-and-clay concentration, to a maximum response (i.e. pegged readings), to a negative turbidity response (defined as false low turbidity), which first occurred at 19:15 on September 28 when the concentration was 26,400 mg/L. The false low turbidity continued until silt-and-clay concentration decreased to 24,600 mg/L at 1:30 on September 29. As this suspended-sediment pulse travelled downstream, a similar false low turbidity was seen at all four downstream gaging stations (Fig. 3).