Monitoring and Modeling Valley Creek Watershed:
3. Surface-Water Hydrology

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Extended Abstract

Valley Creek in southeastern Washington County, Minnesota, is one of the healthiest trout streams remaining in the Minneapolis-St. Paul metropolitan area. The watershed is presently mostly rural but faces potential urbanization in the coming decades. Trout streams are sensitive to land uses such as urbanization and agriculture that can degrade water quality. Urbanization can increase surface-water runoff from impervious surfaces into creeks, thereby increasing summer water temperatures above the range tolerated by trout, altering the macroinvertebrate community, and increasing loads of sediment, nutrients, and toxic substances (see reviews by Klein, 1979; Schueler, 1994; Booth and Jackson, 1997). The purpose of this report is to describe the surface-water hydrology of Valley Creek in order to document baseline conditions against which future changes may be gauged. This report concentrates on baseflow conditions in the creek because no major runoff events occurred during the present study period, which includes the latter half of 1997 and all of 1998. Monitoring will continue through 2007, contingent upon available funding. Selected data collected by the Valley Branch Watershed District from 1973-93 are included for comparison.

The surface-water hydrology of Valley Creek comprised measurements of water quantity (discharge and volume) and water quality at critical branch points along the creek, where automated stream-monitoring stations were established. Site 1 monitored the South Branch, site 2 monitored the North Branch, and site 5 monitored the mouth of the main stem of Valley Creek, about 1 km below the confluence of the south and north branches. Sites 3 and 4 monitored intermittent tributaries that did not flow during the study period. Grab samples were collected about weekly (bi-weekly during winter) and analyzed primarily for suspended solids and nutrients; a few samples were analyzed for major inorganic constituents (dissolved minerals).

Flow volumes were much larger than expected for a surficial watershed the size of that of Valley Creek, indicating that contribution from groundwater came from aquifers extending beyond the basin boundary. Steady groundwater contributions to the creek were indicated by extremely stable flows and stages, which varied typically within just a few centimeters from median. This stability was a result of the relatively level, highly permeable geologic deposits across much of the watershed, which facilitated

infiltration and minimized overland runoff. Consequently, storm peaks were few and short-lived.

Some important water-quality variables were very different between the two main branches of the creek, the South Branch and the North Branch. These differences were due to the different water sources to the branches: the South Branch is fed by groundwater discharge, and the North Branch is fed primarily by outflow from Lake Edith. Because groundwater is relatively stable in temperature, the South Branch had much lower seasonal variation in temperature and reached a summertime maximum of only 16.5°C, well within the range favored by trout (about 10–20°C). In contrast, because of summertime warming of Lake Edith, the North Branch exceeded 20°C for about 22% of 1998 during the period from mid-May to mid-September, making this branch less favorable trout habitat. Biotic processes in Lake Edith also removed dissolved minerals from the water column, giving the North Branch lower concentrations of calcium, magnesium, bicarbonate, and silica than the South Branch. The loss of these dissolved minerals was tracked by specific conductance values, which declined during summer and recovered during winter in the North Branch relative to the South Branch. Both branches had relatively low values of total phosphorus and suspended solids. However, the South Branch had much higher concentrations of total nitrogen, a consequence of receiving nitrate-contaminated groundwater.

The maintenance of Valley Creek as a fine example of a trout stream will depend on guarding against at least two potential problems. First, inputs of overland runoff should be minimized, particularly from impervious surfaces that accompany development. The landscape is suitable for engineering practices that promote infiltration of storm water, rather than those that direct storm water directly to streams via gutters, storm sewers, and ditches. Such practices will minimize increases in runoff peaks and volumes, consequent channel erosion, and inputs of dissolved and suspended substances to the creek, although storm-water infiltration could affect groundwater quality. Second, inputs of eroded fine particulates (siltation) should be minimized, particularly in the South Branch. Because this branch is already well-fertilized with nitrates, additions of fine particulates with their associated bound phosphorus could spur over-abundant growth of aquatic macrophytes and algae. In addition, siltation destroys spawning habitat for trout and reduces the quality of the macroinvertebrate food source for trout. Finally, reducing nutrient inputs to Valley Creek is yet another positive step in improving the quality of the St. Croix River, a natural resource of national significance.

INTRODUCTION

Highly valued natural resources warrant protection and maintenance, or if necessary, restoration and improvement. Trout streams are highly valued natural resources that are sensitive to land-use practices that can degrade water quality (Hicks and others, 1991; Kemp and Spotila, 1997). Valley Creek in southeastern Washington County near the village of Afton (Figure 1) is one of the finest trout streams in the Minneapolis-St. Paul metropolitan area, with all three species of stream trout (brown, rainbow, and native brook) reproducing successfully in the creek (Waters, 1983). In addition, the stream harbors the relatively rare American brook lamprey, a small non-parasitic species of special concern in Minnesota (VBWD, 1995). Presently the watershed is largely agricultural with scattered rural-residential developments. However, the watershed is at the margin of the rapidly developing fringe of the metropolitan area and faces potential urbanization in the coming decades (Pitt and Whited, 1999). Only about 14 trout streams remain in the metropolitan area (MDNR, 1996), and so protecting the quality of Valley Creek is of critical importance in maintaining regional aquatic biodiversity. Moreover, Valley Creek is tributary to the St. Croix River, a designated National Scenic Riverway and one of the cleanest large river systems in the contiguous United States (Waters, 1977). Maintaining the quality of the St. Croix River requires protection of its tributary watersheds. In short, Valley Creek and the St. Croix River are highly valued natural resources that add to the quality of life and deserve protection.

The purpose of this report is to describe the surface-water hydrology of Valley Creek to document baseline conditions against which future changes may be gauged. The literature pertaining to the effects of urban and agricultural land use on stream hydrology is reviewed to provide context for the findings from Valley Creek. This report concentrates on baseflow conditions in the creek because no major runoff events occurred during the present study period, which included most of the latter half of 1997 and all of 1998. Selected data collected by the Valley Branch Watershed District from 1973-93 are included for comparison. The principal finding of the study is that important water-quality variables in the two main branches of Valley Creek were very different. The South Branch, fed primarily by groundwater discharge, had a relatively stable temperature regime favored by trout but also had a relatively high total nitrogen content. In contrast, the North Branch, fed primarily by outflow from Lake Edith, had wide seasonal temperature changes beyond the range favored by trout. Both branches had low suspended sediment and phosphorus content, likely because of the rarity of overland flow events in the watershed. Future efforts should be directed toward protecting the South Branch from erosion and the consequent input of particle-associated phosphorus, as this branch is already nitrogen-rich.

EFFECTS OF LAND USE ON STREAM HYDROLOGY

Virtually all hydrologic flows in watersheds, including overland runoff and groundwater flow, converge on streams and deliver not only water but also dissolved and suspended materials. Streams collect and integrate these converging flows and are therefore sensitive to activities in the watershed. However, the water in the stream is consequently a mix from many different sources and interpreting this mix can be difficult. Nonetheless, streams are critical focal points for monitoring the cumulative, integrated effect of watershed land use. Land uses such as urbanization and agricultural can significantly impact watershed hydrology, including both physical hydrology and water quality. These hydrologic changes can in turn alter the biotic integrity of the stream.

Physical hydrologic impacts include increases in runoff volumes, storm-flow peaks, and channel instability. Urbanization tends to increase both flood peaks and frequencies while reducing baseflow (Klein, 1979; Watson and others, 1981; Simmons and Reynolds, 1982). The influence of urbanization on flood volume is greater for high-frequency events. Hollis (1975) found that urbanization could increase the volume of small, frequent floods by a factor of ten, whereas the volume of 100-yr floods could be doubled by 30% impervious area. Similarly, Moscrip and Montgomery (1997) found that post-urbanization 1- to 4-yr floods were as large as pre-urbanization 10-yr floods. Urbanization can trigger channel erosion as the stream tries to adjust to increases in flood frequencies and runoff volume. Channels may enlarge by widening (Hammer, 1972) or by incising (Booth, 1990); channel slope and bed material modify the degree to which these processes may occur. The loss of floodplain forests and the consequent reduction of large woody debris dams may also accompany urbanization and facilitate further channel incision (Booth, 1990). While the effects of increased storm flows are dramatic, alteration of baseflow can have more permanent consequences, because these are the conditions that affect the biota most of the time. A healthy baseflow may be the most important factor in making a stream resilient to short-term disturbances. In Valley Creek itself, a few large floods in 1965 significantly reduced trout populations, yet a return to healthy baseflow conditions allowed the trout to recover (Elwood and Waters, 1969).

Stream water-quality impacts include increases in loading of nutrients, suspended solids, and toxic materials. Both agriculture and urbanization generally increase loadings of nutrients (nitrogen N and phosphorus P) and suspended solids to receiving waters compared to loadings from forested or otherwise naturally vegetated watersheds. Although loadings vary with regard to agricultural practices and density of urbanization, some studies have shown slightly greater increases in nutrients and suspended solids from agriculture than from urbanization (for example, Spahr and Wynn, 1997; Wernick and others, 1998). Nutrient and suspended solid loadings can be correlated with percentage of land area in row-crop agriculture, although some of these loadings can be ameliorated by riparian buffers (for example, Johnson and others, 1997; Snyder and others, 1998). In general, P tends to be related to suspended solid loadings from overland runoff (for example, Jordan and others, 1997). Loadings of N commonly occur as dissolved nitrate, and concentrations can peak during months when crops are not present, thereby reducing biotic uptake and evapotranspiration and consequently allowing flushing of soils by infiltrating water or shallow subsurface runoff (Boyd, 1996; Jordan and others, 1997; Cambardella and others, 1999). At these times, nitrate-enriched groundwater discharge can constitute a larger proportion of stream flow. Urbanization can produce nutrient loadings from organic debris (leaves, lawn clippings), lawn fertilizers, and septic systems; in addition, toxic materials such as heavy metals may accumulate on urban surfaces and be flushed into receiving waters during storm events (Barbé and others, 1996; Wernick and others, 1998; Duke and others, 1999).

Degradation of biotic integrity of streams can result from these changes in physical hydrology and water quality. Communities of aquatic insects and other macroinvertebrates can be impaired by urbanization, either from known point-source discharges of municipal effluent (Barbé and others, 1996; Wernick and others, 1998; Duke and others, 1999; Kennen, 1999) or from more diffuse nonpoint-source discharges (Jones and Clark, 1987). Deposition of fine-grained sediments (siltation) from either urban or agricultural landscapes can be a significant cause of changes in composition and reductions in diversity in aquatic macroinvertebrate communities (Richards and others, 1993; Richards and Host, 1994). Siltation likewise changes the community composition of fish species, both because of a change in their macroinvertebrate food supply and because of a loss of spawning habitat for lithophilous species such as trout (Waters, 1983; Rabeni and Smale, 1995; Waters, 1995). Wang and others (1997) found that aquatic habitat quality and index of biotic integrity were negatively correlated with percentages of agricultural and urban land in the watershed. Urbanization has been shown to cause declines in brown trout in Pennsylvania (Kemp and Spotila, 1997) and other salmonids in Washington (Moscrip and Montgomery, 1997).

The effect of land use on watershed hydrology and aquatic habitat is a matter of degree, a function of the percentage of watershed area that is urban or agricultural. One measure of urbanization is the percentage of impervious land cover in the watershed. A number of studies suggest that significant degradation of aquatic habitats begins at a threshold of about 10% impervious cover (Schueler, 1994; Booth and Jackson, 1997), although factors such as storm-water engineering practices and regional geology can influence the ultimate effect of impervious surfaces on stream hydrology. An impervious cover of 10% represents about one single-family dwelling per acre.

STUDY AREA DESCRIPTION

As termed in this report, Valley Creek in southeastern Washington County is tributary to the St. Croix River and has two perennial main branches, the North Branch and the South Branch, which combine to form the main stem (Figure 1). The creek has been variously termed Valley Branch (USGS, 1967), Valley Branch Creek (VBWD, 1995), and in earlier days Bolles Creek (Winchell, 1888). The valley lengths of these segments (that is, excluding stream meanders) is about 2.22 km for the North Branch, 3.15 km for the South Branch, and 2.45 km for the main stem below the confluence to its mouth at the St. Croix River. Average gradients for these segments are 1.17% for the North Branch, 1.01% for the South Branch, and 0.43% for the main stem. The contributing surficial sub-watershed areas for these segments above the monitoring stations are about 18.1 km^2 for the North Branch above site 2, 20.5 km^2 for the South Branch above site 1, and 4.9 km^2 for the main stem below sites 1 and 2 and above site 5, for a total gauged watershed area of about 43.5 km^2. Extending the watershed below the gauging station to the actual mouth on the St. Croix River adds another 1.5 km^2 for a total watershed area of about 45 km^2. The headwaters of the North Branch at present comprise outflow from Lake Edith (area 30 ha, depth 12 m). The headwaters of the South Branch comprise a number of springs plus more diffuse groundwater discharge in the uppermost 0.75 km of the valley. The South Branch receives infrequent contributions from intermittent tributaries, which extend to the west and south. Just above the headwater springs of the South Branch, a small reservoir (area about 0.52 ha) is pooled behind an approximately 5-m high dam completed in about 1956. This reservoir receives runoff from the southernmost intermittent tributaries in the watershed and presumably traps much of the sediment from these infrequent flows.

The surficial geology is dominated by coarse glacial outwash with gentle topography (Meyer and others, 1990), promoting infiltration and hindering overland runoff. The southernmost part of the watershed, however, is beyond the extent of the last glacial advance, and in that area shallow bedrock, finer-textured soils, and a naturally developed drainage network can facilitate runoff into the aforementioned reservoir at the headwaters of the South Branch. Most of the soils directly overlie bedrock aquifers, especially the Prairie-du-Chien/Jordan (PdC/J) aquifer, a fractured dolomite unit (PdC) and underlying sandstone (J) unit that are commonly hydraulically well-connected and function as a single aquifer in eastern Minnesota. The two branches of Valley Creek, however, lie in bedrock valleys incised through the PdC/J units to the underlying St. Lawrence and Franconia bedrock units. Where these two valleys coalesce, deeper bedrock units, particularly the Ironton-Galesville, subcrop under the length of the main stem. These deeper bedrock units are higher in elevation here than elsewhere in Washington County because of the Hudson-Afton anticline (Mossler and Bloomgren, 1990). The bedrock valleys are generally deeply filled with glacial drift, especially along the North Branch and main stem. Although some bedrock is exposed near Lake Edith, most exposures occur along the South Branch and particularly along the intermittent tributaries in the southern part of the watershed, beyond the glacial boundary. Several bedrock gorges enter the valley of the South Branch from the south, the largest of which lies along Trading Post Road. These dry gorges only rarely produces runoff, despite thin soils over bedrock, apparently because of their small catchments. Evidently these gorges are remnants of ancient hydrologic processes, perhaps when the late-glacial St. Croix River was much higher, and a consequently higher water table fed perennial streams in the now-dry gorges.

Present land use in the watershed is largely agricultural and rural residential, with several large tracts totaling almost 5 km^2 in the lower watershed set aside for preservation and educational purposes. A few scattered subdivisions exist with densities of one dwelling per one-half to five acres. There are about 20 residential dwellings are within 100 m of the creek, although much of the riparian zone of the perennial reaches of Valley Creek is floodplain forest and shrubs that have revegetated the area during the past 40 years following cessation of farming and grazing. The watershed is within boundaries of three local jurisdictions: 86% in the City of Afton (39 km^2), 13% in the City of Woodbury (5.7 km^2), and 1% in West Lakeland Township (0.3 km^2). The present total number of dwellings in the watershed is about 622, and the present amount of impervious cover in the Valley Creek watershed is only about 2.7% (Pitt and Whited, 1999), well below the threshold of 10% at which other studies have noted significant degradation of aquatic habitats. However, if existing agricultural and other lands become developed under present zoning regulations in Afton and Woodbury, this number would more than quadruple. Afton would absorb about 378 of these units, but most (about 1,723) would be built in Woodbury, in the extreme western edge of the watershed (Pitt and Whited, 1999). If these new units produce a similar amount of impervious surface as the existing units, then the total watershed imperviousness would approach 12%. While this is above the 10% threshold, the effects might be ameliorated because most of the development would occur near the edge of the watershed, and not adjacent to the creek.

RESEARCH HISTORY AND PROJECT METHODS

The importance of Valley Creek is recognized by the Valley Branch Watershed District (VBWD), which states that the management goal for the creek "is preservation of its water quality and trout stream habitat" (VBWD, 1995). Consequently, through their contractor Barr Engineering, the District has monitored the creek for over 20 years at two sites (1B and 5B, Figure 1). Sites 1B and 5B are labeled "B" and "C," respectively, in the Water Management Plan (VBWD, 1995). They were re-labeled for the purposes of this report for clarity in comparison with sites 1 and 5, listed below. Site "A" in the Water Management Plan was not considered relevant for this report, as there is no significant surficial channel connecting it to the present watershed of Valley Creek. Water samples and flow measurements were taken about three times each year, typically in June, August, and October. These two sites do not have permanent instrumentation installed; consequently data from these sites cannot be used to characterize storm flows or total annual loadings. This report summarizes VBWD data for 1973-93; some data from 1993 to 1997 are presently held at Barr Engineering.

Other agencies as well have investigated Valley Creek. The trout biology of South Branch Valley Creek has been studied since at least 1965 by the University of Minnesota (for example, Waters, 1983). The trout biology of the North Branch has not been assessed, to our knowledge. The potential impacts of soil erosion and other non-point source pollution inputs to South Branch Valley Creek were investigated in the early 1980s. The Washington County Soil and Water Conservation District (SWCD, 1982) applied the universal soil loss prediction equation to the South Branch Valley Creek and concluded that soil losses ranged between about 3-5 T a^{-1} yr^{-1} (tons per acre per year), which are generally larger than allowable soil loss limits. In addition, the Agricultural Research Service (ARS) monitored flow in the South Branch in 1983-84 as a calibration site for the development of the computer model AGNPS (AGricultural Non-Point Source model; R. Young, ret., ARS, personal communication, 1997).

Beginning in July 1997, the St. Croix Watershed Research Station received state-legislature funding recommended by the Legislative Commission on Minnesota Resources (LCMR) to install four monitoring stations on Valley Creek and to initiate a program of long-term hydrological monitoring (sites 1–4, Figure 1). Site 1 monitors the South Branch and site 2 monitors the North Branch, the two main perennial branches of Valley Creek, near their confluence; site 1 corresponds closely to VBWD site 1B discussed above. Sites 3 and 4 are on intermittent tributaries to the South Branch that can contribute runoff during snowmelt or extreme rainfall events. Also in 1997 the Metropolitan Council Environmental Services (MCES) expressed interest in installing a station at site 5 (Figure 1) as part of their Watershed Outlet Monitoring Program (WOMP). Because of this interest, the SCWRS included site 5 in its sampling program; this site corresponds reasonably to VBWD site 5B discussed above.

Grab sampling began in August 1997 on a weekly basis (bi-weekly during winter), and discharge measurements were taken about half as frequently. This report summarizes data from these sample collections and discharge measurements taken from

August 1997 through 1998. No known flow occurred at sites 3 and 4 during this time; consequently, data are available only for sites 1, 2, and 5, as well as earlier data for sites 1B and 5B. (Flow did occur at sites 3 and 4 on 17 March 1999, which will be analyzed in a future report.) Methods of site installation, discharge measurement, sample collection, and sample analysis are discussed fully in Schottler and Thommes (1999) and only outlined here. For each grab sample, a multi-parameter water quality sonde was used to measure stream temperature, specific conductance, pH, and dissolved oxygen in the field. One-liter samples were cooled and returned to the laboratory for splitting, filtration, and analysis primarily for total and volatile suspended solids (TSS and VSS), total and dissolved nitrogen (TN and DN), total and dissolved phosphorus (TP and DP), and dissolved inorganic and organic carbon (DIC and DOC). A few samples were analyzed more completely for nitrogen speciation (especially nitrate nitrogen NO_3-N) and major inorganic ions. Discharge was measured either with a standard Price AA current meter or with a dye-dilution method, which gave more precise results and ultimately became the favored method. These grab samples and discharge measurements were not collected with any systematic relation to storm events. Consequently, most of the data represent baseflow conditions and do not adequately represent storm flows or compositions.

Automated equipment to record stream stage, temperature, and specific conductance was installed at sites 1-4 in January 1998. Data were recorded at hourly intervals during baseflow conditions and at 15-minute intervals during runoff events. Similar equipment was installed at site 5 in November 1998; however, this record was too short to include for the reporting period. Stage data were converted to discharge based on empirical stage-discharge relations developed from the discharge measurements. These relations are still being investigated and appear sensitive to small changes in channel conditions; the reader is cautioned that discharge data from these calculations may be in error by up to about 20 percent. Automatic water samplers were installed in August 1998 at sites 1-4 and in November 1998 at site 5 to allow precise storm-flow sampling; however, only a few minor runoff events occurred in 1998 after that time.

Much of the data in this report was summarized with “non-parametric” statistics, which do not require the data to follow a “normal” distribution with a symmetric “bell-shaped curve.” Hydrologic data are typically non-normal with data clustering around a low value and a long tail of a few samples extending toward much higher values. For example, most of the time flow is at the relatively low baseflow condition; however, for a few hours during a few days each year, flow can be several times higher as a consequence of a storm event. A “parametric” measure such as an average would be greatly influenced by these few extreme events and therefore not representative of typical flows, whereas the non-parametric median (the middle value) is virtually uninfluenced by extreme events and is a good measure of typical conditions. The median is also called the 50th percentile, because 50 percent of the samples had lower values. A non-parametric measure of variability is the interquartile range (IQR), which is the difference between the 75th percentile and the 25th percentile. “Box plots” are commonly used in this report to display non-parametric summary statistics such as the median and IQR (see Glossary for more explanation).

This report summarizes primarily baseflow conditions in Valley Creek. Baseflow conditions occur when the stream is not receiving significant overland runoff from storm or snowmelt events. These runoff events are likely important to the creek, but the assembled data at present do not adequately represent such events. Characterization of baseflow is still of critical importance, however, because these are the conditions that the biota see most of the time, and urbanization is known to alter baseflows. This report assumes that median values calculated for each variable (flow, temperature, and so forth) represent baseflow conditions during the study period. The very strong stability of flow in Valley Creek, discussed below, indicates that most of the time the stream is at baseflow, and therefore that most data were collected at baseflow, justifying the contention that median values represent this condition. This report does not systematically analyze for trends from 1973 to 1998; differences between the 1973-93 and 1997-98 data sets are most conservatively interpreted as inter-annual variability.

WATER QUANTITY

Valley Creek had very stable stages and discharges during 1997-98. Hourly data for sites 1 (South Branch) and 2 (North Branch) show relatively flat hydrographs with only small spikes in flow corresponding to precipitation events (Figure 2a). The reader is cautioned that the flows in Figure 2a were calculated with preliminary stage-discharge relations; in particular, flows for site 1 may be overestimated. From flow measurements, median flows were larger at site 1 than at site 2, 0.27 cms (cubic meters per second) versus 0.22 cms, respectively (Figure 3a and Appendix). There is some evidence that these flows are larger than before: Waters (1983) estimated baseflow in the South Branch (corresponding to site 1) at 0.14 cms, and median flow in the South Branch from 1973-93 was 0.19 cms (site 1B, Figure 3a and Appendix). The main cause is probably that precipitation was 40% above normal during our period of study (August 1997 through 1998). Variability may be measured by the interquartile range (IQR), which represents the "middle half" of the data: the larger the IQR, the greater the variability. For measured flows, the IQR was only 0.03 cms for site 1 and 0.06 cms for site 2 (Figure 3a and Appendix). More striking is the low variability in stream stage, for which the IQR was only 1.3 cm for site 1 and 2.9 cm for site 2 (Figure 3b). In other words, about half the time the stream was sampled, its stage was within just a few centimeters (the IQR) of the median stream stage.

The flow response at site 1 was more "spiked" than at site 2; that is, site 1 had larger but shorter-lived peak flows than did site 2 (Figure 2a). The ratio of maximum hourly flow to median flow was about 4.6 for site 1 and 1.8 for site 2. The spikes in flow in the South Branch (site 1) likely resulted from runoff from the immediately surrounding gorge, which caused a response that was fast because of its steepness but short-lived because of its limited area. Storage in Lake Edith, which feeds the North Branch, moderated the response at site 2 to precipitation events but extended their influence over a longer time. If one assumes that the median value represents baseflow and that any value above the median represents storm flow, then storm flow accounted for only 15% of the total annual runoff volume at site 1 and only 7% at site 2.

Overall, the surficial geology and topography of the watershed work together to cause this stable flow pattern punctuated by brief but potentially severe spikes in flow. Much of the watershed is flat with high infiltration capacity. These conditions promote infiltration of most precipitation events, with little or no overland runoff. However, the topography near the creek itself is steep, particularly along the South Branch. During extreme rain or snowmelt events, and with wet antecedent conditions, the infiltration capacity can be exceeded in some places. Standing water can accumulate on portions of the flat lands, particularly near the north rim of the South Branch gorge, and when this water spills over the edge into the gorge, its input into the stream can be rapid and the attendant gully erosion severe. In addition, the headwaters of South Branch can receive runoff from a large contributing area in the south and south-west parts of the watershed. Because this area is beyond the extent of the last glaciation, its drainage system is well developed and more prone to generate overland runoff than are the flatter outwash plains to the north. At present, the South Branch is buffered from these runoff inputs by the reservoir above the headwater springs.

Annual runoff is the volume of stream water that passes out of a watershed in a year's time. Often this volume is divided by the watershed area to give a "depth" of water that runs off of the landscape. Runoff is the net amount of water that passes through the watershed and equals precipitation minus evapotranspiration, where evapotranspiration is the amount of water that re-enters the atmosphere by evaporation from water bodies and transpiration from plants. The long-term runoff for the eastern part of Minnesota where Valley Creek is located is about 15 cm (6 inches) per year (Gunard, 1985). This means that in a typical watershed in this part of the state, where about 73 cm (29 inches) of precipitation falls, about 58 cm (23 inches), or nearly 80%, is lost back to the atmosphere by evapotranspiration, and only about 15 cm ends up as stream flow, reaching the stream either quickly by overland runoff or slowly by groundwater flow that seeps into the channel. The area of landscape that could in theory contribute overland runoff to the stream is called the surficial watershed, or simply watershed, which is delimited by a "height of land" boundary. The area of aquifer that can contribute groundwater to the stream is called the groundwatershed, which is delimited by the high points of the water table for a shallow aquifer. Typically the surficial watershed and the groundwatershed are assumed to be nearly congruent, that is, similar in size, shape, and position.

Valley Creek is not typical. Baseflow (median discharge) was measured at site 5B as 0.43 cms (or 15.2 cfs, cubic feet per second) during 1973-93, and at site 5 as 0.55 cms (19.4 cfs) during 1997-98 (Figure 3a and Appendix). Multiplying by the number of seconds each year translates these rates into runoff volumes of 13,560,480 cubic meters per year during 1973-93 and 17,344,800 cubic meters per year during 1997-98. When these annual volumes are divided by the contributing watershed area of 43.5 km^2 (16.8 mi^2), runoff is calculated as about 31 cm (12.3 inches) during 1973-93 and as 40 cm (15.7 inches) during 1997-98. So, whereas a typical stream in this region of the state has an average annual runoff of about 15 cm, Valley Creek's baseflow alone represents a runoff of 31 cm during most years, and up to 40 cm during wet years such as 1997-98, when precipitation was about 40% greater than normal. Furthermore, these runoff numbers for Valley Creek do not include the amounts contributed by storm flows, which, although brief, add significantly to the total (about 7–15%, for example). Clearly, the flow of Valley Creek is far greater than would be expected if the surficial watershed alone were the contributing area. Consequently, the groundwatershed must be much larger than the surficial watershed, perhaps about twice as large given the fact that baseflow runoff (31 cm) is about twice as large as expected total runoff (15 cm). This inference is supported by maps of the groundwater levels in the surrounding bedrock aquifers. These maps indicate that the groundwatershed for Valley Creek is about 60–80 km^2 and extends to the northwest beyond the boundary of the surficial watershed (Almendinger and Grubb, 1999).

WATER QUALITY

Water quality is defined here to include variables measurable on a parcel of water, apart from its flow. These variables include some physical measures, such as temperature, as well as concentrations of suspended and dissolved materials. This report will discuss primarily the following variables: *field variables* (temperature, specific conductance, dissolved oxygen, and pH; Figures 2 and 3); *suspended solids and nutrients* (total and volatile suspended solids, total phosphorus, total nitrogen, and dissolved organic carbon; Figure 4); and *major inorganic constituents* (calcium, magnesium, sodium, bicarbonate, sulfate, chloride, and silica; Figure 5). Bivariate relations between some of these data are depicted in Figure 6. Data on these and other variables are tabulated in the Appendix for reference. Additional variables in the Appendix include dissolved phosphorus, dissolved nitrogen, ammonium ion, unionized ammonia, potassium, turbidity, and fecal coliform. The glossary gives additional explanation about the more common of these variables.

Site locations are shown in Figure 1: sites 1, 2, and 5 monitored the South Branch, North Branch, and main stem mouth, respectively, for the 1997-98 study period, as sampled by the SCWRS; sites 1B and 5B monitored the South Branch and main stem mouth, respectively, for the 1973-93 period, as sampled by Barr Engineering for the VBWD. Much of the discussion focuses on contrasting sites 1 (South Branch) and 2 (North Branch), as more hourly data were available for these sites; site 5 tended to reflect a mixture of waters from these two main branches.

Field Variables

Field variables include temperature, specific conductance, dissolved oxygen (DO), and pH, so called because they are measured in the field directly in the stream (Figures 2 and 3). When grab samples were collected, a portable multi-probe water-quality sonde was used to measure temperature, specific conductance, DO, and pH. Once the stations were instrumented with data loggers, in-stream probes measured temperature and specific conductance hourly.

Seasonal temperatures differed significantly between the two main branches (Figure 2b). Assuming 1998 is representative, from October through April the two branches have similar temperatures, with the South Branch being slightly warmer during the mid-winter months. However, from May through September the South Branch was much cooler (site 1 maximum 16.5°C) than the North Branch (site 2 maximum 26.2°C). These differences result from the South Branch being fed by groundwater, in contrast to the North Branch being fed largely by outflow from Lake Edith. Local groundwater temperatures fall in a narrow range of about 9–12°C and provide a relatively constant input to the South Branch, reducing seasonal temperature variations at site 1 (range 16.2°C). In contrast, Lake Edith is influenced by large seasonal variations in ambient air temperatures, and thus the North Branch is also (range 25.7°C). In contrast to seasonal variation, daily variation in temperature was greater at site 1 (about 3–4°C) than at site 2 (2–3° C). The heat capacity of Lake Edith likely modulated the daily temperature variations at site 2; in addition, certain reaches of the South Branch are not well shaded, allowing greater influence of daily solar radiation. Summary statistics show that during 1997-98, median temperature was lower at site 1 (9.7°C) than at site 2 (12.7°C), and that site 5 was a mix of the two main branches with an intermediate median temperature (11.8°C; Figure 3c and Appendix). Sites 1B and 5B (1973–93) had slightly higher medians than the corresponding sites 1 and 5 (1997–98), but this is expected because the 1973–93 data do not include any samples from winter (Figure 3c).

These temperature data clearly demonstrate that the South Branch provides much better trout habitat than the North Branch. Trout prefer temperatures less than about 20°C, and the North Branch exceeded that temperature about 22% of the time in 1998 (1,926 hourly readings), from mid-May to mid-September (see Figure 2b). Despite inputs of warm water from Lake Edith and the North Branch, maximum temperatures near the mouth were below 20°C for both 1973–93 and 1997–98 data sets (sites 5 and 5B in Figure 3c and Appendix).

Specific conductance measures the ability of the water to conduct an electrical current and is correlated to the dissolved mineral content of the water. Groundwater, which has flowed through pores in mineral-bearing soil and rock, generally has a higher specific conductance than does overland runoff or snowmelt, which is derived from dilute precipitation. Site 1 on the South Branch had a relatively high (median 516 $\mu S\ cm^{-1}$) and stable (IQR 19 $\mu S\ cm^{-1}$) specific conductance, indicating a strong influence of groundwater (Figure 3d). A positive spike (short-term increase) in early March corresponded to a small spike in temperature and probably represented a snowmelt event delivering road-salt runoff into the stream (Figure 2c). Negative spikes (short-term decreases) in specific conductance generally corresponded to precipitation events that delivered dilute runoff to the stream. Site 2 on the North Branch had specific conductance that started the year only slightly lower than at site 1, declined progressively during the summer months, and rose gradually in late fall and early winter (Figure 2c). This seasonal progression probably resulted from biotic processes in Lake Edith modifying the dissolved mineral content of its water. Lake Edith probably receives groundwater seepage, as well as inflow from an adjacent marsh (Metcalf Marsh) which is itself likely groundwater fed. During the winter months, biotic activity in Lake Edith is reduced and its outflow chemistry approaches that of groundwater. During the summer months, algal productivity and higher temperatures can cause precipitation and sedimentation of calcium carbonate minerals, thus removing them from the water column and decreasing its specific conductance. As with temperature, specific conductance values at site 5 tended to be an average of those at sites 1 and 2.

Values of pH and DO generally fell within accepted levels for healthy streams (Figures 3e and f). The pH values were commonly circumneutral, between 7.5 and 8, indicating slightly alkaline conditions buffered by the calcium carbonate system. DO concentrations were generally very high in Valley Creek; most values were near 100% saturation. DO concentration was influenced by temperature: generally lower temperatures at site 1 allowed greater concentrations of DO there than at site 2. The DO values at site 1 were high in spite of the strong influence of groundwater, which is often presumed to have low or zero DO. In fact, groundwater from the nearby shallow bedrock aquifer (the Prairie-du-Chien/Jordan aquifer) tends to have significant DO concentrations (J. E. Almendinger, SCWRS, unpublished data from 1999). In addition, turbulent processes in the creek likely can quickly bring the stream water to saturation with respect to atmospheric oxygen. A few samples from Valley Creek have had DO levels considerably below 100% saturation (about 50–80%). Continued sampling will help determine whether these values are real or the result of instrument errors. Again, site 5 tended to have intermediate values of pH and DO compared to sites 1 and 2.

Suspended Solids and Nutrients

Suspended solids include total suspended solids (TSS) and volatile suspended solids (VSS). VSS comprises the organic fraction of TSS, as opposed to the inorganic fraction (presumably mostly silt and very fine sand). Nutrients in this report include primarily total phosphorus (TP) and total nitrogen (TN); dissolved phases and other species are discussed as necessary. These nutrients are often the limiting factors that drive biotic productivity in aquatic ecosystems. Dissolved organic carbon (DOC) is also included, as it is related to biotic processes in both the aquatic and terrestrial ecosystems.

Concentrations of TSS were low in Valley Creek, with median values well below 10 mg L^{-1} at all sites (Figure 4a). During 1997–98, TSS was lowest at site 1, higher at site 2 receiving water from Lake Edith, and intermediate at site 5, a mixture of the two. Site 2 had the highest TSS measured (92.5 mg L^{-1}; see Appendix). Most of the TSS was composed of VSS, which comprises organic matter such as algal cells and bits of plant detritus (Figure 4b). The higher TSS and lower VSS at site 2 is somewhat surprising, given that Lake Edith is likely both a trap for inorganic sediment and a source of algal particles that contribute to VSS. However, perhaps higher outflows from Lake Edith during 1997–98, coupled with the steeper gradient of this branch than elsewhere along the creek, were enough to cause slight erosion of channel and streambank silts. During 1997–98 site 5 had TSS and VSS contents intermediate to those at sites 1 and 2; the relatively high TSS measured at site 5B during 1973–93 is unexplained.

Annual baseflow load of TSS may be estimated by multiplying annual baseflow volume times median TSS concentration at a site. Annual baseflow loads of TSS were about 16.4 metric tons at site 1, 45.1 metric tons at site 2, and 55.3 metric tons at site 5, indicating that about 6.2 metric tons (16.4 + 45.1 – 55.3) were trapped in the main stem between the monitoring stations. (One metric ton equals 1000 kg, or about 2,205 lbs.) The reader is cautioned that baseflow loadings of TSS may be far below total annual loadings because storm flows are not included, where TSS loadings would be expected to be greatest. In addition, these calculations ignore the contribution of bed load (typically medium to coarse sand), which is not included in measurement of TSS.

Preliminary analysis of the 1997–98 data indicated that TSS was related to stream discharge, but in complex, site-specific ways (Figure 6a). Because of the complexities of sediment erosion and deposition in watersheds, a simple relation between TSS and discharge should not be expected (Linsley and Franzini, 1979). In Valley Creek, most samples clustered around a relatively low baseflow TSS value, different for each site. Because automatic samplers were not installed until the latter part of 1998, sampling was inadequate to characterize TSS at higher storm flows. The few samples collected during runoff events suggested that the TSS content was not a single-valued function of discharge: higher flows can have widely different TSS contents (see site 5, Figure 6a). Other studies have found that flows during the rising limb of a storm hydrograph have higher TSS content than the same flows during the falling limb, giving a double-valued, hysteretic relation between TSS and discharge (Banasik, 1995). Such hysteretic relations result from mobilization of available particles on the watershed surface mostly during the initial flush of overland runoff, or from exhaustion of a limited supply of available particles in the stream channel during the rising limb of a storm event. The limited data for site 2 suggested a steep relation between TSS and discharge, which might be expected if increased flows out Lake Edith have slightly destabilized the channel and if in-channel sources of fine sediment are not limiting. However, storage in Lake Edith moderated flows and kept runoff peaks relatively small, thus minimizing potential erosion. If outflow from Lake Edith increases in the future, erosion of the North Branch channel may increase significantly, as indicated by the steepness of the preliminary relation shown in Figure 6a. We emphasize, however, that these data are not well-characterized at present, and that more representative sampling of storm flows will be required to quantify the relationships between TSS and discharge.

Total phosphorus (TP) values, which include both dissolved and particulate forms of phosphorus, were relatively low in Valley Creek during 1997–98. The median TP concentrations at sites 1, 2, and 5 were all below 25 $\mu g\ L^{-1}$ (Figure 4c). For comparison, lakes are considered "mesotrophic" if their TP falls within the range of 10–30 $\mu g\ L^{-1}$; during fall and winter, Lake Edith was slightly above that range, with TP values of about 40 $\mu g\ L^{-1}$. Because phosphorus is often bound to particulates, the low TP concentrations in the creek were partially a function of the low TSS values. Although weak, the relation between TP and TSS in Valley Creek was positive (Figure 6b; $R^2 = 0.485$). Consequently, site 2, with the highest median TSS value, also had the highest median TP concentration (24 $\mu g\ L^{-1}$). The relatively higher TP concentrations at sites 1B and 5B during 1973–93 are unexplained, although median values were still no more than 40 $\mu g\ L^{-1}$. TP was partitioned between particulate and dissolved forms differently in the two branches. In the South Branch, with its low particulate (TSS) concentrations, dissolved phosphorus (DP) constituted about 68% of the TP (median value, n = 52). In the North Branch, with higher particulate concentrations, DP constituted only about 39% of the TP (median value, n = 49).

Annual baseflow load of phosphorus may be calculated by multiplying annual baseflow volume times median TP concentration. Annual baseflow loads of TP were about 140 kg at site 1, 169 kg at site 2, and 368 kg at site 5, indicating that about 59 kg TP was added to the stream between the monitoring stations. This is somewhat surprising, as calculations of TSS loading indicated a trapping of sediment between monitoring stations, which should likewise have trapped particle-bound phosphorus. However, because the generally low TP values can cause relatively high data variability, this 59 kg TP difference may not be statistically significant. The reader is cautioned that baseflow loadings of phosphorus, as with TSS, may be much lower than total annual loadings because storm flows are not included. It seems probable that much phosphorus loading occurs during storm flows, when more erosion occurs and loads of TSS with particle-bound phosphorus are likely higher.

Values of total nitrogen (TN) were significantly different between the North and South branches in 1997–98 and reflected their different water sources (Figure 4d). Groundwater-fed site 1 (South Branch) had the highest median TN concentration at 6.5 mg L^{-1}; subsequent analysis of a few samples indicated that most of this TN was in the form of nitrate (median about 94%, n = 4). While this value was below the drinking-water standard of 10 mg L^{-1} nitrate-nitrogen, it was far above expected natural concentrations (0.1– 1 mg L^{-1}) and indicated significant contamination from anthropogenic sources. Groundwater is commonly contaminated with nitrates in agricultural areas, especially those with high infiltration rates such as in the Valley Creek watershed. Regional data bases of groundwater quality show nitrate contamination in groundwater near Valley Creek (Washington County and Minnesota Dept. of Health, electronic communications, 1999), and subsequent local investigation by the SCWRS has confirmed nitrate-rich groundwater discharging into the South Branch.

Site 2 (North Branch, fed by Lake Edith) had the lowest median TN concentration (2.3 mg L^{-1}), though still high enough to indicate anthropogenic input (Figure 4d). Subsequent analysis of a few samples indicated that about 77% of the TN was in the form of dissolved nitrate (median value, n = 3). Even if Lake Edith and adjacent Metcalf Marsh are themselves fed by nitrate-contaminated groundwater, processes within the lake and wetland may reduce these concentrations. Surface-water bodies, especially wetlands that remain perennially saturated, are known to reduce nitrate concentrations by microbial denitrification, which converts nitrate to atmospheric nitrogen, and by biotic uptake (for example, see review by Almendinger, 1999). As with most other water-quality variables, concentrations of TN at site 5 were intermediate between those at sites 1 and 2 (Figure 4d).

Annual baseflow load of TN can be estimated by multiplying annual baseflow volume times median TN concentration. Annual baseflow loads of TN were about 54.2 metric tons at site 1, 16.0 metric tons at site 2, and 75.1 metric tons at site 5, indicating that about 4.9 metric tons of TN are added to the stream between the monitoring stations, although this value may not be statistically significant. Contributions from groundwater discharge to the main stem of Valley Creek could explain this addition. Again, the reader is cautioned that storm flows are not included, which would increase total annual loadings beyond those calculated here.

Aquatic vegetation is sensitive to nutrient inputs, but can be held in check if either of the two main nutrients, nitrogen or phosphorus, is in low concentrations and therefore limiting. The South Branch is clearly not limited by nitrate, which is supplied constantly in relatively high concentrations by the discharging groundwater. Instead, phosphorus is probably the limiting nutrient, and any significant increase in phosphorus to the South Branch could spur growth of aquatic vegetation (both macrophytes and algae). Siltation (by which we mean to include both silt- and clay-sized particles) from upland erosion into this branch should be minimized to the extent possible, as input of fine particulates will likely deliver particle-bound phosphorus to the creek. Siltation has further negative consequences by physically altering the stream bed material and degrading habitat for macroinvertebrate production and trout spawning. More work needs to be done to characterize the partitioning between the particulate and dissolved phases of both nitrogen and phosphorus in the creek, and to better understand the cycling of these nutrients (sources, sinks, and transformations) from the uplands through the creek ecosystem.

Values of dissolved organic carbon (DOC) were highest at site 2 (North Branch), lowest at site 1 (South Branch), and intermediate at site 5 (main stem mouth) (Figure 4e). Biotic activity in Lake Edith probably produced the DOC found at site 2. In contrast, groundwaters commonly have very low DOC, hence the low DOC content at site 1. Samples collected by the automatic samplers at sites 1 and 2 were rejected from data summaries of DOC because of apparent contamination; the mechanism of this contamination has not yet been fully determined, but may to be due to biofilm growth in the sampler intake tubing.

Major Inorganic Constituents

Major inorganic constituents include calcium (Ca), magnesium (Mg), sodium (Na), bicarbonate (HCO_3), sulfate (SO_4), chloride (Cl), and silica (SiO_2). Only a few samples (4–5) were analyzed for most of these constituents by the end 1998 and therefore included in this report. However, since that time about 40 more samples from Valley Creek itself and about 50 samples from elsewhere in the watershed (lakes, wetlands, and wells) have been collected and submitted for analysis, and will be summarized in a future report. For the samples discussed in this report, total cations averaged 5.36 meq L^{-1} and total anions averaged 5.04 meq L^{-1}, for an average charge balance error of about +3.1%.

The two main branches of the creek were different with respect to their major ion and silica chemistries (Figure 5), as suggested by the specific conductance data (Figure 3d). The South Branch had higher concentrations of Ca, Mg, HCO_3, and SiO_2 than the North Branch (Figure 5a, b, d, and g). As discussed earlier, the difference was likely due to biotic processes in Lake Edith, which feeds the North Branch. Algal photosynthesis removes dissolved CO_2 from the lake water, which raises pH; calcium carbonate minerals such as calcite are less soluble as pH rises and so tend to precipitate out of solution and fall to the lake bottom as sediment. Surface sediment from Lake Edith indeed contains carbonate minerals (SCWRS, unpublished data, 1998), supporting the contention that Lake Edith loses calcium carbonate from its water column. Mg was probably lost as a co-precipitate with the calcium carbonate. Diatoms are ubiquitous algae that create silica-shelled cell walls, thereby removing silica (SiO_2) from the water column and trapping it in the sediment as these cells settle to the lake bottom.

Ca was highly correlated with dissolved inorganic carbon (DIC), a measure of HCO_3 (Figure 6C); Mg likewise showed a high correlation with DIC. These relations indicated that the source of these ions was dissolution from Ca-Mg carbonate minerals, primarily calcite and dolomite, in the surrounding glacial drift and bedrock. Nonetheless, the available HCO_3 balanced only about 80% of the total meq of Ca plus Mg, with the remaining 20% being balanced by other anions such as SO_4 or Cl. Other major ions (Na, SO_4, and Cl) were found in relatively low concentrations (Figure 5c, e, and f). Cl was highly correlated to Na (Figure 6d), implying that a NaCl mineral such as halite (rock salt) was possible mineral source. However, no samples were collected during times of suspected snowmelt with road-salt runoff; only one such period was suggested by the hourly specific conductance record (in early March at site 1; Figure 2c) and was too brief to sample. Further, Na balanced only 60% of the meq of Cl, the remaining 40% of which was balanced by other cations such as Ca or Mg.

SUMMARY AND CONCLUSIONS

Valley Creek is a healthy trout stream in southeastern Washington County facing potential urbanization of its watershed in the coming decades. Urbanization can alter watershed hydrology by increasing runoff from impervious surfaces, thereby increasing storm peaks, runoff volumes, erosion, nutrient loadings, and summer water temperatures beyond the range tolerated by trout. One step towards the protection of such a highly valued resource is documentation of baseline conditions against which future changes can be gauged. The purpose of this report is to document such baseline conditions for the surface-water hydrology of Valley Creek.

Flow volumes were much larger than expected for a surficial watershed the size of that of Valley Creek, indicating that contribution from groundwater came from aquifers extending beyond the basin boundary. Steady groundwater contributions to the creek were indicated by extremely stable flows and stages, which varied typically within just a few centimeters from median. This stability was a result of the relatively level, highly permeable geologic deposits across much of the watershed, which facilitated infiltration and minimized overland runoff. Consequently, storm peaks were few and short-lived.

Some important water-quality variables were very different between the two main branches of the creek, the South Branch and the North Branch. These differences were due to the different water sources to the branches: the South Branch is fed by groundwater discharge, and the North Branch is fed primarily by outflow from Lake Edith. Because groundwater is relatively stable in temperature, the South Branch had much lower seasonal variation in temperature and reached a summertime maximum of only 16.5°C, well within the range favored by trout (about 10–20°C). In contrast, because of summertime warming of Lake Edith, the North Branch exceeded 20°C for about 22% of 1998 during the period from mid-May to mid-September, making this branch less favorable trout habitat. Biotic processes in Lake Edith also removed dissolved minerals from the water column, giving the North Branch lower concentrations of Ca, Mg, HCO_3, and SiO_2 than the South Branch. The loss of these dissolved minerals was tracked by specific conductance values, which declined during summer and recovered during winter in the North Branch relative to the South Branch. Both branches had relatively low values of total phosphorus and suspended solids. However, the South Branch had much higher concentrations of total nitrogen, a consequence of receiving nitrate-contaminated groundwater.

The loss of trout from streams with urbanized watersheds in the Minneapolis-St. Paul metropolitan area is perhaps the strongest evidence of the threat that urbanization poses to Valley Creek (MDNR, 1996). While the present amount of imperviousness from development in the watershed is well below the published 10% threshold, this limit may be approached or exceeded by planned future urbanization. Even if urbanization can be held in check below levels that significantly degrade the hydrology and biotic integrity of streams, other factors such as fragmentation of terrestrial habitat and loss of open space should also be considered when planning future development densities for watersheds such as that of Valley Creek.

The maintenance of Valley Creek as a fine example of a trout stream will depend on guarding against at least two potential problems. First, inputs of overland runoff should be minimized, particularly from impervious surfaces that accompany development. The landscape is suitable for engineering practices that promote infiltration of storm water, rather than those that direct storm water directly to streams via gutters, storm sewers, and ditches. Such practices will minimize increases in runoff peaks and volumes, consequent channel erosion, and inputs of dissolved and suspended substances to the creek, although storm-water infiltration could affect groundwater quality. Second, inputs of eroded fine particulates (siltation) should be minimized, particularly in the South Branch. Because this branch is already well-fertilized with nitrates, additions of fine particulates with their associated bound phosphorus could spur over-abundant growth of aquatic macrophytes and algae. In addition, siltation destroys spawning habitat for trout and reduces the quality of the macroinvertebrate food source for trout. Finally, reducing nutrient inputs to Valley Creek is yet another positive step in improving the quality of the St. Croix River, a natural resource of national significance.

ACKNOWLEDGMENTS

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FIGURES

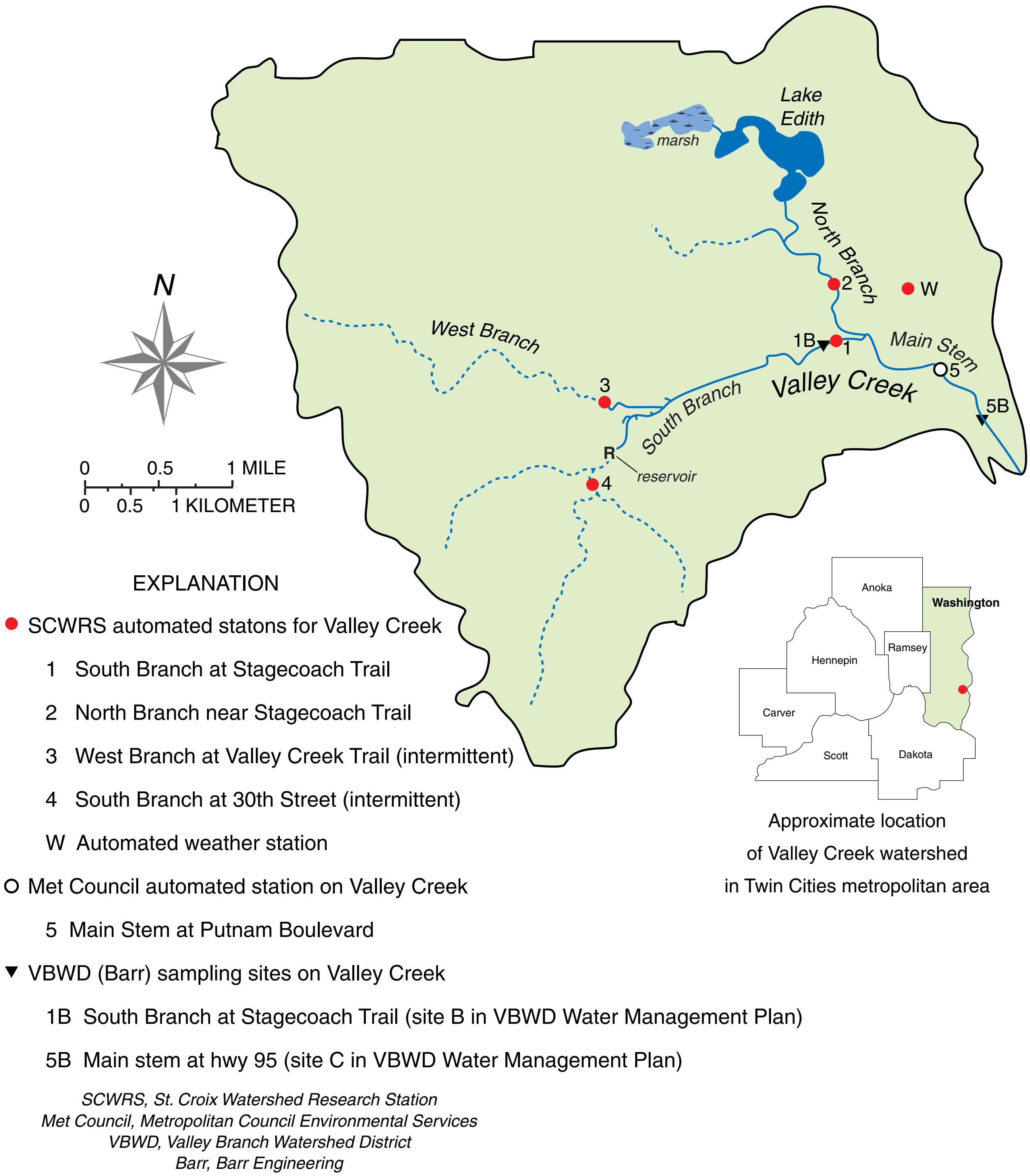


Figure 1. Valley Creek Watershed and locations of long-term monitoring sites

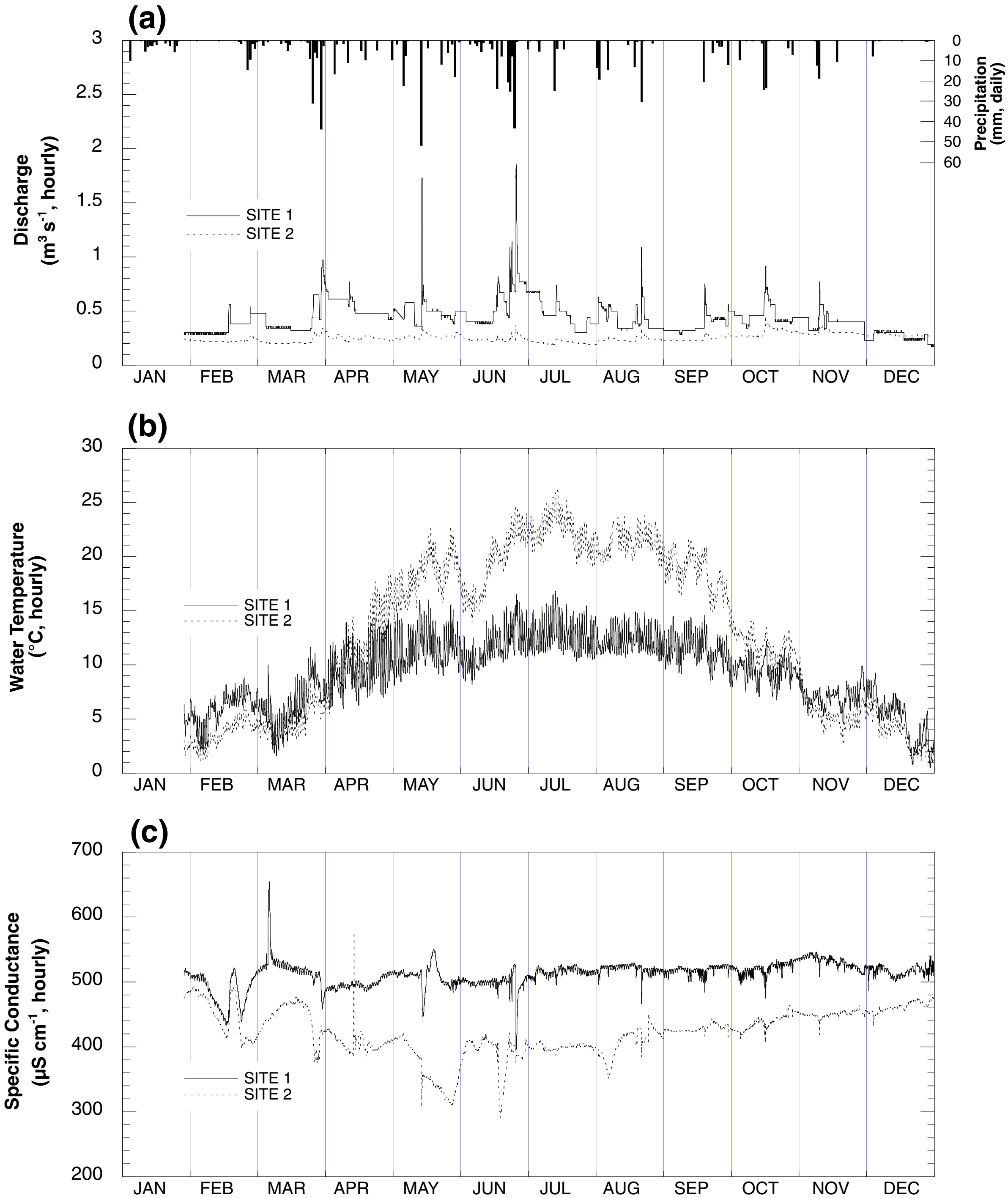


Figure 2. High-frequency data for (a) precipitation and discharge, (b) water temperature, and (c) specific conductance for sites 1 and 2, Valley Creek, 1998

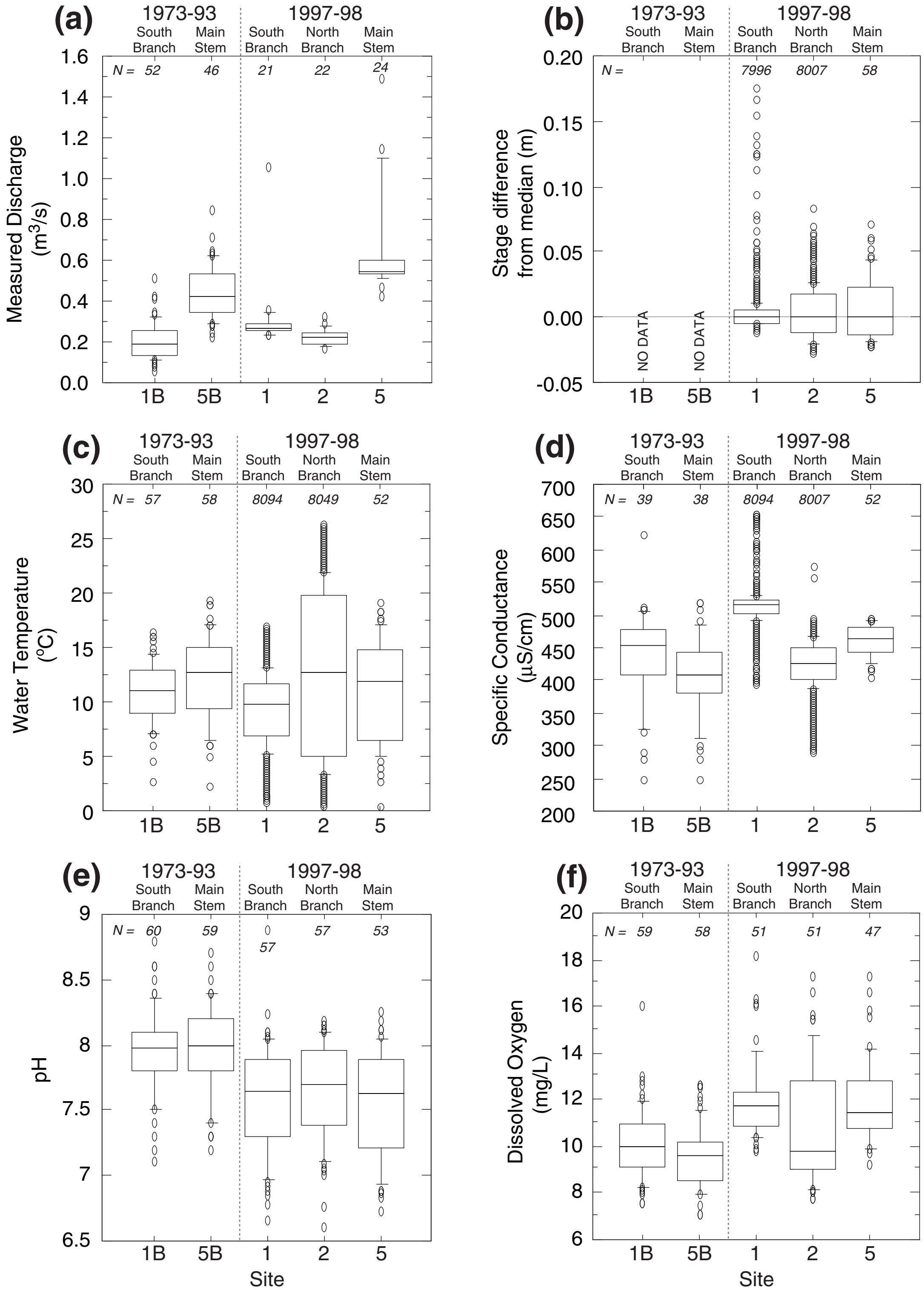
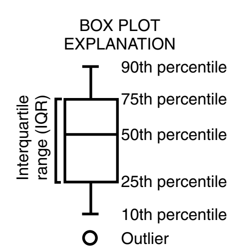


Figure 3. Discharge, stage, and field water-quality variables for Valley Creek

1973-93 data from Barr Engineering;
1997-98 data from St. Croix Watershed Research Station.
See Figure 1 for site locations.
See Appendix for tabulated summary statistics.



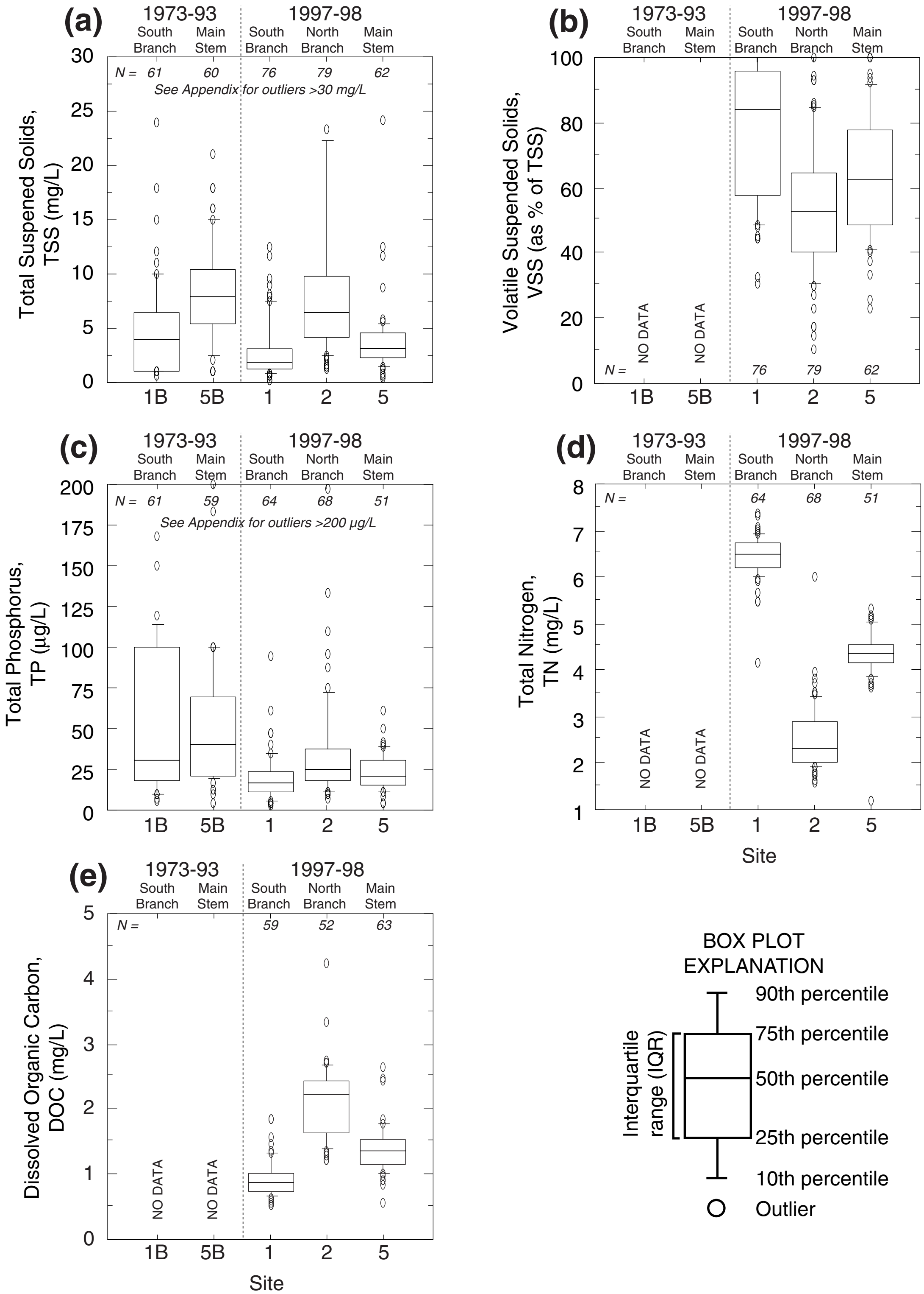


Figure 4. Selected suspended solids and nutrient variables for Valley Creek

1973-93 data from Barr Engineering;
1997-98 data from St. Croix Watershed Research Station.
See Figure 1 for site locations.
See Appendix for tabulated summary statistics.

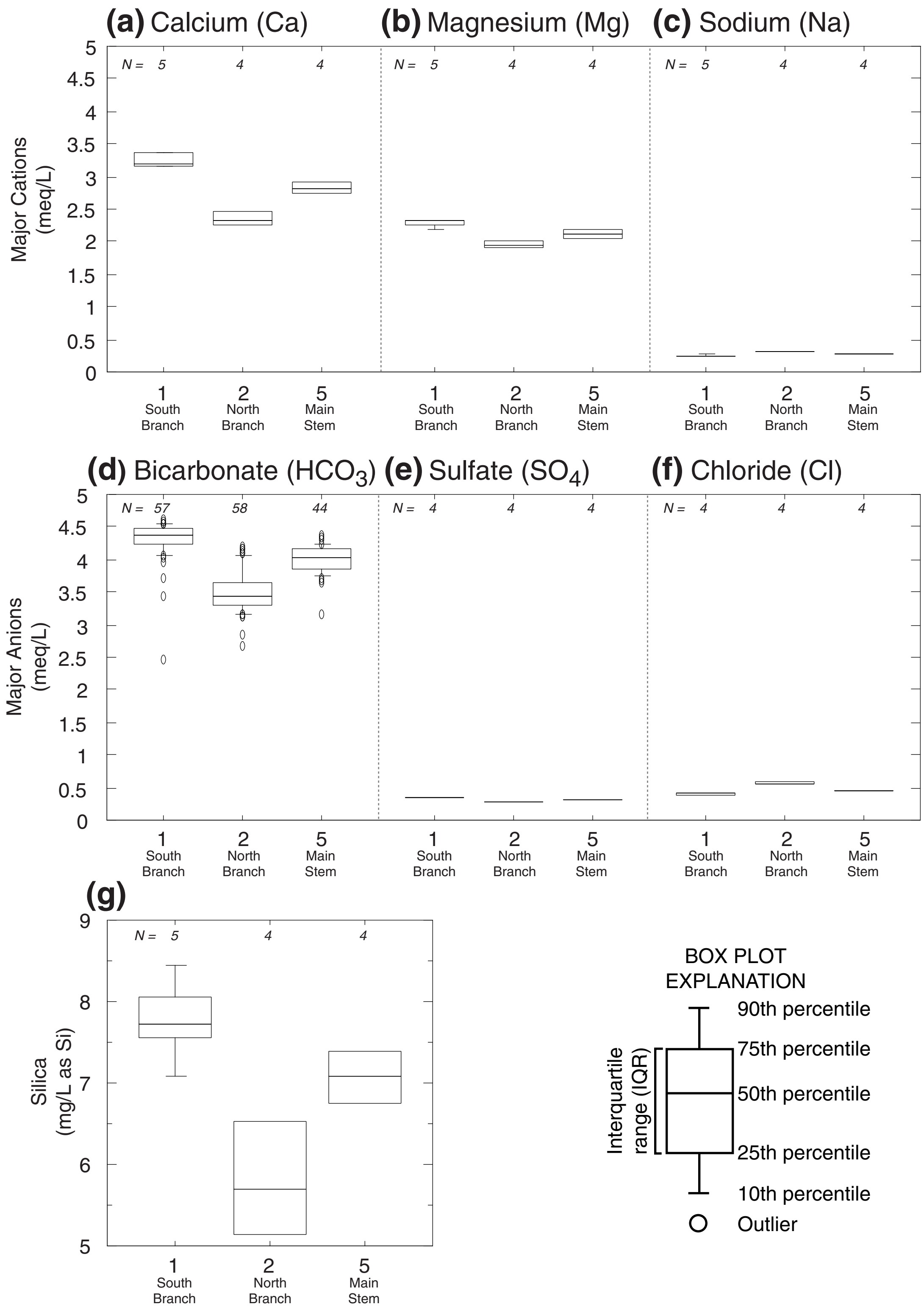


Figure 5. Major cations, anions, and silica for Valley Creek

1997-98 data from St. Croix Watershed Research Station.
See Figure 1 for site locations.
See Appendix for tabulated summary statistics.

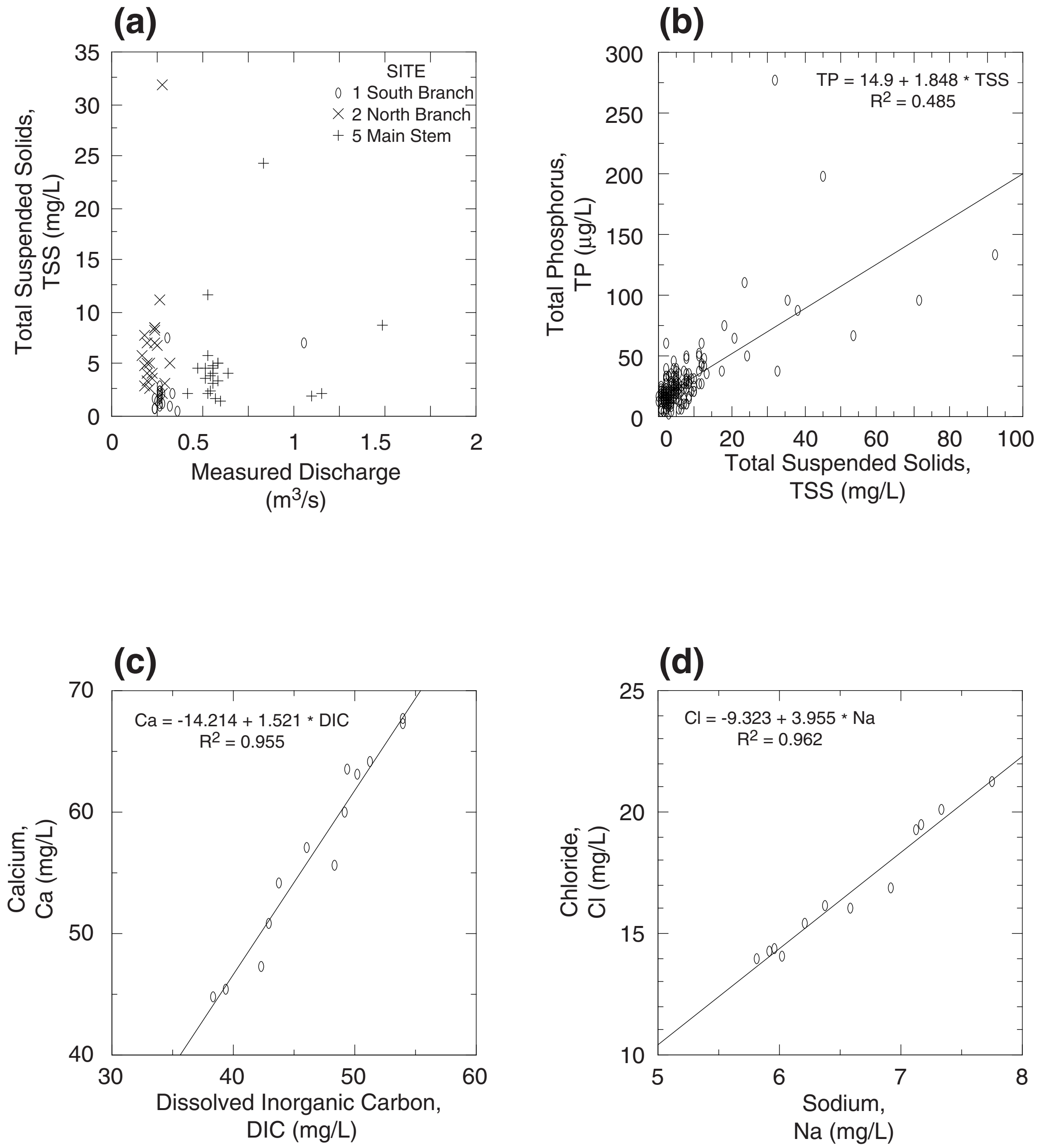


Figure 6. Bivariate relations for selected water-quality variables for Valley Creek

1997-98 data from St. Croix Watershed Research Station.
See Figure 1 for site locations.
See Appendix for tabulated summary statistics.

APPENDIX

Selected hydrologic statistics for Valley Creek

Appendix--Selected hydrologic statistics for Valley Creek

Notes: 1973-93 data from Barr Engineering; 1997-98 data from St. Croix Watershed Research Station. See Figure 1 for site locations. Sites 2B and 5B are the same as sites B and C, respectively, in Valley Branch Watershed District Water Management Plan. This table prepared by St. Croix Watershed Research Station.

Abbreviations: Med, median; IQR, interquartile range; SD, standard deviation; Min, minimum; Max, maximum; n, number of samples; m^3/s, cubic meters per second; ft^3/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter or parts per million (ppm); µg/L, micrograms per liter or parts per billion (ppb); NTU, nephelometric turbidity units; CFU/100 ml, colony-forming units per 100 ml; --, no data.

Discharge and selected field water-quality variables

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
			DISCHARGE (Q, in m^3/s) (from flow measurements)		
Med	0.19	0.27	0.22	0.43	0.55
IQR	0.12	0.03	0.06	0.19	0.07
Mean	0.21	0.31	0.23	0.45	0.64
SD	0.09	0.18	0.04	0.13	0.25
Min	0.05	0.23	0.17	0.22	0.42
Max	0.51	1.06	0.32	0.85	1.49
n	52	21	22	46	24
			TEMPERATURE (T, in °C)		
Med	11.0	9.7	12.7	12.8	11.8
IQR	4.0	4.9	14.9	5.6	8.4
Mean	11.0	9.3	12.6	12.1	10.9
SD	3.0	3.1	7.4	3.9	4.8
Min	2.8	0.6	0.5	2.2	0.5
Max	16.5	16.8	26.2	19.4	19.2
n	57	8094	8049	58	52
			DISSOLVED OXYGEN (DO, in mg/L) MPCA std: ≥ 7 mg/L		
Med	10.0	11.7	9.8	9.6	11.5
IQR	1.9	1.4	3.8	1.7	2.0
Mean	10.1	12.0	10.7	9.5	11.9
SD	1.5	1.7	2.5	1.6	2.1
Min	7.6	9.8	7.7	4.6	4.6
Max	16.0	18.1	17.3	12.6	17.3
n	59	51	51	58	47

Discharge and selected field water-quality variables

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
			DISCHARGE (Q, in ft^3/s) (from flow measurements)		
Med	6.8	9.4	7.8	15.0	19.4
IQR	4.1	0.9	2.1	6.7	2.3
Mean	7.2	10.9	8.0	15.7	22.7
SD	3.2	6.2	1.4	4.6	8.9
Min	1.8	8.1	6.0	7.7	14.8
Max	18.0	37.4	11.3	30.0	52.6
n	52	21	22	46	24
			SPECIFIC CONDUCTANCE (SC, in µS/cm)		
Med	455	516	424	410	464
IQR	69	19	48	61	39
Mean	435	512	423	407	461
SD	75	19	35	61	24
Min	250	395	291	250	406
Max	625	654	576	521	496
n	39	8094	8007	38	52
			pH MPCA std: 6.5-8.5		
Med	8.0	7.6	7.7	8.0	7.6
IQR	0.3	0.6	0.6	0.4	0.7
Mean	7.9	7.6	7.6	8.0	7.6
SD	0.3	0.4	0.4	0.3	0.4
Min	7.1	6.7	6.6	7.2	6.7
Max	8.8	8.9	8.2	8.7	8.3
n	60	57	57	59	53

Appendix--Selected hydrologic statistics for Valley Creek (continued)

See first page of appendix for notes and abbreviations.

Selected nutrient species

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
TOTAL PHOSPHORUS (TP, in µg/L) MPCA std: ≤ 1000 µg/L					
Med	30	17	24	40	21
IQR	82	13	20	49	16
Mean	55	20	37	58	23
SD	56	15	43	65	12
Min	5	3	0	4	4
Max	250	95	276	450	61
n	61	64	68	59	51
TOTAL NITROGEN (TN, in mg/L)					
Med	--	6.5	2.3	--	4.3
IQR	--	0.5	0.9	--	0.4
Mean	--	6.5	2.5	--	4.3
SD	--	0.5	0.7	--	0.6
Min	--	4.2	1.6	--	1.2
Max	--	7.4	6.0	--	5.3
n	0	64	68	0	51
AMMONIUM ION (NH_4, in mg/L, assumed as N)					
Med	0.08	--	--	0.10	--
IQR	0.15	--	--	0.11	--
Mean	0.13	--	--	0.13	--
SD	0.17	--	--	0.17	--
Min	0.02	--	--	0.02	--
Max	0.70	--	--	0.70	--
n	15	0	0	15	0

Selected nutrient species

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
DISSOLVED PHOSPHORUS (DP, in µg/L)					
Med	--	10	9	--	11
IQR	--	8	6	--	9
Mean	--	13	13	--	12
SD	--	9	16	--	8
Min	--	2	2	--	2
Max	--	45	97	--	49
n	0	59	54	0	49
DISSOLVED NITROGEN (DN, in mg/L)					
Med	--	6.5	2.2	--	4.3
IQR	--	0.4	1.0	--	0.5
Mean	--	6.4	2.5	--	4.3
SD	--	0.9	0.8	--	0.5
Min	--	0.5	1.6	--	2.6
Max	--	7.4	5.3	--	5.4
n	0	59	52	0	49
UNIONIZED AMMONIA (NH_3, in mg/L as N) MPCA std: ≤ 0.016 mg/L as N					
Med	4.0E-04	--	--	1.0E-03	--
IQR	1.0E-03	--	--	2.0E-03	--
Mean	1.0E-03	--	--	2.0E-03	--
SD	3.0E-03	--	--	4.0E-03	--
Min	8.0E-05	--	--	6.0E-05	--
Max	1.6E-02	--	--	2.0E-02	--
n	35	0	0	34	0

Appendix--Selected hydrologic statistics for Valley Creek (continued)

See first page of appendix for notes and abbreviations.

Major cations

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
			CALCIUM (Ca, in mg/L)		
Med	--	64.2	46.4	--	56.3
IQR	--	3.9	4.0	--	3.7
Mean	--	65.2	47.1	--	56.7
SD	--	2.2	2.7	--	2.5
Min	--	63.0	44.9	--	54.1
Max	--	67.8	50.8	--	60.0
n	0	5	4	0	4
			MAGNESIUM (Mg, in mg/L)		
Med	--	28.1	23.5	--	25.8
IQR	--	0.7	1.2	--	1.6
Mean	--	27.8	23.8	--	25.6
SD	--	0.7	1.0	--	1.2
Min	--	26.6	23.1	--	24.1
Max	--	28.3	25.2	--	26.9
n	0	5	4	0	4
			SODIUM (Na, in mg/L)		
Med	--	5.9	7.2	--	6.5
IQR	--	0.2	0.4	--	0.5
Mean	--	5.9	7.3	--	6.5
SD	--	0.1	0.3	--	0.3
Min	--	5.7	7.1	--	6.2
Max	--	6.0	7.8	--	6.9
n	0	5	4	0	4

Major anions

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
			DISSOLVED INORGANIC CARBON (DIC, in mg/L)		
Med	--	52.4	41.3	--	48.5
IQR	--	2.7	4.1	--	3.4
Mean	--	51.6	41.9	--	48.1
SD	--	3.9	3.9	--	2.7
Min	--	29.6	32.1	--	37.7
Max	--	55.3	50.3	--	52.5
n	0	57	58	0	44
			SULFATE (SO_4, in mg/L)		
Med	--	17.2	13.4	--	15.2
IQR	--	0.2	0.5	--	1.0
Mean	--	17.2	13.3	--	14.8
SD	--	0.1	0.4	--	0.8
Min	--	17.1	12.7	--	13.6
Max	--	17.3	13.6	--	15.3
n	0	4	4	0	4
			CHLORIDE (Cl, in mg/L) MPCA std: ≤ 50 mg/L		
Med	8.0	14.2	19.8	10.0	16.1
IQR	4.9	0.3	1.3	5.0	0.8
Mean	7.8	14.2	20.0	9.4	16.1
SD	2.8	0.2	0.9	5.3	0.6
Min	1.0	14.0	19.3	1.0	15.4
Max	15.0	14.3	21.3	42.0	16.9
n	60	4	4	58	4

Appendix--Selected hydrologic statistics for Valley Creek (continued)

See first page of appendix for notes and abbreviations.

Suspended solids and turbidity

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
TOTAL SUSPENDED SOLIDS (TSS, in mg/L)					
Med	4.0	2.0	6.5	8.0	3.2
IQR	5.5	2.0	5.7	5.0	2.3
Mean	5.0	3.3	10.8	8.5	3.9
SD	4.7	4.6	15.0	4.6	3.4
Min	0.7	0.2	1.2	1.0	0.5
Max	24.0	35.1	92.5	21.0	24.2
n	61	76	79	60	62
VOLATILE SUSPENDED SOLIDS (VSS, in mg/L)					
Med	--	1.7	3.3	--	2.0
IQR	--	1.2	2.9	--	1.2
Mean	--	2.1	4.7	--	2.2
SD	--	1.6	5.0	--	1.0
Min	--	0.2	0.3	--	0.3
Max	--	10.6	31.0	--	6.3
n	0	76	79	0	62
VOLATILE SUSPENDED SOLIDS (VSS, as %TSS)					
Med	--	84	53	--	62
IQR	--	38	24	--	29
Mean	--	82	54	--	64
SD	--	28	21	--	19
Min	--	30	10	--	23
Max	--	163	133	--	100
n	0	76	79	0	62
TURBIDITY (in NTU) MPCA std: ≤ 10 NTU					
Med	1.0	--	--	2.1	--
IQR	0.6	--	--	1.3	--
Mean	1.3	--	--	2.5	--
SD	0.9	--	--	1.2	--
Min	0.1	--	--	0.7	--
Max	4.5	--	--	6.0	--
n	58	0	0	60	0

Miscellaneous water-quality variables

	South Branch		North Branch	Main Stem	
	Site 1B 1973-93	Site 1 1997-98	Site 2 1997-98	Site 5B 1973-93	Site 5 1997-98
DISSOLVED ORGANIC CARBON (DOC, in mg/L)					
Med	--	0.9	2.2	--	1.4
IQR	--	0.3	0.8	--	0.4
Mean	--	0.9	2.1	--	1.7
SD	--	0.3	0.6	--	2.6
Min	--	0.5	1.2	--	0.6
Max	--	1.8	4.2	--	21.5
n	0	59	52	0	63
POTASSIUM (K, in mg/L)					
Med	--	1.2	1.3		1.3
IQR	--	0.2	0.2		0.2
Mean	--	1.2	1.3		1.3
SD	--	0.1	0.2		0.1
Min	--	1.1	1.2		1.2
Max	--	1.4	1.6		1.4
n	0	5	4		4
SILICA (as Si, in mg/L)					
Med	--	7.7	5.7	--	7.1
IQR	--	0.5	1.4	--	0.6
Mean	--	7.8	5.8	--	7.1
SD	--	0.5	0.9	--	0.4
Min	--	7.1	5.0	--	6.7
Max	--	8.4	6.9	--	7.4
n	0	5	4	0	4
FECAL COLIFORM (in CFU/100 ml) MPCA std: ≤ 200 CFU/100 ml					
Med	30	--	--	50	--
IQR	63	--	--	70	--
Mean	81	--	--	71	--
SD	164	--	--	88	--
Min	4	--	--	4	--
Max	970	--	--	540	--
n	57	0	0	60	0

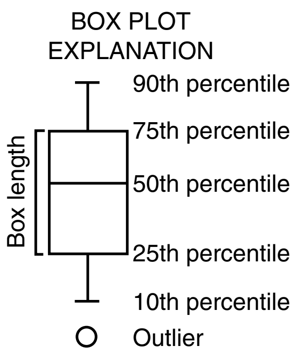
GLOSSARY

Glossary of common hydrologic and water-quality terms

Glossary of common hydrologic and water-quality terms

Baseflow. The flow of a stream when there is no evident runoff from rainfall or snowmelt events. Baseflow is often assumed to equal the amount of groundwater discharging into a stream.

Box plot. A graphical way of summarizing a single data set (simply a list of collected numbers, such as temperatures at a site over a period of time). In each box plot, the line in the middle of the box represents the median, or 50th percentile: half (50%) the samples had lower values, and half the samples had higher values. Likewise, the bottom of the box represents the 25th percentile (25% of the samples had lower values) and the top of the box represents the 75th percentile (75% of the samples had lower values). The box length, called the interquartile range (IQR), is a measure of the variability among samples: the longer the box, the more variable (widely scattered) the data. The whiskers extend from the box top (75th percentile) up to the 90th percentile, and from the box bottom (25th percentile) down to the 10th percentile. The small circles show outlier samples with values far from most of the others (relative to the box length). These outliers are not mere sampling mistakes, but demonstrate that stream systems can have highly variable flows during short-interval runoff events.



Carbon. An element commonly found in natural waters, essential as a building block of aquatic life and, in some forms, as a chemical buffer against acidification or other pH changes. Inorganic carbon in the water comes from carbon dioxide gas and limestone rocks dissolving into the water. Organic carbon in the water comes from algae or other small bits of plant debris plus liquid decomposition products from decaying organisms (mostly plants). Carbon in water can be categorized according to the way it is measured:

Dissolved inorganic carbon (DIC). The concentration (mg/L) of inorganic carbon measured on a *filtered* (0.45 m) water sample.

Dissolved organic carbon (DOC). The concentration (mg/L) of organic carbon measured on a *filtered* (0.45 m) water sample.

Total organic carbon (TOC). The concentration (mg/L) of organic carbon measured on an *unfiltered* water sample.

Celsius (C). The temperature scale used by most scientists. Water freezes at 0¡ C and boils at 100¡ C at sea level. To convert ¡C to ¡F (degrees Fahrenheit), double the value, subtract 10% of that result, and add 32. For example, to convert 10¡ C: double the value to get 20, subtract 10% (2) to get 18, and add 32 to get 50¡ F. This method is equivalent to the standard formula ¡F = (9/5) ¡C + 32.

Data logger. A small (shoe-box sized) electronic device to control other devices or probes and to record data from them.

Discharge. The volumetric rate of water flow, in units such as cubic feet per second (cfs), or cubic meters per second (cms); generally synonymous with flow. Hydrologists often use this term in two ways:

Stream discharge. The rate of stream flow, in cfs or cms; generally synonymous with stream flow.

Groundwater discharge. The rate of groundwater flow, also in cfs or cms. More generally, groundwater discharge is the movement of water out of an aquifer into a stream or lake. A spring is a localized site of groundwater discharge.

Dissolved oxygen (DO). Oxygen that is dissolved in the water and, when high enough, available for use by aquatic organisms. Cold water can hold more dissolved oxygen than warm water can. At any given temperature, when the water is holding as much dissolved oxygen as possible, the water is said to be at 100% saturation.

GIS. Geographic information system, which is a software program to store and manipulate spatial data on a computer. Most simply, a GIS is a computer-mapping program can be used to make, display, and print maps. More importantly, a GIS allows such maps to be analyzed on the computer, showing where certain features (land use, soil type, slope, depth to water table, etc.) overlap.

mg/L. Milligrams per liter, a measure of mass per unit volume, giving concentration. Because a liter of water weighs 1 kilogram, which is a million milligrams, the units mg/L are sometimes called **ppm**, or parts per million.

Model. Generally, a simulation of a natural system. Specifically in our project, computer models are used to simulate surface water and groundwater flows mathematically. Models are valuable because they can be used to test the effects of changing certain variables (such as land use due to development) before such changes actually occur on the ground. Models are dangerous because they necessarily make simplifying assumptions about the natural system and consequently can make errors when used to predict effects of changing that system.

Nutrients. Generally, substances needed for organism growth and function. However, in many environmental studies, nutrients refer almost exclusively to substances required for plant growth, and particularly to limiting substances such as phosphorus (P) and nitrogen (N). Nutrients can be categorized according to the way they are measured:

Dissolved phosphorus (DP) and **dissolved nitrogen (DN).** All the P and N in a sample of *filtered* (0.45 m) water, measured as a concentration (mg/L). Common forms of DP include phosphate ion (PO_4, sometimes called orthophosphate) and phosphorus in dissolved organic matter (org-P). Common forms of dissolved nitrogen include nitrate (NO_3), ammonium (NH_4), and nitrogen in dissolved organic matter (org-N).

Total phosphorus (TP) and **total nitrogen (TN).** All the P and N in a sample of *unfiltered* water. This would include not only DP and DN but also the P and N in or adsorbed to particles such as algal cells, bits of organic debris, and inorganic silts and clays.

pH. The pH is a measure of the acidity of the water. The lower the pH, the more acid the water; the higher the pH, the more alkaline the water. The pH can range, in theory, from 0 to 14; however, the pH of natural waters generally falls between 5 and 9, and water with a pH near 7 is said to be circumneutral.

Specific conductance. A measure of how easily the water conducts an electric current. Distilled water has a low conductance, but water with dissolved minerals has a high conductance. This is because when most minerals dissolve, they form *ions* (atoms or groups of atoms with either a positive or negative electrical charge), which help transmit the electric current through the water. So, specific conductance is a surrogate measure of the total amount of dissolved minerals in the water.

Stage. The height of water in the stream, relative to a selected reference point. For example, stream stage relative to the stream bottom is simply water depth.

Suspended solids. Particles that can be filtered out of stream or lake water; also called suspended sediment. Suspended solids can be categorized as follows:

Total suspended solids (TSS). This is measured by filtering a known volume of water through a glass-fiber filter (1 m) and then measuring the increase in weight of the now-dirty filter. The units are given in mg/L (milligrams per liter).

Volatile suspended solids (VSS). The organic-matter part of TSS, such as plant debris and algal cells. It is measured by baking the previous filter at a hot enough temperature (500¡ C) to burn away the organic matter and re-weighing the filter.