Using temporal changes in water quality in Noonday Creek to describe pollutant transport and pinpoint sources.

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Abstract

Time series measurements on Noonday Creek (Georgia) indicated changes in stream height followed by rapid changes in conductivity (2-5X increases with in 1 hour) several hours later. No time lags occurred upstream at a site where a quarry was found to periodically discharge high conductivity water. This study takes advantage of pulses of easily measured ions discharged at semi-regular intervals from a single point to describe the relationship between water discharge and dissolved ion load in an urban stream. Travel time as estimated by stream height changes exceeded travel time based on current velocity. This suggested that low conductivity stream water was displaced downstream as a translatory wave when the quarry discharged effluent. Travel time as estimated by conductivity changes were less than travel time based on current velocity. Conductivity measurements at three depths within the sediment showed that peaks occurred first at the surface and later at deeper depths. This suggested retention of quarry water within the hyporheic zone and later release into the stream. Understanding temporal patterns of water movement in natural stream channels is necessary to improve model estimates of pollutant loads which are often estimated by interpolating and extrapolating changes based on few samples. In addition, such information could be used to develop a novel approach in determining (i.e. pinpointing) the distance upstream of pollutant sources. Presumably, the greater the time difference between the arrival of a translatory wave and a given pollutant, the farther upstream the source.

Introduction

One of the most important physical forces affecting movement of pollutants within natural open channel systems is flow, however water movement does not directly reflect transport of even dissolved substances. Numerous factors complicate our understanding of the relationship between water movement and pollutant transport.

First, in uniform open channels, disturbances such as sudden additions of water masses create translatory (Pickford, 1969) or kinematic (Runkel et al., 1998; Nolan & Hill, 1989; Lee & Yen, 1997; Leopold et al., 1964) waves ("old" water is displaced downstream), which move faster than stream current. Downstream, this phenomenon can explain rapid increases in stream height prior to changes in water quality within natural creeks and rivers (pers. obs.).

A second complication in understanding the relationship between flow and load in natural channels arises from the interaction of channel water with the subsurface of the streambed (hyporheic zone). Significant exchange of materials occur between the surface water and the hyporheic zone (e.g. Hendricks &White, 1995; White, 1993; Williams, 1993; Jones & Holmes, 1996; Fortner & White, 1988; White, 1989; Runkel et al., 1998). Retention of solutes within the hyporheic zone can potentially delay the transport of pollutants downstream, as suggested by higher concentrations of ions, phosphorous, nitrogen, organic matter, etc. than in either surface water or ground water (Fortner & White, 1988).

In natural surface stream channels (creeks and rivers), translatory waves and hyporheic interactions are difficult to characterize. Studies dealing with wave and solute transport model links between rain events (characterized by hydrographs) and stream response, but these interactions are complex (Nolan & Hill, 1989). Rain events are irregular in duration and intensity, and are heterogeneous over watersheds that are in themselves complex mosaics of natural and impervious surfaces. As a result, it is usually not possible to attribute a particular change in flow and concentration to a specific input event. This study describes the relationship between water discharge and dissolved ion load in an urban stream receiving short but significant additions of ions during non-rain events. We take advantage of pulses of high ion concentrations discharged at semi-regular intervals from a single point source, a granite quarry.

In this study, we investigate two factors:

1) We compare travel times based on spatial changes in stream height and ion concentration and on direct measurements of current velocity to characterize the relationship between the translatory wave and movement of the actual water mass. The relationship is examined over several dates that differ in baseline (pre-event) stream height, a function of previous rainfall.
2) We measure changes in ion concentration at different depths within the sediment during releases from the quarry to evaluate the potential for the hyporheic zone to impede pollutant transport downstream.

Accurate determinations of pollutant loads are currently important in water quality permitting, but model estimates of load must often interpolate or extrapolate changes in pollutant concentration and discharge from only few measurements. Understanding the effects of translatory waves and hyporheic interactions on timing of water movement and pollutant transport in natural stream channels is necessary to improve model estimates of pollutant loads. In addition, such information might be used to determine (i.e. pinpoint) the distance upstream of pollutant sources. Presumably, the greater the time differences between the arrival of a translatory wave and a given pollutant, the farther upstream the source. However, an accurate prediction of upstream distance requires knowledge of factors that influence the movement of translatory waves and pollutants downstream in natural channels.

Methods

Study sites:

The Noonday Creek watershed is 15% urban (U.S. EPA, 1998) and lies in a rapidly developing suburban area NW of Atlanta. Surface geology of the watershed is mainly composed of various schists and gneisses (part of the Metamorphic Region of the Upper Piedmont physiographic province) resulting in low conductivities (typically < 100 µS/cm) in area streams (U.S. EPA, 1998). Sampling and data collection were done along a third-order section of Noonday Creek at two sites along. Site 1 was located < 50m downstream from a final retention pond flowing out of a granite mining/quarry area and cement plant with Site 2 located 5.3 km downstream of Site 1 (elevation changes at ~3.5 m per stream kilometer between sites). Previous observations documented rapid irregular increases in conductivity (up to 3 fold within 1 h) up to 3 times per day downstream of the quarry, but not upstream. Also it was noted in the water quality report for Cobb County that the settling ponds were full and therefore ineffective at removing the quarry pollutant load (Bourne, 1996).

Experimental design:

To measure movement of water along the stream channel, conductivity and stream height (using an ISCO bubbler flow meter) were measured at site 2 (5.3 km downstream of the quarry) every 15 minutes over several days using automated data loggers. Ion concentration was measured indirectly as conductivity (temperature corrected). At site 1, conductivity was measured using an automated conductivity probe over 15-minute intervals for several days. Stream height was not measured at site 1 and previous studies show that it changes synchronously over time with changes in conductivity.

Current velocity was measured at sites 1 and 2 and at three sites in between sites 1 and 2 on two different dates. At each site current velocity, using a Teledyne Gurley PRICE 622 current meter, was measured along nine randomly selected transects at 1 meter intervals across each transect (n = 81 measurements). This sampling was performed at six tenths of the stream depth during periods sampled by automated monitoring described above at sites 1 and 2.

The corresponding travel time based on stream height and based on conductivity were compared to travel time based on average velocity of the stream flow. Travel times were determined by calculating the time difference between appearance of a peak in conductivity at site 1 (upstream) and the appearance of a similarly shaped peak for both conductivity and stream height downstream at site 2. A peak was defined as the maximum value following any abrupt increase in conductivity or stream height.

Three conductivity probes with an automated data logger recorded conductivity and temperature in the hyporheic zone. One week prior to data collection, two probes were buried below channel water - sediment interface at 15 cm and 30 cm depth very near each other and the third was placed at the surface of the sediment.

In order to understand conductivity changes within the hyporheic zone and stream channel, the major route by which quarry water enters the creek had to be determined. Either most water enters directly as surface flow from the final retention pond or as subsurface intrusion from the retention pond to the stream via the streambed. Discharge and the concentration of conductivity in three locations near the quarry retention pond were determined using a flow meter and a conductivity probe. Site 1A was located ~150 feet upstream of the retention pond outflow, Site 1B was located at the pond outfall, and site 1C was ~200 feet downstream of the pond outfall. From this the calculated total dissolved solids (TDS) load (estimated from conductivity and discharge) at 1A and 1B were added together and compared to the load at 1C. If the combined load from upstream and at the outflow should equal the downstream load, then the effluent enters the stream via a surface flow.

Results

The shape of conductivity and stream height peaks varied with quarry discharge events making it possible to identify each events movement and timing. For example, on April 24, 1998 from 12:45 A.M. to 6:45 P.M. (Figure 1a) the shape of conductivity changes over time upstream and downstream and of stream height changes downstream are very similar in shape, but occurred at different times. Each stream height peak was followed several hours later by its correspondingly shaped conductivity peak (Figure 1a-d). Stream height peaks traveled faster than water in the stream (as estimated by in-stream current measurements) (Figure 2a). Peaks in conductivity traveled slower than both peaks in stream height and water velocity (Figure 2a).

The time between peaks in conductivity at the quarry (site 1) and peaks in stream height and conductivity at site 2 varied by date (Figure 1a-d). Travel time varied from 2 to 29 hours based on peak stream height and decreased with increasing baseline stream height (stream-height prior to quarry discharge events) (linear regression based on natural log of stream height travel time versus base line stream height; $r = 0.92$, $P<0.001$) (Figure 2b). Rate of travel based on conductivity peaks was correlated with baseline stream height (linear regression based on natural log of conductivity travel time versus base line stream height; $r = 0.96$, $P<0.001$) (Figure 2b). When the creek was low during drier periods, velocities of peaks in conductivity and stream height were much slower.

There was a measurable interaction between the surface water and the hyporheic zone. Conductivity increased initially within the stream channel, followed by increases at 15 cm below sediment surface, followed by increases to near surface values at 30 cm. Time between peaks in conductivity among depths varied from 45 minutes to 2 hours and occurred on all dates of discharge (Figure 3a). Temperature changes indicate similar patterns in water movement through the hyporheic zone, though the patterns are less obvious because these changes are superimposed on variation caused by diel changes in air temperature (Figure 3b).

The observed conductivity increases in Noonday Creek are primarily from direct surface inflow from the quarry retention pond, and hyporheic/groundwater inflow from the quarry contributes little, if any, to stream conductivity load. The estimated total dissolved solid (TDS) load upstream of the quarry plus the load from the quarry pond surface discharge was very similar to the TDS load downstream of the quarry pond (Figure 4; 72,513mg/l versus 67,070 mg/l respectively). The upstream Noonday Creek channel load was only 38,957 mg/l.

Discussion

In an urban stream receiving short but significant additions of ions, downstream changes in stream height occurred prior to downstream changes in conductivity. The asynchronous relationship between stream height peaks and maximum dissolved ion concentration can be explained by the translation of energy due to the disturbance created by discharges from the quarry. Pickford (1969) observed that any disturbance within a body of water causes translatory waves, which displace the energy of the disturbance. This wave moved downstream faster than the actual water mass containing the ions discharged by the quarry, and partially explains the lags within the stream over the 5.3 km.

The high conductivity water mass appeared to move more slowly down Noonday Creek than would be predicted from current velocity estimated directly within the stream channel. In Noonday Creek, the ion effluent infiltrated the hyporheic zone at least as deep as 30 cm. The ion pulse entered the hyporheic zone faster than it left, with relatively high conductivity at 30 cm after >15 hours, indicating a slow release of ions into the channel. This delay may explain, at least in part, why ions moved slower than the average water velocity in the stream. Alternatively, surface phenomena such as eddies and pools would contribute to over-estimation of velocity if they were not accurately represented in current velocity sampling. Hyporheic retention can explain observed difference in travel time by date. As baseline stream height (a function of past rainfall events and ground water saturation) decreased, the travel time increased, which would be expected because the ratio of stream-bottom area to stream volume increases as stream height decreases.

The effects of baseline stream height and hyporheic interaction on the transport of ions, as demonstrated in this study, complicate the relationship between discharge and pollutant concentration. Streams lying in watersheds that differ in land use and geology presumably will differ in the degree to which hyporheic interaction effects downstream transport of pollutants. Sediment porosity/permeability can affect surface to hyporheic interaction, which may be related to land use (Williams, 1993; Jones & Holmes, 1996). Likewise, temporal differences in discharge within a stream due to past rain history effect the relationship between discharge and pollutant travel time. It is outside the scope of this paper to determine the degree to which these effects could cause significant error in models that estimate loading. Potentially, significant pollutant transport might occur well after stream level has returned to pre-event levels as pollutants continue to be released from the hyporheic zone. Also, translatory waves may mislead investigators to concentrate sampling efforts earlier in a storm event, prior to time of maximum pollutant transport.

Time lags between pollutant loads and stream height could be useful in developing a novel approach to determine (i.e. pinpoint) the distance upstream to a pollutant source. Because the time lag in itself is a function of stream height and potentially hyporheic interaction, the absolute magnitude of the time lag is of little use in estimating distance upstream to a pollutant source from stream to stream or date to date. However, it may be possible to derive this estimate by comparing time lags between two or more sites. During a single event within a single stretch of stream over which geology and hydrology do not vary greatly, the proportion of lag times at two locations should be equal to the proportion of the distances downstream of these locations from the source. For instance, if the lag is 100% longer at Point A than upstream at Point B, then the pollutant source is the same distance upstream from Point B as the distance from Point A to B. If such a relationship is established in streams with known pollutant sources, unknown point sources could be pinpointed precisely using automated water quality sensors at two downstream sites. Determining the location non-point source pollutants transported during storm events would be more complex, but even measurement made at only two sites might provide a general estimate of the distance of problematic sub-watersheds.

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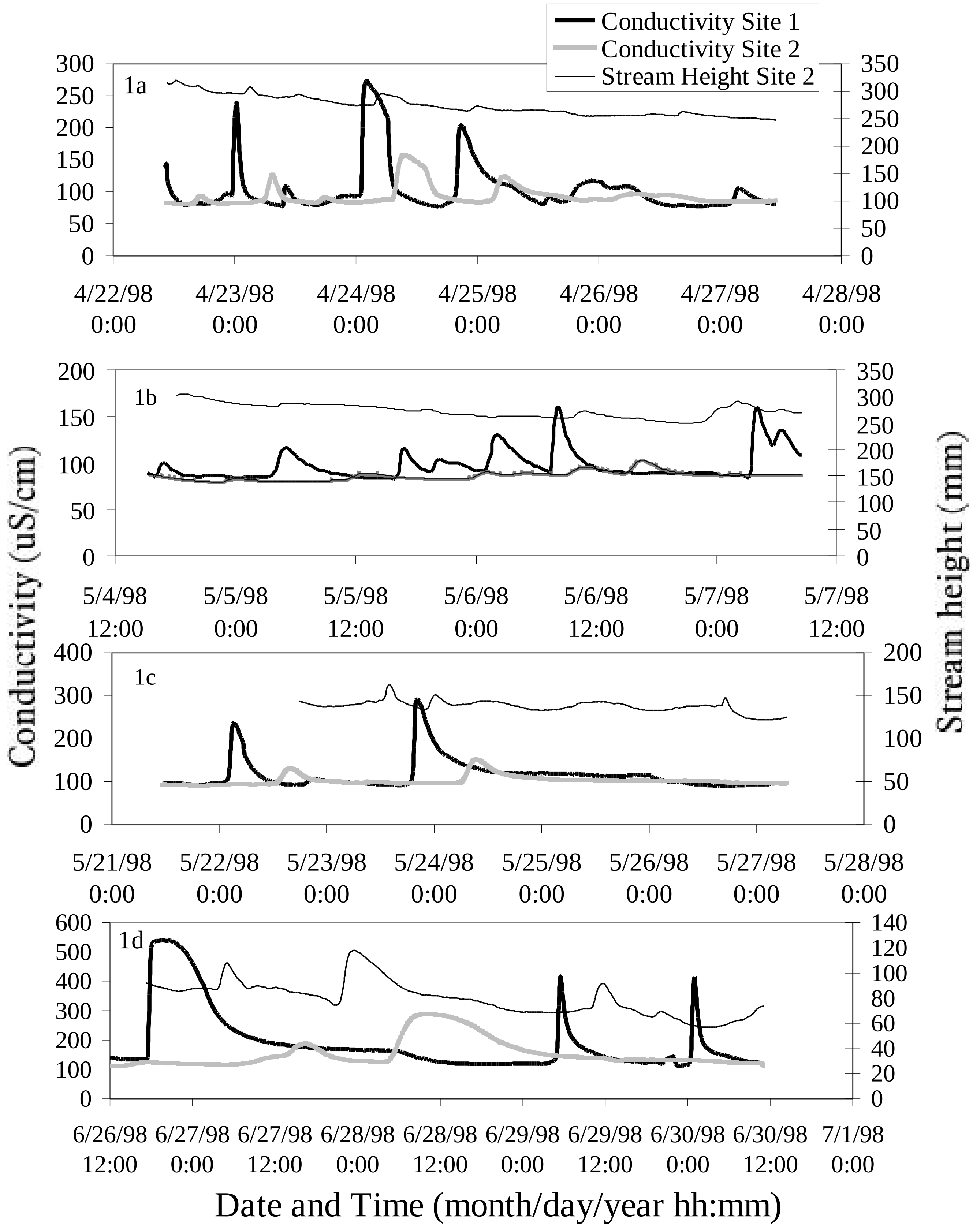
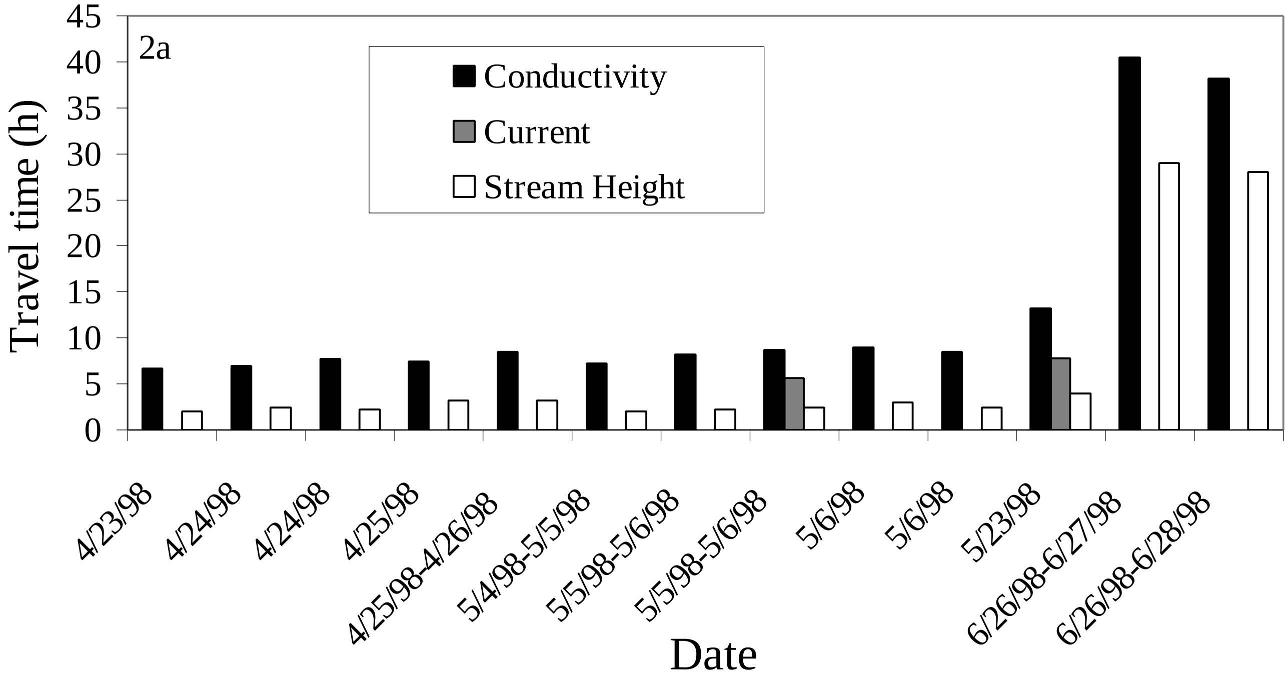


Figure 1. a-d: Conductivity at Site 1 (upstream) and conductivity and stream height at Site 2 (downstrem) measure at consecutive 15 minute intervals over several dates. Steam height was not measured at Site 1but is known from previous observations to coincide with changes in conductivity at this site. Note that axes scales vary among panels.



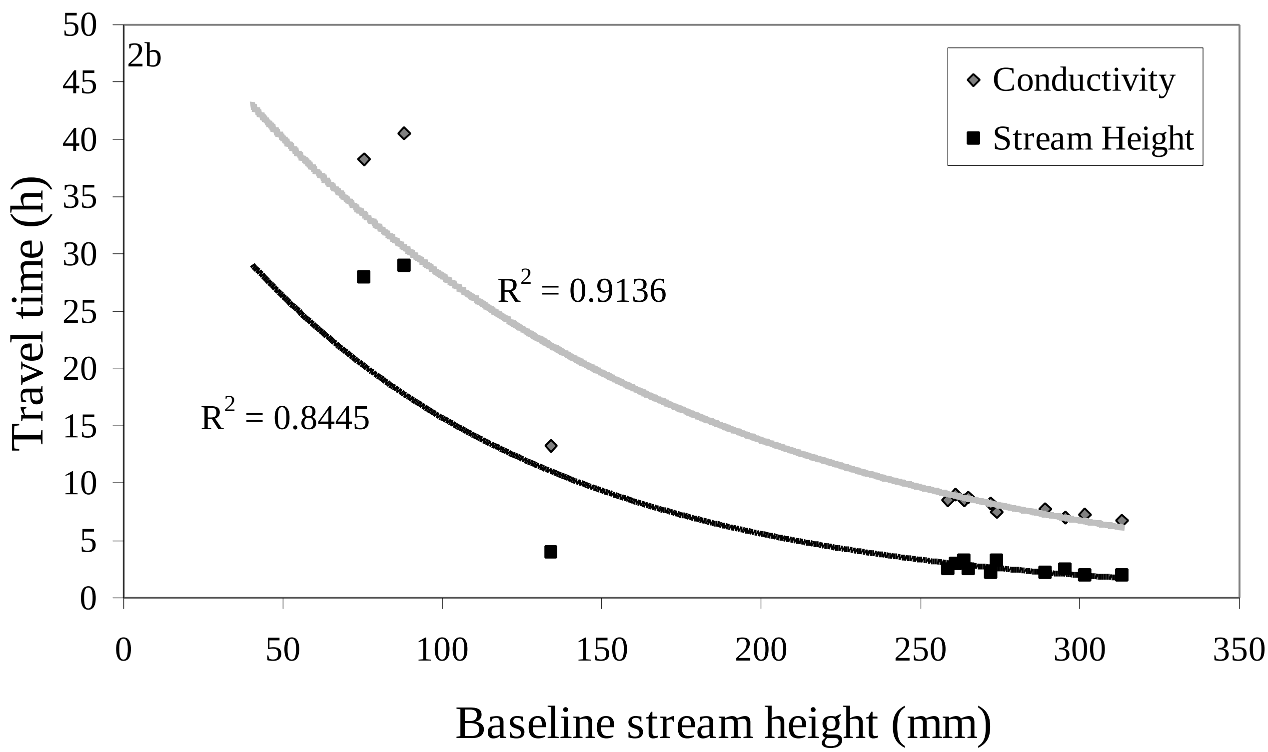


Figure 2. a: Comparison of the travel time based on conductivity changes, on stream height changes, and in-channel current velocity over several dates. **b:** Comparison of the travel time based on conductivity changes and on stream height changes as a function of baseline stream height (stream height prior to discharge event).

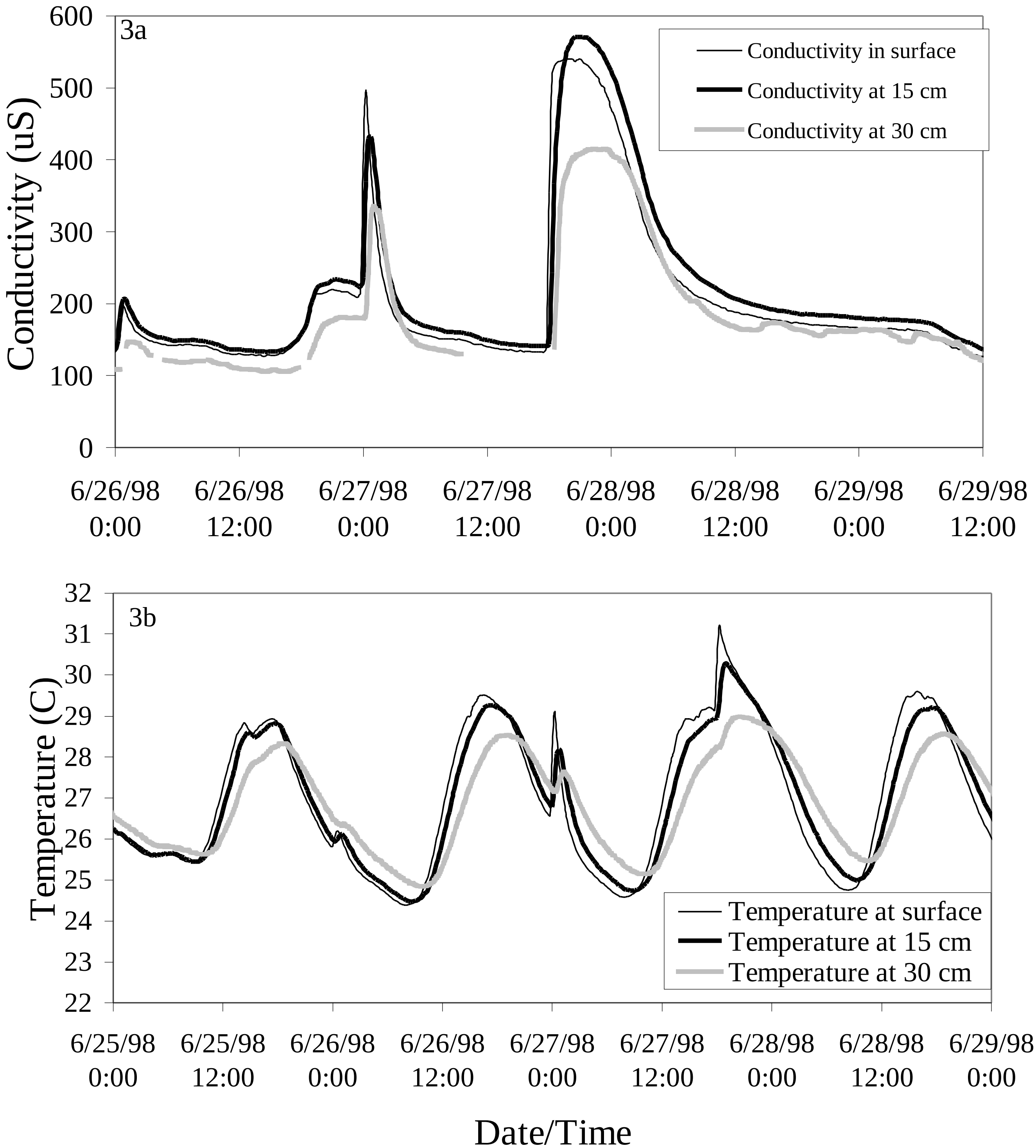


Figure 3. a: Conductivity at the surface, 15 cm, and 30 cm in the stream bed over time (note that the 30 cm conductivity probe failed to record over several intervals). **b:** Temperature at the surface, 15 cm, and 30 cm in the stream bed over time.

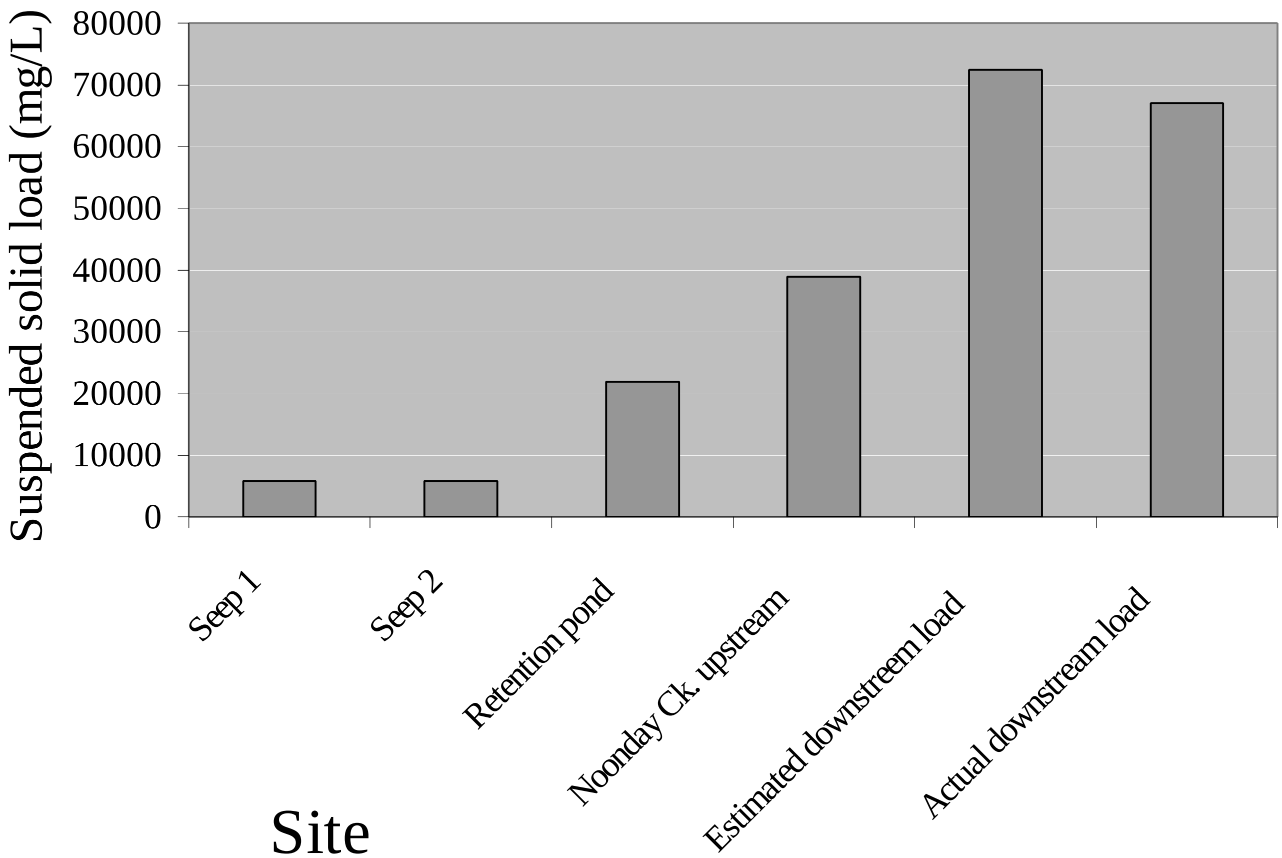


Figure 4: Comparison of dissolved ion loads. "Total estimated load" is the sum of all sources upstream of and including the quarry retention pond discharge. "Seeps" refer to small leaks from the wall of the retention pond.