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A WATER QUALITY INVESTIGATION OF KIMAGES CREEK

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science
at Virginia Commonwealth University.

by

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Abstract

A WATER QUALITY INVESTIGATION OF KIMAGES CREEK

By Michael Parker Trop, M.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science at Virginia Commonwealth University.

Virginia Commonwealth University, 2012

Director: Dr. Paul Bukaveckas, Associate Professor, Department of Biology and Center for Environmental Studies

Analysis of continuous monitoring water quality data (temperature, specific conductivity, depth, pH, dissolved oxygen, and turbidity) at two locations in a tidal freshwater creek (Kimages Creek) characterized seasonal variation and responses to short-term events. Supplemental water quality measurements were collected to describe longitudinal variations in the creek. There were significant differences in water quality between the two continuous monitoring stations (one tidal and unforested, the other non-tidal and forested) over varying time scales. Rain events showed increases in turbidity, depth and dissolved oxygen, and reductions in temperature, conductivity, and pH at both stations. Tides influenced the water quality at the downstream monitoring station, but there were also influences at the upstream site despite the presence of beaver impoundments. At the downstream station, changes in conductivity and pH were linked to the tidal cycle while temperature and dissolved oxygen were linked to a diel cycle but also responded to tidal influence.

Introduction

Water quality is an important determinant of stream health and various attributes of water quality are commonly used to make inferences about stream and watershed processes.

Automated monitoring allows these parameters to be measured continuously and analyzed over a range of temporal scales from episodic events (e.g., storm water runoff) to seasonal variation and long-term trends. A variety of parameters are amenable to continuous monitoring including temperature, dissolved oxygen, pH, specific conductivity, and turbidity. Each of these parameters can provide useful insights regarding anthropogenic influences on stream and watershed processes.

Water temperature influences all biological processes including rates of consumption, production, respiration and activity (Hester and Doyle, 2011). Species have specific temperature optima such that temperature conditions determine in part their presence at a given location and time of year. Temperature also has a large effect on dissolved oxygen concentrations by influencing the saturation potential of water. Stream temperature may be affected by hydrology (particularly groundwater inputs but also tributary inputs), shading by the riparian canopy, anthropogenic effects (including dams, loss of riparian cover and discharge of heated effluent), and perhaps most importantly, by climate (Hester and Doyle, 2011). Stream temperature data are often used to gauge habitat suitability for various species, particularly fish, and as a response variable for land use effects on stream riparia.

The dissolved oxygen (DO) content of water is affected by temperature and by rates of respiration, photosynthesis and atmospheric exchange (Gardner et al., 2006). Low dissolved oxygen concentrations may result from anthropogenic effects associated with nutrient and organic matter inputs (Allan and Castillo, 2007; MacPherson et al., 2007). Streams may also exhibit naturally low dissolved oxygen concentrations where the presence of wetlands supports high rates of respiration. Oxygen data are often used in evaluations of stream health since many organisms are sensitive to low oxygen stress (hypoxia). The DO standard for tidal waters in the coastal zone is a minimum of 4.0 mg/L with a daily average of 5.0 mg/L (Virginia Water Quality Standards, 2011). Oxygen data are also used to infer ecosystem production and respiration from diel data, provided that atmospheric exchange can be determined.

pH is a measure of the hydrogen ion concentration of water and is used to determine the water's acidity. Stream pH is affected by the geology of the catchment, precipitation, and the flow paths by which water travels to the stream. Precipitation is naturally acidic (~5.6) (Measuring Acid Rain, 2007) but anthropogenic effects increase acidity (e.g., pH < 4.5 in the VA region). Limestone acts to buffer acidity as rainwater interacts with catchment soils; longer or shorter flow paths influence how much the catchment geology will affect stream pH (Allan and Castillo, 2007). Low pH is generally of greater concern than high pH as acidification is associated with loss of species from all trophic levels (Nierzwicki-Bauer et al., 2010). While anthropogenic acidification is associated with the presence of strong mineral acids, (i.e., sulfuric and nitric), natural sources of acidity are organic acids derived from terrestrial and wetland vegetation. Naturally acidic streams are often characterized by the presence of colored dissolved organic matter. Stream pH data are often used to track storms as rain events result in inputs of low-pH runoff, thereby increasing the acidity of the stream.

Specific conductivity is a measure of the concentration of dissolved ions present in water as indicated by the temperature-corrected electrical conductance (Allan and Castillo, 2007). Stream conductivity is influenced by the geology of the catchment (i.e., presence of easily-weathered minerals), the hydrology of the catchment (flowpaths that determine the soil-water contact time) and anthropogenic factors that enhance solute concentrations. Of these, the application of road salt is the most common anthropogenic effect on conductivity (Rosenberry et al., 1999). Elevated conductivity arising from road salt and other inputs has been shown to be harmful to aquatic biota (Notovny and Stefan, 2010). As natural sources of solutes are dependent on soil-water interaction, precipitation events tends to lower conductivity by diluting solute-rich groundwater with solute-poor rain water. For this reason, stream discharge is inversely related to conductivity (i.e. high discharge associated with low conductivity) and conductivity, like pH, is used to track storm water effects on stream chemistry (Swanson and Baldwin, 1965).

Turbidity is caused by suspended particulate matter which includes sediments, algae, and colloidal matter. These particles scatter and absorb light and thus restrict the transmission of light. High turbidity can limit the autotrophic potential of streams through light attenuation (Kirk, 1985). Of greater concern is the effect of sedimentation on stream biota which has deleterious effects on benthic biofilms and filter-feeding organisms (Eriksson and Johansson, 2005). Transport of suspended sediments can increase dramatically during rain events as overland flow and increased water velocity within the channel enhance sediment transport and re-suspension (Allan and Castillo, 2007). Streams draining catchment with land disturbance (e.g., agriculture, development) are particularly vulnerable to erosion and elevated stream turbidity. Turbidity data are used to gauge the effects of land use activity on streams.

A number of prior studies have established linkages between stream water quality and watershed hydrology, geology and land use (Tran et al., 2008; Cornell and Klarer, 2008; Leach and Moore, 2011). Comparable studies in the Coastal Plain are generally lacking, particularly for streams influenced by tidal forces. Tidal freshwater streams are situated where unidirectional fluvial forces encounter estuarine waters experiencing tidal (bi-directional) water movements. Thus tidal systems exhibit physical and chemical properties of both upstream and adjacent estuarine environments. During high discharge events, water quality will likely be dominated by upstream processes, whereas during low discharge, and particularly during elevated tides, water quality will correspond more closely to the estuary. The influence of the estuary only extends as far upstream as the tide reaches. This can vary depending on water levels in the creek and river as well as the season and strength of the tide.

The specific goal of this project was to characterize spatial and temporal variations in water quality for a tidal freshwater stream, Kimages Creek. Of specific interest was to assess the timing and nature of fluvial (watershed) vs. tidal (estuarine) influences on water quality. To assess spatial and temporal variation in water quality, historical data from continuous, fixed-station monitoring were used as well as periodic longitudinal sampling. Results from this study provide a basis for characterizing water quality and stream health in these dynamic systems which are found throughout the Coastal Plain, but which have previously received comparatively little attention in water quality assessments.

Methods

Kimages Creek is a Coastal Plain stream whose confluence with the James River estuary is located at the Virginia Commonwealth University Rice Center. The creek drains a 1269 hectare watershed which is comprised of forest (70%), wetlands (12%), scrub/shrub vegetation (11%), and development/cultivation (7%). Though the stream is ungauged, the annual average discharge has been estimated as 129 L/s based on data from nearby gauged watersheds and the runoff/unit area method (Dougherty, 2008). The site has a long history of land use changes including early European settlement, Civil War era encampments and 19th century development. In 1927, a dam was erected at the mouth of the creek, separating it from the James River and creating an impoundment (Lake Charles). In October 2007, the dam was partially breached after heavy rains and by Spring 2008, the breach had incised and allowed for tidal exchange with the James River. In December 2010, a large segment of the dam was removed to restore the original confluence of the creek and the James River. The continuous monitoring data used in this study was from 2009 and the water quality surveys were taken from June-December 2011. In relation to the long-term climate, the 2009 average temperature was 14.8 C° which was warmer than the long-term average of 14.2 C°. The long-term average rainfall is 1115 mm; however in 2009, the area received 1227 mm of rainfall.

The segment of Kimages Creek located on the Rice Center property is approximately 1800 m, of which 1700 m is restored (previously impounded) and approximately 1300 m is

believed to be tidally influenced. Stream width ranges from <3 m in the upper segment (unrestored and non-tidal restored) to >20 m in the lower, tidal-restored segment. Throughout its length, depth of Kimages Creek is typically less than 1 m.

Continuous water quality monitoring stations were located at two sites within Kimages Creek. The upper Kimages monitoring station was located in the non-tidal, unrestored segment where the creek enters the Rice property (hereafter, Route 5 monitoring location; Figure 1). The lower Kimages station was located mid-way to the confluence with the James (~ 800 m from Route 5 station) in the restored, tidal segment (hereafter, Finger Pier location). Water quality measurements (temperature, depth, specific conductivity, pH, dissolved oxygen, and turbidity) were recorded at 15 minute intervals at both stations. Along with water quality parameters, the sondes also measured changes in depth which were used to interpret effects from rain events and tides. Data were screened for illogical or out-of-range values (e.g. negative dissolved oxygen concentrations) as these may arise due to sensor malfunction or deployment problems (e.g., low water). In addition to issues with data collection, missing records can also result from data storage and communication problems. For 2009, data records were 73% complete for the Route 5 location and 85% complete for the Finger Pier location (Table 1). Notable gaps include missing records for January (both sites) and September (Route 5 only).

Analysis of the continuous monitoring data focused on characterizing seasonal variation and response to short-term (primarily rain) events. Seasonal variation was assessed by comparing monthly-averaged values for each parameter. During the study period, there were 33 events with a rainfall greater than 10 mm. Of these, an average 19 mm event on April 20 was used to illustrate typical responses in water quality.

Longitudinal surveys of water quality were performed at approximately two week intervals at 9 locations (Figure 1, Table 2). Locations 1-6 were in the presumed non-tidal segment of the creek as these were located above a beaver dam near the former island. The first two locations were in the unrestored portion of the stream while locations 3-9 were in the restored section. Stations 1-7 were spaced at intervals of ~80 m, with Station 1 being just downstream of the Route 5 sonde (prior to it being moved to location 3). Location 8 was at the Finger Pier monitoring station (~275m downstream from location 7) and location 9 was at the confluence of Kimages Creek and the James River. The seven upstream sites were sampled for six months from June 24, 2011 to December 23, 2011. The two downstream sites were sampled for three months from September 16, 2011 to December 23, 2011. A Hydrolab MS5 sonde and surveyor were used to sample at each location.

The statistical program JMP 9 was used for the statistical analysis. To compare monthly averages and seasonal differences between Route 5 and the Finger Pier, paired, two-tailed t-tests were used. A test of linear correlation was used to assess longitudinal variations in the survey data.

Results

Seasonal Variation

Seasonal patterns in water quality differed between the two monitoring locations (Figure 2). Water temperature was similar during winter and spring, but in the summer and fall, the Finger Pier site had significantly higher temperatures (by 3.5 C°; $t=3.5$, $df=9$, $p=0.006$). Over the entire year, the water temperature at the Route 5 site was 2.1 C° cooler than the Finger Pier site, a statistically significant difference ($t=3.3$, $df=10$, $p=0.008$). Conductivity at the Route 5 site was lowest in the spring (March-May = 0.059 mS/cm) and highest in late summer/early fall (August-October = 0.113 mS/cm). Conductivity was consistently higher (1.5 x) at the Finger Pier site (annual mean = 0.146 mS/cm) relative to the Route 5 site (mean = 0.092 mS/cm; $t=3.5$, $df=10$, $p=0.005$). Differences were particularly evident during September-November (Route 5 = 0.107 mS/cm, Finger Pier = 0.219 mS/cm). Measurements of water depth at the two sites cannot be compared directly because the sites are not referenced to the same elevation. However they are useful for assessing influences of rain events and tides. Water depth at the Route 5 site generally decreased from a maximum in January (0.76 m) to a minimum in July (0.08 m) before rising to about 0.20 m near the end of the year. At the Finger Pier, the depth in February was low (-0.1 m potentially indicating that the sensor was not properly zeroed or was out of the water) before it rose and leveled off in May to about 0.2 m.

The pH of Kimages Creek was moderately acidic with typical monthly average values ranging between 5.5 and 6.5 at both sites. Values tended to be lower at the upstream (Route 5) site (6.0) relative to the Finger Pier site (6.4) and differences were found to be statistically significant ($t=2.8$, $df=10$, $p=0.018$). In October, pH at the Finger Pier site reached an exceptionally high maximum (mean = 7.7) before it dropped into the typical monthly average range for the remainder of the year. At Route 5, the maximum of 6.4 was reached in September and there were no exceptionally high or low values at the site during the year.

Turbidity at the Route 5 site was generally low (<100 NTU) with the exception of March, April and December. At the Finger Pier, turbidity was more variable with consistently high values (>350 NTU) observed during August to October. Thus the two sites differed with respect to both the range (Route 5 = 5 NTU to 468 NTU, Finger Pier = 27 to 657 NTU) and seasonal patterns of turbidity; however, the difference in turbidity between the two sites was not statistically significant ($t=0.92$, $df=8$, $p=0.38$). The two sites were significantly different during August to October (Route 5 = 33 NTU, Finger Pier = 491 NTU; $t=4.7$, $df=2$, $p=0.0418$).

Monthly average dissolved oxygen concentrations generally followed a declining pattern from winter to summer at both sites. There was a significant difference between the sites for dissolved oxygen for the entire year (Route 5 = 3.3 mg/L, Finger Pier = 6.2 mg/L; $t=3.8$, $df=10$, $p=0.0035$). During January to July, DO was considerably higher at the Finger Pier relative to Route 5 (8.8 mg/L and 4.0 mg/L respectively; $t=12.8$, $df=5$, $p<0.0001$). During August-November, concentrations were not significantly different between the two sites. Minimum values were <2 mg/L at Route 5 (June-August) and <3 mg/L at the Finger Pier (August to November). At the Finger Pier, the dissolved oxygen was below 4.0 mg/L 38% of the time and 66% of the time at Route 5.

Episodic Events

Rainfall data were used to identify storm events; data from multiple events were used to identify general patterns in water quality fluctuations. Interpretation of short-term changes in water quality was complicated by tidal influences. Changes in depth are the most direct indicator of tidal influences. Comparisons of water depths at the two locations suggest possible tidal influence at the Route 5 site which became apparent during periods of low water level (Figure 3). At the Finger Pier, changes in depth were constant year-round and averaged a 0.2 m change in water level. At Route 5, tidal effects were seen only during some periods (particularly May through October) and averaged a 0.01 m change. The two daily tides were not of the same magnitude; one was stronger than the other and this was only noticeable at the Finger Pier.

At the Finger Pier, specific conductivity and pH exhibited cyclical patterns related to tidal variation in water depth (i.e. they increased with the incoming tide and decreased with the outgoing tide) (Figure 4). The typical change in conductivity and pH associated with the tides was about 0.08 mS/cm and 0.40 respectively. From February to mid-July, the tidal change associated with conductivity was consistently 0.02 mS/cm; however, from late-July through August, occasional larger (0.13 mS/cm) changes were seen. Large changes (0.30 mS/cm) frequently occurred in September and October, but November and December returned to the 0.02 mS/cm change that was seen earlier in the year. pH tidal changes from February to mid-May averaged about 0.10. From mid-May to October, the changes became larger (up to 1.0), but there were still smaller (0.20) changes among the larger changes. October through December had typical changes of 0.40 per tidal cycle.

In contrast to tidal variations, temperature and dissolved oxygen followed diel (solar) patterns whereby maximum values were reached mid-afternoon and minimum values were

observed shortly before sunrise. Temperatures varied by 8-10 C° from February to August and from August to October varied by about 5 C° per day. From October through December, daily temperatures on average changed by less than 5 C° per day. Daily dissolved oxygen values from February to mid-May ranged between 70% and 120% saturation. Mid-May to mid-August values varied more (20% to 200% saturation). There were periods in early September, early October, early November, and mid-December where the dissolved oxygen varied between 50% and 200%; however, the dissolved oxygen during this time stayed relatively flat (near 10% saturation) and showed little diel or tidal variability. Apart from these larger diel patterns, there were also interactive effects between tidal and solar cycles. For example, when high tide coincided with daytime increases in temperature, temperature increased at a slower rate. Dissolved oxygen had different small-scale changes as a result of tidal influences where the major observable effect occurred at low tide and constituted a sharp decrease followed by an equally sharp increase in the dissolved oxygen levels. High tides caused slower rates of change in the dissolved oxygen. At Route 5, the depth oscillation followed the tidal cycle (and the tides are a likely cause of this effect) but with a weak signature as compared to the Finger Pier. The Route 5 depth was the only parameter that followed a tidal cycle variation (temperature, conductivity, pH, and dissolved oxygen followed a diel cycle) (Figure 5) and thus, there is no clear effect of tidal-induced variation on water quality at Route 5.

In response to the April 20 rain event, Kimages Creek exhibited increases in turbidity, depth and dissolved oxygen, and reductions in temperature, conductivity, and pH (Figure 6). Stream depth at Route 5 increased from 0.3 m to about 0.7 m while the Finger Pier depth increased from 0.1 m to 0.4 m. At the onset of the rain event, water temperature at the Route 5 site dropped from 15.5 C° to 12.5 C° while the Finger Pier had a larger drop from 20 C° to 13 C°.

The two temperatures were more similar as a result of the rain event (4.5 C° difference before the rain event and 0.5 C° difference after). The drop in stream temperature was typical of warm-weather events, whereas rain events in winter generally caused an increase in water temperature. For example, an event on December 2-3 caused stream temperature to increase by 4 C°. Specific conductivity decreased from 0.10 mS/cm to 0.05 mS/cm within 6 hours at the Finger Pier and from 0.07 mS/cm to 0.04 mS/cm in about 3 hours at Route 5. The conductivity then returned to pre-event values over a 10-14 day period with the Finger Pier exhibiting a slightly faster recovery. pH followed a similar trend to conductivity, exhibiting a sharp initial drop before recovering to pre-event values. pH at the Finger Pier site showed a smaller decrease (from 6.2 to 5.8; H⁺ concentration drop of 9.5x10⁻⁷ mol/L) than that observed at the Route 5 site (from 5.4 to 5.2; H⁺ concentration drop of 2.3x10⁻⁶ mol/L). During non-rain event periods, the dissolved oxygen at the Finger Pier varied in response to the diel cycle and just prior to the rain event was oscillating between 7 mg/L and 10.5 mg/L. When the rain event occurred, this oscillation dampened to between 8.5 mg/L and 9.5 mg/L. By contrast, the rain caused the dissolved oxygen at Route 5 to double from about 4 mg/L to 8 mg/L. Brief but large upswings in the turbidity of the water in Kimages Creek were seen during rain events. The turbidity at Route 5 rose from about 20 NTU to about 1300 NTU while the Finger Pier rose from about 20 NTU to only 150 NTU.

In Kimages Creek, there were a number of periods during which short-term (hourly) fluctuations in water quality were observed. These were frequently observed at the Route 5 location from May to November. During this period, minimum water temperatures were observed in the morning and maximum temperatures occurred at night (Figure 7). This pattern is opposite of what would be expected from diel solar heating. This cycle of high temperatures

occurring near midnight began on May 11 and went until November 27. Outside of these dates, the temperature is similar to what would be expected (maximum daily water temperatures in the afternoon and minimum in the morning). Conductivity, pH, and dissolved oxygen also followed cyclical diel patterns during this period; however, the diel range of conductivity was not as pronounced as for pH and dissolved oxygen. Dissolved oxygen exhibited the largest change from near 0% saturation to 30% in only a few hours and usually reached its peak during the night. Temperature, conductivity, and pH had the same pattern of peaking near midnight during this period. The observed variations in temperature, conductivity, and pH were not related to tidal-driven variations in depth observed downstream (Finger Pier site). There was a tendency for dissolved oxygen to peak on the alternate (larger) high tide though this pattern was not consistent. Thus, while regular daily oscillations in water quality were observed at the Route 5 site, these were not clearly linked to either solar cycles or tidal-driven fluctuations.

Longitudinal Variations

The water quality surveys showed that there were statistically significant longitudinal trends in temperature, conductivity, and dissolved oxygen, but these trends were not consistent across sampling dates (Figure 8). Water temperature increased from site 1 to site 9 except in two instances (October 28 when the temperature decreased and November 11 when there was no observed trend) (Table 3). The summer/early fall temperature (which was only measured in the upstream segment of Kimages Creek: sites 1-7) tended to increase from site 1 to site 7. The Finger Pier location and Kimages Creek's confluence with the James River (sites 8 and 9) were much farther downstream than the upstream sites (1-7) (Table 2). This caused trends at the later sampling dates to be primarily driven by higher values at the Finger Pier and James River confluence and thus, caused more positive trends for all parameters.

For pH, the summer/early fall sampling dates (those in which no measurements were taken in the downstream segment) showed no statistically significant trend between the sites. For the last 8 sampling dates, 7 of these had a significant positive trend. pH showed a general drop at site 2 which was particularly pronounced on November 11 and 25 when the pH dropped from just over a pH of 5 down to 4 on the 11th and then to 3 on the 25th. From June through mid-August (a period of 5 samples), the pH remained fairly constant at this location (average pH: 5.8 ± 0.1). From September through October however (also a period of 5 samples), the pH had dropped to 5.2 ± 0.2 . The larger pH impact came when the water was sampled on November 11 and November 25. The average pH for these two dates was 3.5 ± 0.6 and it is unknown what would have caused such a large decrease. After that, pH returned to near its normal level (5.5 ± 0.2). The other upstream sites (3-7) stayed constant between about 5.5 and 6 before increasing at the Finger Pier and James River confluence (sites 8 and 9) to between 6.4 and 7.

Dissolved oxygen showed a statistically significant negative trend on two dates (July 28 and August 5) and a significant positive trend on four instances (September 16, October 28, November 11, and December 23). Overall, the dissolved oxygen showed a general trend of decreasing values in the upstream segment (from site 1 to 6) with the drop more pronounced in the summer than winter. While there was especially a larger drop in the summer from sites 1-6, a large portion of that overall drop occurred at sites 5 and 6 which were the closest sites upstream of the large beaver dam that was between sites 6 and 7. The dissolved oxygen values were about 0.8 mg/L higher below the dam (site 7) than the final sampling site just above the dam (site 6). From site 7 to the Finger Pier (site 8) the values decreased slightly before increasing again at the James River confluence.

For conductivity, only once during the summer/early fall sampling dates was there a statistically significant trend (positive on July 28). The final 8 sampling days (September 16-December 23) all showed significant positive trends. In general, conductivity showed few correlations especially in the summer and fall because the values stayed nearly the same in the upper segment of the creek (sites 1-7). Conductivity values were typically higher at the Finger Pier and at the confluence with the James.

Tropical Storm Irene passed through the area on August 27 (directly between the mid-August and the first September longitudinal sampling) knocking down numerous trees, and causing widespread flooding. The first September sampling showed noticeable decreases across all sites in pH (0.4 decrease), dissolved oxygen (0.4 mg/L decrease), and conductivity (41 $\mu\text{S}/\text{cm}$ decrease).

Discussion

In this discussion, I will first consider the fluvial effects on stream water quality at the two continuous monitoring locations then describe tidal influences on water quality at the two sites. Seasonal and episodic analysis indicates that there were significant differences in water quality between the two continuous monitoring stations located in the tidal, unforested and the non-tidal, forested segments of Kimages Creek. Tidal influences in water quality were seen at the downstream monitoring station, but tidal effects on water depth were also observed at the upstream site which was previously believed to be non-tidal.

Variation in water temperature followed expected seasonal patterns but revealed interesting differences between the two monitoring sites. Studinski et al. (2012) demonstrated that stream reaches without riparian cover display significantly higher temperatures than reaches of a stream with riparian cover. Their investigation showed that where there was only 10% canopy cover, stream temperature increased by about 4 °C. This was similar to the maximum difference between the two permanent stations in Kimages Creek. Additionally, Bukaveckas (2007) found that significantly higher temperatures were associated with the relocation of a stream with a riparian buffer composed of mature trees to an area with a newly vegetated buffer which was also similar to the differences between the upstream and downstream sections of Kimages Creek. During the summer, the Route 5 station was in a section of the creek that was shaded by trees whereas the Finger Pier was in an unshaded reach and this was likely the reason

for the larger difference in the temperature between the sites in the summer/fall (when there are leaves on the trees shading Route 5) and the winter/spring (when the trees are bare). The winter/spring temperatures were similar because sunlight was able to penetrate the canopy and warm the water at Route 5 to a temperature that was similar to the Finger Pier. This effect was also seen in the longitudinal data. Episodic events showed that the temperature at the two locations became similar when rainwater dominated at both sites.

The conductivity of Kimages Creek varied seasonally as a result of a number of factors. March and April had higher rainfall totals than January and February and the rain (having low conductivity) diluted the ions in stream water consequently causing the conductivity to fall. In December, there was an upward spike in conductivity at the Route 5 site, which might indicate the application of road salt to Route 5. Road salt has been shown to cause increases in conductivity (Rosenberry et al., 1999). Rain on December 5, 8, and 13 combined with daily low temperatures near freezing could have necessitated the application of salt to the road or bridge over the creek. While Kimages Creek shows decreased conductivity during rain events, Robson et al. (1992) showed increased conductivity during rain events at a Welsh stream. The difference between the two studies was that the rainfall at the Hafren stream had conductivity values that were significantly higher than that of the stream (up to 0.18 mS/cm), which caused the conductivity to increase. This high conductivity was a result of the prevailing westerlies which have rain that was enriched with sea salts from the Irish Sea and the Atlantic Ocean (Robson, et al., 1993). Conductivity of a rain event in Pennsylvania (which would not have picked up sea salt or large amounts of other ionic compounds) measured an average of 0.025 mS/cm which was nearly three times lower than the initial (pre-rain event) conductivity at Route 5 on the April 20 rain event (Moyle and Lamb, 2008). The Finger Pier conductivity reached a maximum in

August when the water levels were near their minimum depth and there are two explanations for this. The first is that the low water levels simply caused the ions in the water to become more concentrated. The second is that higher conductivity in the James River could have had a larger effect on the creek as a result of lower freshwater inputs. The conductivity rise that was seen at sampling sites 8 and 9 was due to the tidal effects of the James River on the creek. It is possible that there was a minimal effect farther upstream and that is what resulted in the small changes from site 1 to site 7.

Seasonal variation in water depth generally followed expected trends of higher water levels in colder months and more shallow water in summer months at Route 5. January and February had the highest water levels while July-September recorded the shallowest depths. After September, the depths increased again; however, they do not reach the depths that were seen in January and February. A potential reason that November and December (the two rainiest months of the year) did not record deeper depths was because most of the rain for those two months fell during only a few days (1-2) of very heavy rain. This caused the depth to spike up very high before it quickly dropped back down closer to the average value for the month (i.e. the system recovered quickly). The construction or destruction of beaver dams may also have contributed to variation in water level at the Route 5 site. Periods where Route 5 measured higher water levels could indicate the presence of a beaver dam, while periods where the water level drops could indicate the destruction of a dam.

Turbidity values of Kimages Creek at Route 5 for March and April were higher than most of the other months and this was likely due to the higher rainfall totals in those months. Similarly, January and February had lower turbidity and correspondingly lower rainfall. The reason that the Route 5 monthly average for December was much higher than any of the other

months could be due to the few short periods of heavy rain which could have caused more erosion and suspension of sediments in the water column. Wetlands reside upstream of the part of the creek on the Rice Center property and these wetlands could have helped to filter the water and lowered the turbidity year-round.

Dissolved oxygen levels in Kiamages Creek were generally low (Route 5: 3.1 mg/L, 29% saturation; Finger Pier: 6.1 mg/L, 63% saturation). Virginia has a 4.0 mg/L minimum standard for dissolved oxygen (Virginia Water Quality Standards, 2011) and a previous study (Mallin et al., 2009) found a rural stream (similar to Kiamages Creek) that was affected by low dissolved oxygen. A potential causes for these low dissolved oxygen levels were higher levels of heterotrophic respiration in the summer. The presence of wetlands upstream of Route 5 could also have contributed to lower dissolved oxygen levels at the Route 5 site. Wetlands are highly productive systems and heterotrophic respiration in these systems causes oxygen to be consumed leading to low dissolved oxygen levels in outflow (Cornell and Klarer, 2008). Dissolved oxygen levels in the creek underwent increases during rain events due to higher stream velocities which can cause increased mixing and aeration. Also, the rainwater contains higher levels of dissolved oxygen (near saturation) than were observed in the stream (below saturation). The dissolved oxygen decrease that was noticed from sites 1-6 (the sites above the beaver dam) was likely a result of the large beaver dam between these sampling locations. The beaver dam caused the water in the creek to stagnate allowing for greater oxygen loss through heterotrophic respiration. Also, increased water depth near the dam reduces oxygen renewal from the atmosphere. Downstream from the dam (at site 7), the dissolved oxygen increased slightly from reaeration both a result of the moving water and from the water gaining oxygen as it flowed over the dam.

Dams have been shown to increase downstream dissolved oxygen concentrations over short longitudinal distances (Cox, 2003).

The seasonal variations that were seen in the pH (Route 5: 0.9 higher; Finger Pier: 0.7 higher) can probably be attributed to higher levels of photosynthetic activity (Michaud, 1991). Additional reasons for localized changes in pH could be acidic soils which contain weak acids or pine needle decay which can also cause lower pH levels (Duffy et al., 1989; Cooper, 2000). Other studies of streams have shown some longitudinal differences in pH (Mill et al., 2006).

Continuous monitoring data from both sites were evaluated for oscillations in depth and water quality that would indicate tidal influences. Tidal influences were clearly seen at the Finger Pier with a continuous oscillation in depth while Route 5 showed only slight influences in depth. Wood (2010) showed that water levels at the Finger Pier were determined by tidal exchange and the water level in the James River, while Route 5 was determined to be non-tidal. During rain events, the depth at both the Finger Pier and Route 5 location increased due to water flowing into the creek from both upstream and from the tidal James.

The Finger Pier (which had warmer water temperatures) had fewer periods where the dissolved oxygen was below the minimum standard (4.0 mg/L) as compared with Route 5. However, it is likely that the tidal influence of the James River was able to keep the dissolved oxygen levels higher than those at Route 5. The pH at the Finger Pier sharply increases around October and this could be the result of an influence from the James River since the Finger Pier is in the tidal reach of the creek. October also shows a large increase in conductivity which would be consistent with a James River influence. Wood (2010) showed that the volume of water Kimages Creek exchanged with the James River during a single tidal cycle reached its maximum in October. It has been previously shown that longitudinal variations in pH occur in tidal

systems and these variations can be attributed to the pH of the influxing freshwater from upstream waters (Howland et al., 2000; Mill et al., 2006).

As for the tidal variation in water quality, the movement of water into Kimages Creek from the James River had an obvious effect on the temperature, dissolved oxygen, conductivity, and pH at the Finger Pier. Parameters that had relatively high values in the river water would cause the water in the creek to become dominated by those characteristics and the values of the parameters will rise (and vice versa for lower parameter values in the river water) (Mill et al., 2006). At Route 5 the depth of the water appears to be the only parameter which is tidally affected which suggests that there may be another mechanism that affects the depth. Given the fact that the large beaver dam would prevent tidal effects from reaching Route 5, fluctuations in groundwater could possibly account for the change seen at Route 5. The other possibility is that there just isn't enough water that reaches Route 5 from the James River to affect any other water quality parameter apart from depth.

Uncles and Stephens (2010) showed that suspended sediments are transported upstream during high tide. The high tide can also cause resuspension of sediments from the banks of the channel or mudflats; however, tidal variation in turbidity was not seen in Kimages Creek at either site. The difference between Kimages Creek and the Tavy Estuary (as studied by Uncles and Stephens) was that there were significant (0.25m) waves in the Tavy Estuary which helped erode the stream bed as the tides changed. The period from August to October showed large increases in the turbidity (and corresponding decrease of dissolved oxygen) at the Finger Pier which could have been due to excavation efforts which stirred up sediments and caused the sensor to sit in pools of relatively deoxygenated water, giving erroneous readings of the true water quality. The other possibility is low water levels caused the sensor to sit out of the water.

Conclusion

This study characterized spatial and temporal variation in water quality of Kimages Creek. It was shown that there are consistent differences between the two permanent sonde locations as well as short-term variations in water quality driven by rain and tidal effects. Temporal differences existed for all parameters and were particularly pronounced for temperature, turbidity, and dissolved oxygen. It was also determined that tidal interactions and rain events can significantly alter the water quality in the creek at least over the short term. From this, it may be possible to apply what has been learned here to other tidal freshwater creeks to determine their watershed processes and how their overall stream health can be impacted by different variables.

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Table 1: Data availability for water quality measurements at two monitoring locations at the VCU Rice Center during 2009.

Month	Route 5		Finger Pier	
	Records	%	Records	%
January	1750	59	0	0
February	1824	68	2254	84
March	2537	85	2976	100
April	2877	100	2876	100
May	2919	98	2966	100
June	2804	97	2880	100
July	2576	87	2171	73
August	1369	46	2057	69
September	36	1	2879	100
October	2739	92	2976	100
November	2555	89	2885	100
December	1493	50	2976	100
Total	25479	73	29896	85

Table 2: Sampling locations for water quality surveys of Kimages Creek performed at the VCU Rice Center.

Site #	Latitude	Longitude	Dist. From Rt. 5 (m)
1	37 20.290	77 12.380	60
2	37 20.257	77 12.399	145
3	37 20.218	77 12.394	220
4	37 20.182	77 12.380	295
5	37 20.164	77 12.424	375
6	37 20.135	77 12.426	445
7	37 20.105	77 12.443	515
8	37 19.983	77 12.410	795
9	37 19.620	77 12.253	1800

Table 3: Linear trends in water quality variables as a function of distance for 9 stations in Kimages Creek (VCU Rice Center).

Run #	Date	All Sites											
		Temperature			Conductivity			pH			Dissolved Oxygen		
		R ²	p-value	Correlation	R ²	p-value	Correlation	R ²	p-value	Correlation	R ²	p-value	Correlation
1	6/24/2011	0.86	0.0082	Positive	0.21	0.37		0.24	0.32		0.53	0.10	
2	7/8/2011	0.88	0.0017	Positive	0.25	0.25		0.34	0.18		0.003	0.90	
3	7/28/2011	0.91	0.0007	Positive	0.64	0.0301	Positive	0.13	0.42		0.70	0.0182	Negative
4	8/5/2011	0.97	<0.0001	Positive	0.26	0.24		0.02	0.74		0.71	0.0172	Negative
5	8/19/2011	0.91	0.0009	Positive	0.03	0.71		0.44	0.10		0.48	0.0837	
6	9/2/2011	0.78	0.0084	Positive	0.28	0.22		0.42	0.13		0.56	0.0530	
7	9/16/2011	0.97	<0.0001	Positive	0.87	0.0003	Positive	0.83	0.0006	Positive	0.66	0.0078	Positive
8	9/30/2011	0.90	<0.0001	Positive	0.92	<0.0001	Positive	0.90	<0.0001	Positive	0.34	0.0979	
9	10/14/2011	0.89	0.0001	Positive	0.89	0.0001	Positive	0.76	0.0021	Positive	0.0004	0.96	
10	10/28/2011	0.69	0.0052	Negative	0.91	<0.0001	Positive	0.80	0.0011	Positive	0.84	0.0005	Positive
11	11/11/2011	0.01	0.85		0.94	<0.0001	Positive	0.47	0.0401	Positive	0.78	0.0015	Positive
12	11/25/2011	0.89	0.0001	Positive	0.90	<0.0001	Positive	0.33	0.11		0.34	0.0973	
13	12/9/2011	0.86	0.0003	Positive	0.89	0.0001	Positive	0.58	0.0169	Positive	0.02	0.71	
14	12/23/2011	0.60	0.0137	Positive	0.90	<0.0001	Positive	0.52	0.0282	Positive	0.86	0.0003	Positive



Figure 1: Aerial photo of Kimages Creek showing the sampling locations for the longitudinal survey (sites 1-9) and the current locations of continuous monitoring stations (sites 3 and 8). Note: Seasonal and episodic data comes from the Route 5 sonde when it was located just upstream of site 1).

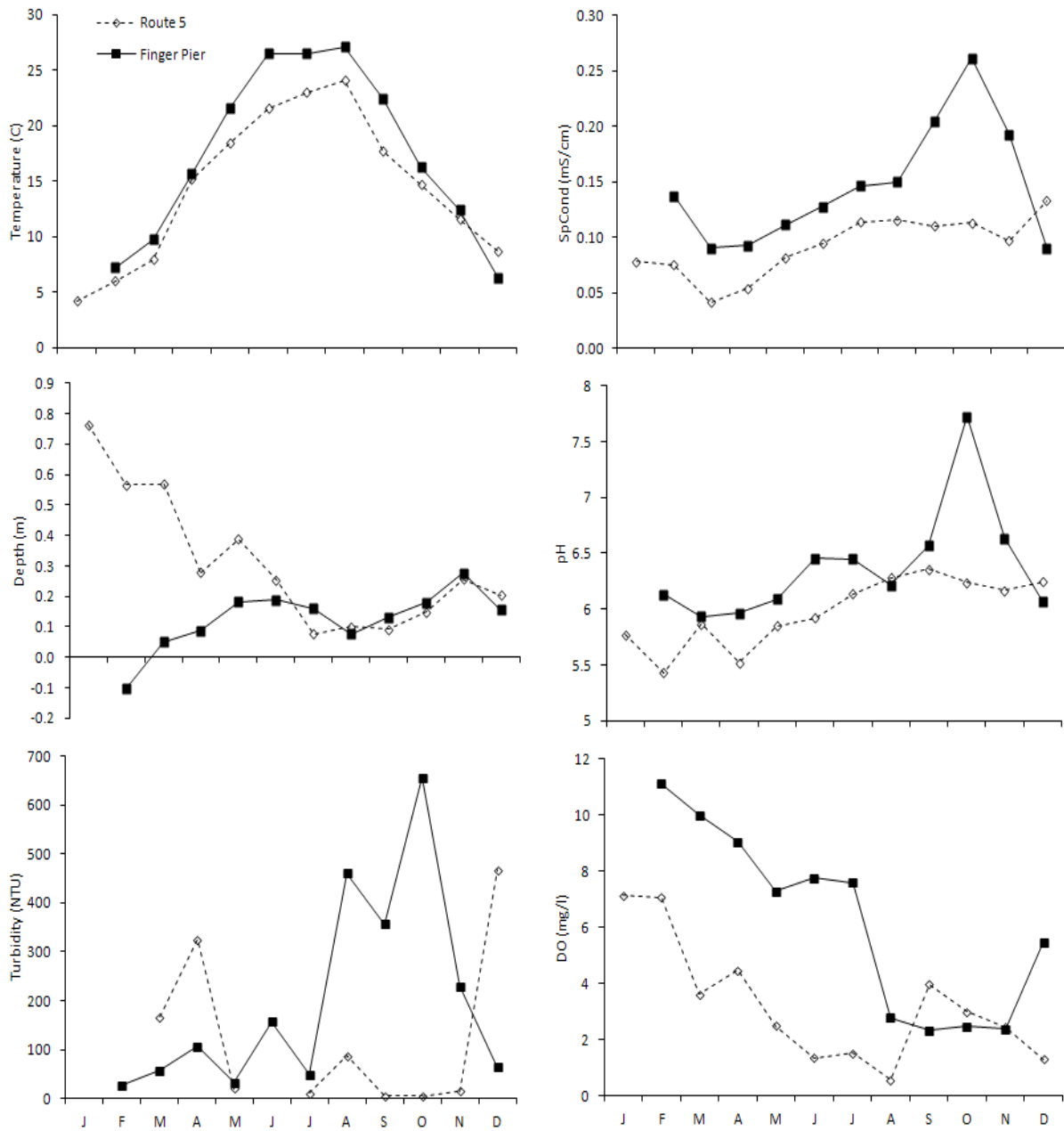


Figure 2: Monthly average values of water quality monitoring parameters recorded at two stations in Kimages Creek.

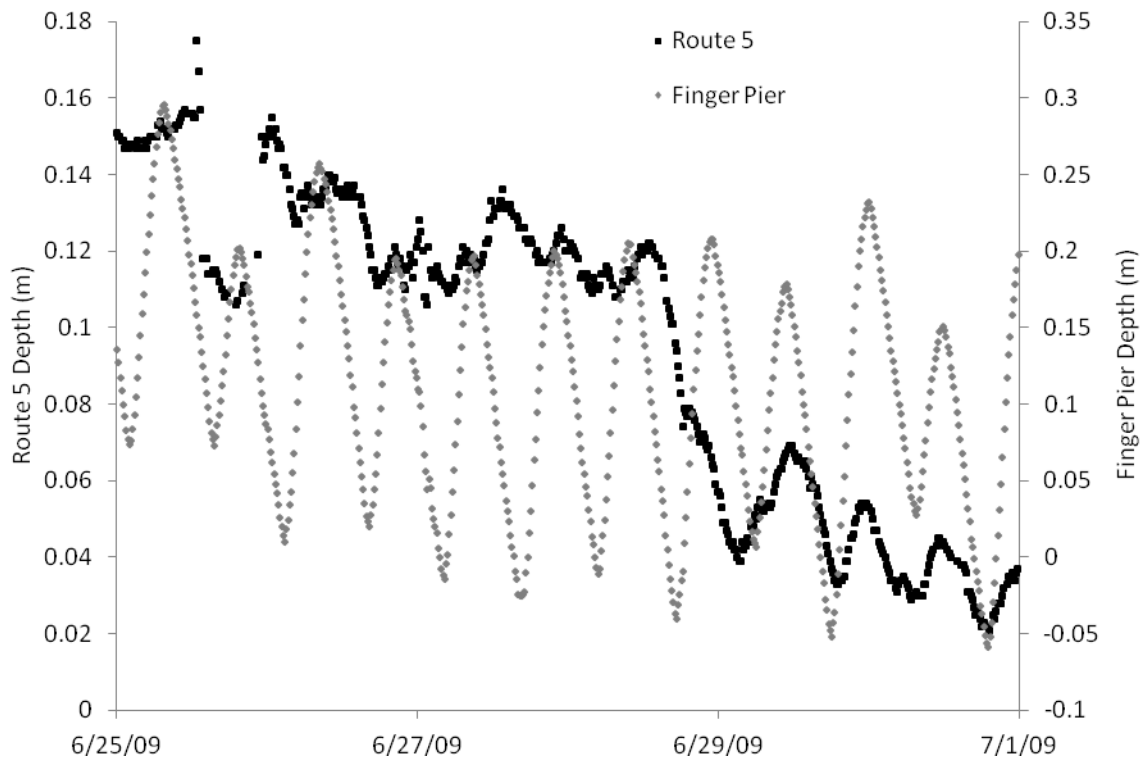


Figure 3: Variations in water depth at two locations in Kimages Creek.

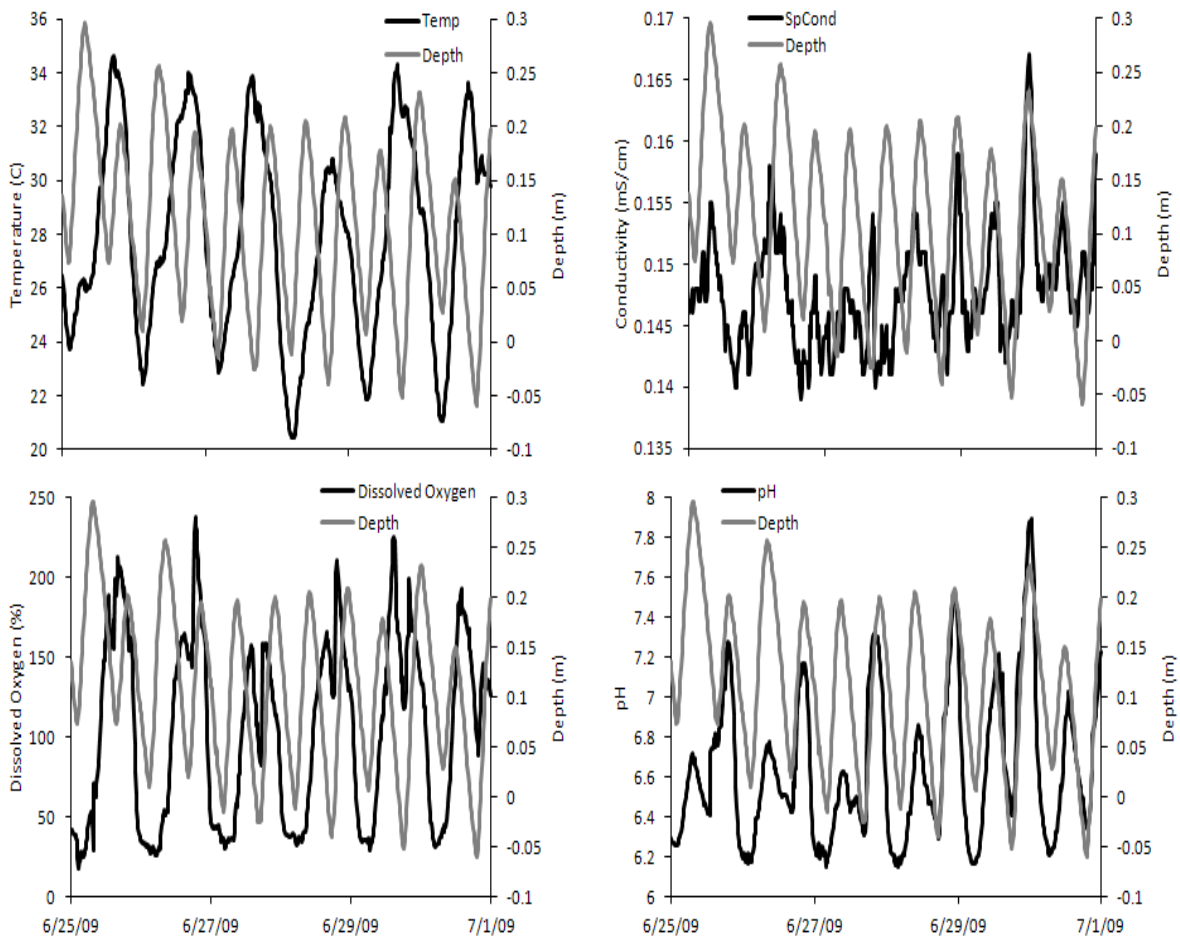


Figure 4: Variations in depth and water quality at the Finger Pier monitoring location in Kimages Creek.

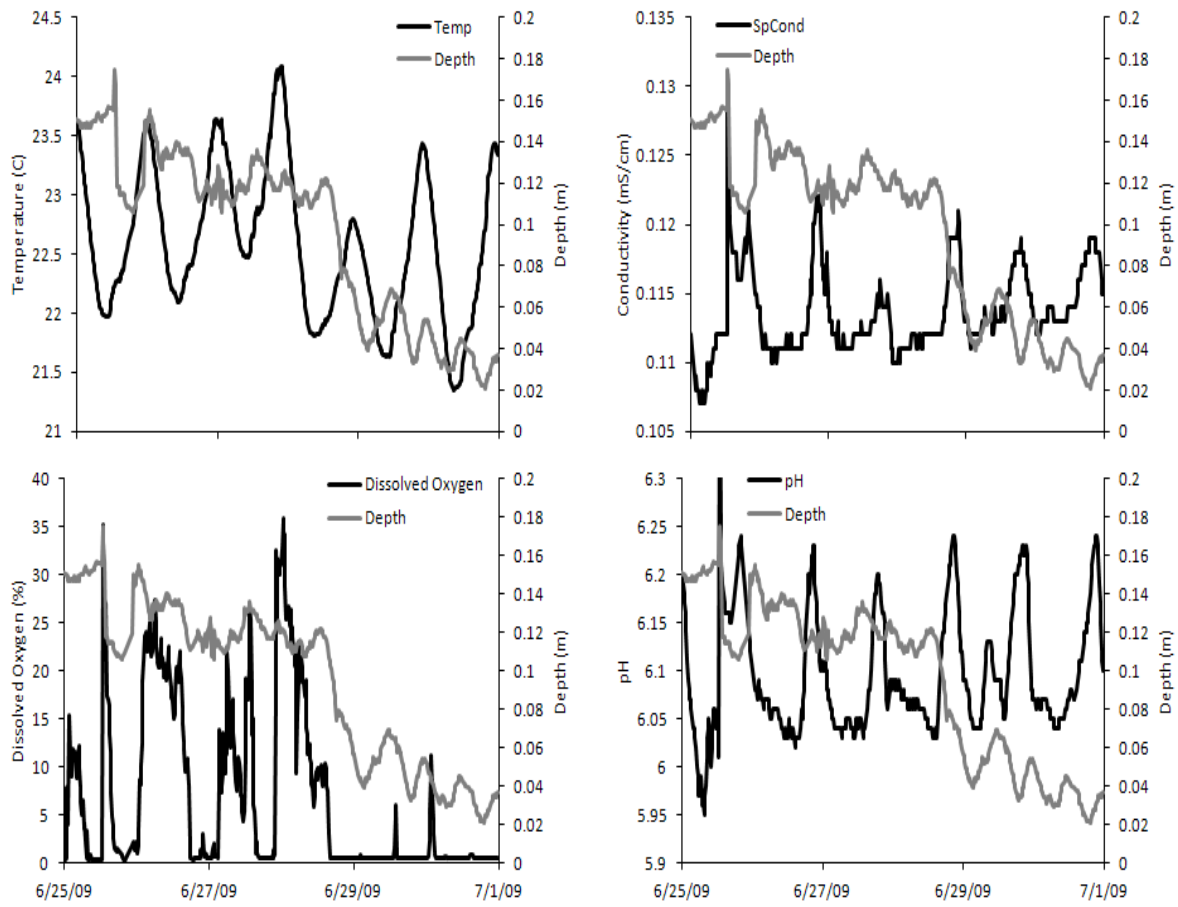


Figure 5: Variations in depth and water quality at the Route 5 monitoring location in Kimages Creek during June 2009.

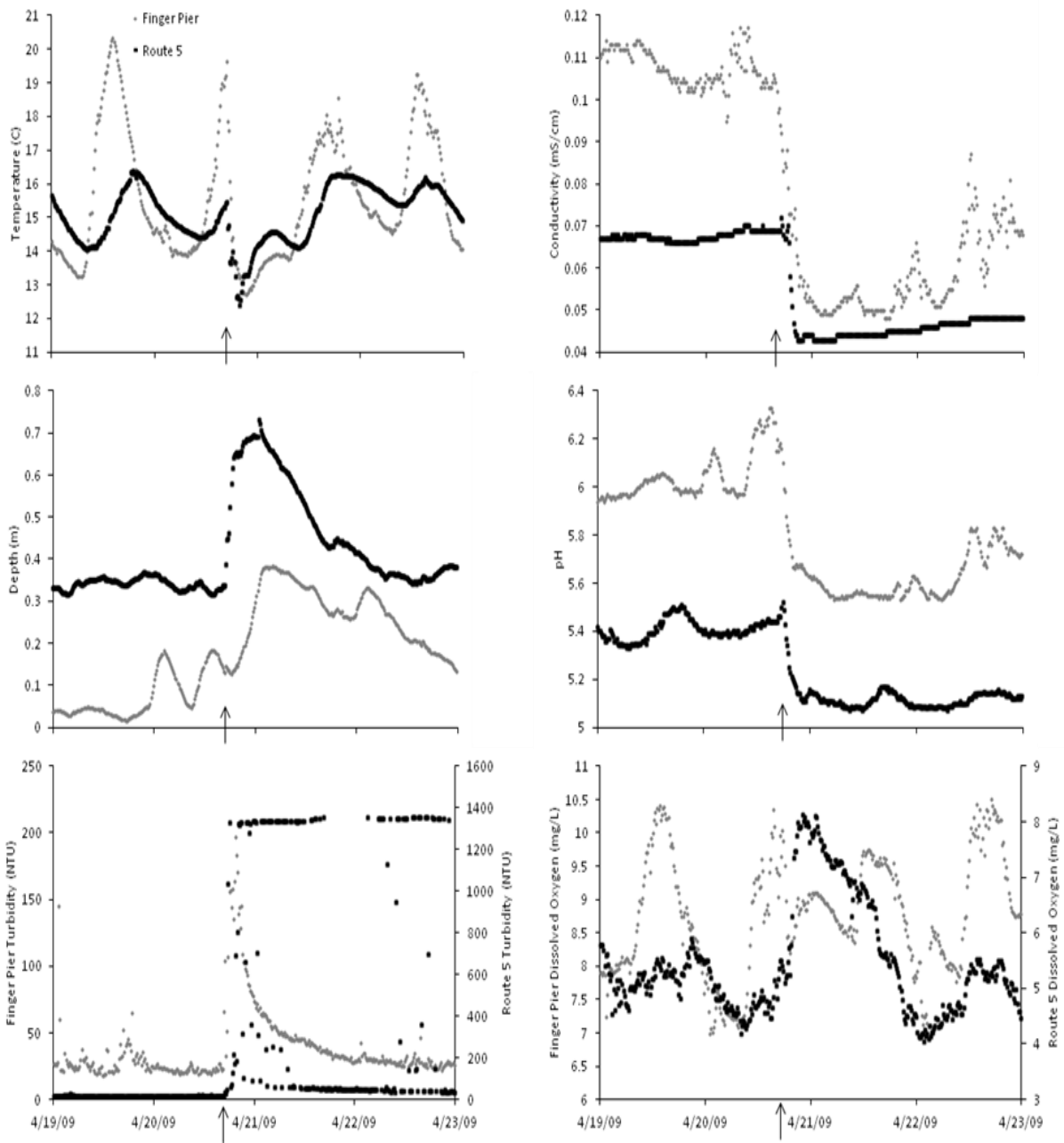


Figure 6: Changes in water quality conditions in Kimages Creek during an April 20 rain event. The arrows indicate when the rain event occurred.

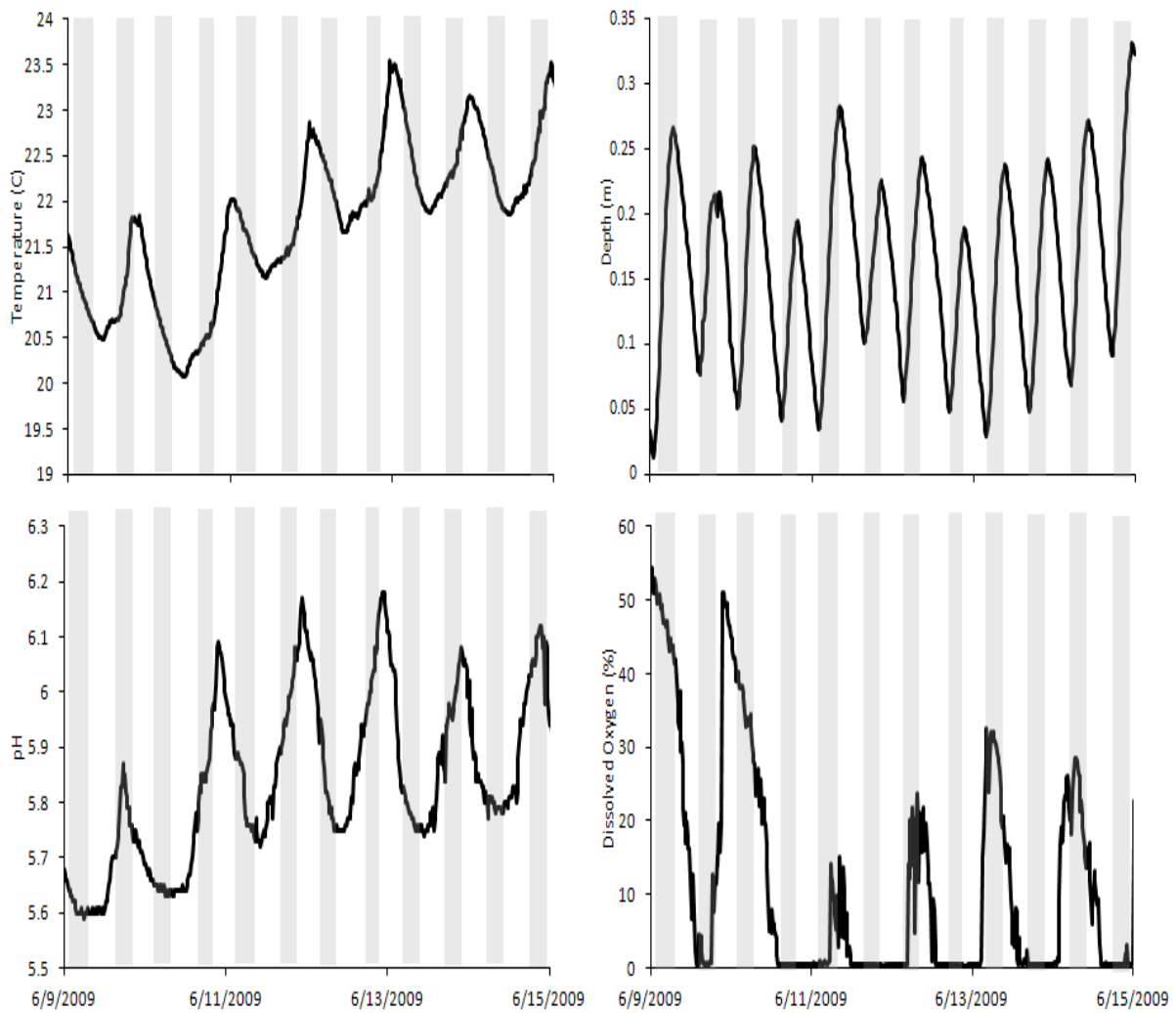


Figure 7: Cyclical patterns of depth at the Finger Pier and temperature, pH, and dissolved oxygen at Route 5. Gray bars indicate periods of incoming tides.

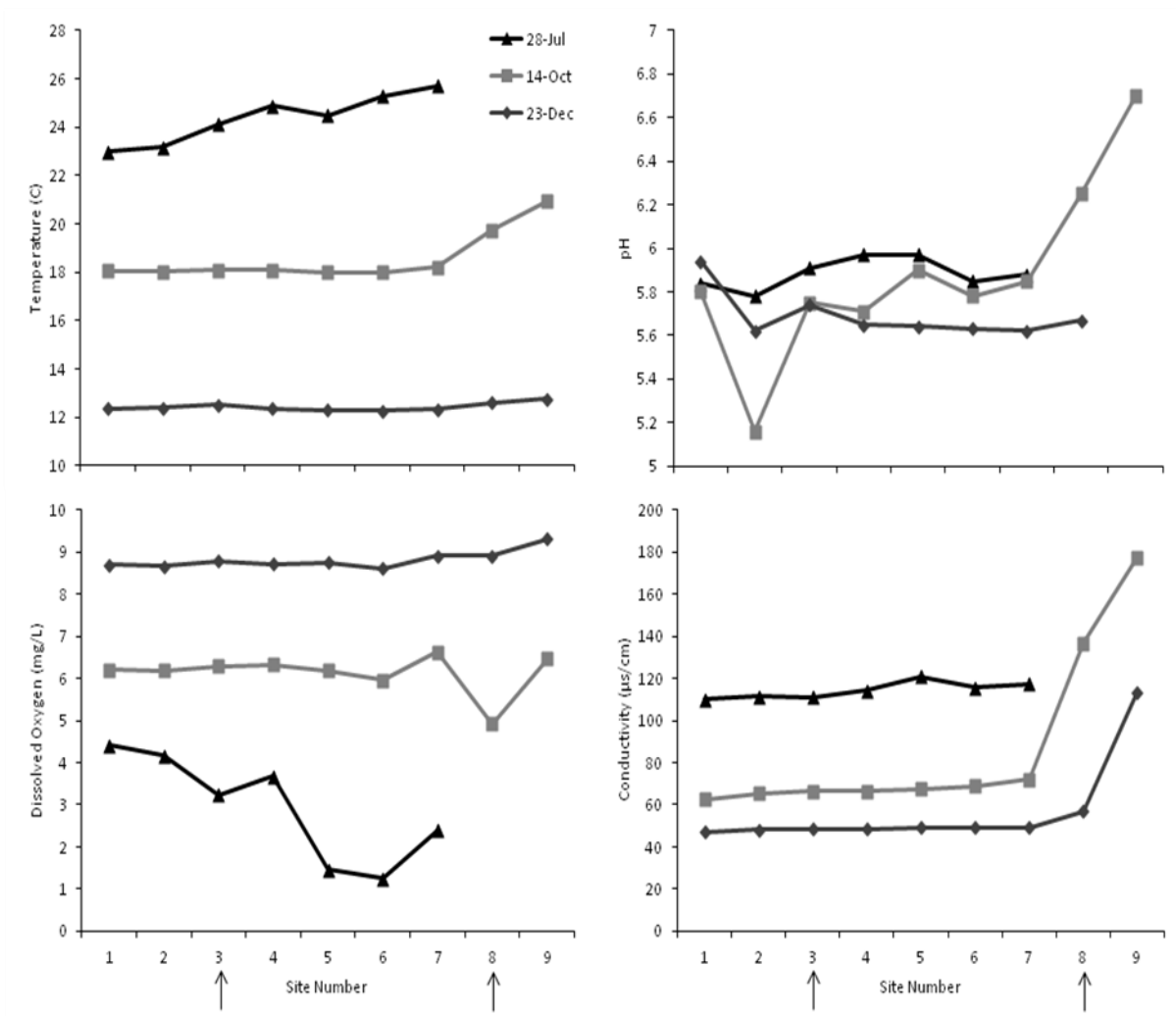


Figure 8: Longitudinal variation in the water quality of Kimages Creek on 3 dates. Arrows indicate the current locations of the permanent sondes (Note: The Route 5 sonde was located at site 3 during the period of sampling, but was previously located upstream of site 1).