Nutrient Dynamics and Water Quality of Valley Creek, a high-quality trout stream in southeastern Washington County

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I. PURPOSE

The purpose of this project was to help maintain and improve the high-quality trout-bearing waters of Valley Creek by a) identifying nutrient sources, dynamics, and relations to aquatic vegetation, and b) maintaining the existing automated hydrologic monitoring stations.

II. INTRODUCTION

Background and previous work

Valley Creek (variously called Valley Branch Creek or Valley Branch) in southeastern Washington County near Afton is generally regarded as the highest-quality trout stream in the Minneapolis-St. Paul metropolitan area. All three species of stream trout (brown, rainbow, and native brook) reproduce successfully in the creek. The stream also harbors the American brook lamprey, a small native, non-parasitic species of special concern in Minnesota because of its rarity. Protecting the quality of Valley Creek is a critical component of maintaining aquatic biodiversity in the metropolitan area and the St. Croix Valley. Many other streams in the area have lost species such as trout, which are sensitive to water-quality degradation caused by various land-use practices in the watersheds. The management goal of the Valley Branch Watershed District (VBWD) for the creek is preservation of its water quality and trout stream habitat (VBWD, 1995).

The watershed of Valley Creek is located on the urban fringe of the Minneapolis-St. Paul metropolitan area. Row-crop agriculture and rural-residential housing are the most common land uses in the watershed. Similar to other peri-urban areas, the watershed is a mix of land uses, serving as an agricultural area and a residential alternative for city dwellers (Moissidis and Duquenne, 1997). Because of the expanse of available open land now used for agriculture, the watershed is under increasing pressure for residential and commercial development as the metropolitan area spreads eastward (Pitt and Whited, 1999).

In 1997, the St. Croix Watershed Research Station (SCWRS) initiated a long-term monitoring program on the creek to establish baseline conditions and to identify changes resulting from watershed development, should it occur. Four automated stream monitoring stations were installed to measure flow, water temperature, and specific conductance, as well as to collect samples in response to runoff events (stations VC-1 through VC-4, Figure 1). In 1998 the Metropolitan Council added a fifth station near the mouth of the creek (VC-5, Figure 1), as part of the Watershed Outlet Monitoring Program (WOMP). These stations collect data at hourly intervals, complementing grab samples (about three per year) taken for over 20 years by the VBWD at two sites on this part of the creek.

Nutrient and Sediment Issues

Eutrophication, caused by increases in nutrient loads to streams, has been identified as a major threat to water quality in the United States (USEPA, 1996). There are many natural sources of nutrients, but commonly anthropogenic sources are the major supply in systems where nutrients exist at elevated levels (Puckett, 1996). Stream-water quality can be an indicator of cumulative effects from different land uses in a watershed. In watersheds with mixed agriculture and urban land uses, streams commonly have elevated nutrient concentrations (Johnson and others, 1997; Spahr and Wynn, 1997). Many studies have related the area of agricultural row crops in the watershed with nitrate levels in surface water (Osborne and Wiley, 1988; Miller and others, 1997; Jordan, Correll, and Weller, 1997; Correll, Jordan, and Weller, 1999; Liu and others, 2000; Randall and Mulla, 2001). Current literature concludes that land use in a watershed clearly has an influence on nutrient concentrations in streams (Johnson and others, 1997; Castillo, Allan, and Brunzell, 2000).

Despite its high-quality status, Valley Creek is presently affected by human activities in the watershed. Under baseflow conditions, the South Branch of Valley Creek had a median total nitrogen (TN) concentration of 6.7 milligrams per liter (mg/L) in 1997-98, most of which is in the form of dissolved nitrate (NO_3) (Almendinger, Schottler, and Thommes, 1999). This value is much higher than would be expected under natural conditions (e.g., <1 mg/L NO_3-N) and indicates an anthropogenic source (Clark, Mueller, and Mast, 2000). Conversely, the 1997-98 median total phosphorus (TP) concentration was only 21 micrograms per liter (g/L); values in other metro-area streams can be several times larger. Likewise, the 1997-98 median total suspended solids (TSS) concentration was only 1.7 mg/L under baseflow conditions. To some extent the hydrogeologic setting explains these values. Much of the upland watershed is relatively flat or pocked outwash plain directly overlying permeable bedrock aquifers, a setting that encourages infiltration rather than overland runoff. Most of the time the stream is under baseflow conditions, as it arises from headwater springs that appear to derive ultimately from bedrock aquifers (the Prairie-du-Chien/Jordan aquifer). This spring-fed streamflow is equable in temperature (median 10.3¡ C and maximum 15.0¡ C in 1997-98), a primary reason the stream is favored by trout. The high NO_3 values found under such baseflow conditions, when groundwater is the main source of water to the South Branch, suggests that the groundwater itself is contaminated. Because phosphorus is often associated with particulates, the low TP values in the stream during baseflow conditions are due in part to the low TSS concentrations in this spring-fed branch of the creek (Almendinger, Schottler, and Thommes, 1999).

Although much of the upland is relatively flat, the main channel of the South Branch lies in a steep-walled gorge. Under certain infrequent conditions, the infiltration capacity of the upland soils can be exceeded, and severe runoff events can occur. Normally dry channels can flow and cause intense erosion upon reaching the steep topography of the main gorge. In the past four years, only three significant runoff events have occurred. After these events, conditions returned to baseflow within about a day. During such events, large amounts of sediment appear to be delivered to the creek. A study by the Washington County Soil and Water Conservation District (SWCD), using the universal soil loss equation for representative sub-watershed transects, concluded that soil losses generally exceed the allowable soil loss limits (SWCD, 1982). Siltation of eroded material can change habitats by covering the stream bottom and retaining nutrients and organic matter (Ellis, 1936). Macrophyte patches can help trap fine sediments, reducing the available area of gravel-bottomed streambed required for trout to spawn successfully (Thornton, Aby, and Clary, 1997). The Water Management Plan for Valley Creek states that (f)oremost among local concerns is the problem of siltation, which destroys trout spawning habitat (VBWD, 1995).

We hypothesized that this sediment can also deliver a significant load of phosphorus to the creek bed in areas of deposition. This sediment and phosphorus may linger for a long (but unknown) period of time after such a runoff event, as the streamflow lowers back to baseflow and loses the energy to transport significant amounts of suspended sediment. Because of the already-high NO_3 values in stream-water, the aquatic vegetation in the South Branch of Valley Creek may be poised to respond to any significant input of phosphorus. Rooted macrophytes can take advantage of nutrients present in both the water column and stream sediment (Carignan and Kalff, 1979). Anecdotal evidence from residents along the creek suggests that beds of aquatic macrophytes have indeed expanded in recent years.

Project Goals

Our specific goals for this study were to:

- Continue hydrologic monitoring efforts
- Measure annual sediment and nutrient output loads from the creek
- Identify sources of nitrogen, phosphorus, and sediment to the creek
- Conduct a stream survey to inventory macrophytes populations, gullies, and stream bed sediments, along with identifying sources of sediment (and its associated phosphorus) to the creek
- Investigate the role sediment-bound phosphorus plays in macrophyte growth and density
- Estimate gross nutrient and sediment budgets (inputs vs. outputs)

III. RESULTS AND DISCUSSION

Hydrologic monitoring

The network of automatic stream monitoring stations provided the foundation for calculating annual flows and loadings of constituents (e.g., nutrients and suspended solids) and for documenting change over time (Figure 1). The network was fully operational during the two-year study period. Measures of stream stage, flow, specific conductance, and temperature were taken continuously, along with bi-weekly measurements of dissolved oxygen and pH. Twenty-seven storm events were sampled by automatic samplers during the two-year period. Baseflow grab samples were acquired bi-weekly. All water samples were analyzed for total suspended solids, total and dissolved phosphorus and nitrogen, dissolved inorganic carbon, and dissolved organic carbon. Monitoring data from 1999 were used to estimate annual nutrient loads, and data from both 1999 and 2000 were used to estimate mass budgets described later in this report. This report describes monitoring data for only the South Branch of the creek, although comparisons to the entire Valley Creek system are made to demonstrate the importance of nutrient loading from the South Branch.

Boxplots were constructed to display statistics for selected stream variables (flow, total phosphorus, total nitrogen and suspended solids) from the South Branch during both baseflow and stormflow (see Figure 2; boxplot explanation included). Baseflow during the two-year study was very stable, as seen by the very small interquartile range in Figure 2a. Flow rates for the stream ranged from a minimum of 0.18 m^3/s to a maximum of 3.54 m^3/s during the 2000 snowmelt event. Baseflow stability and range measured during the study period were comparable to values measured in 1997-1998 by the SCWRS (Almendinger, Schottler, and Thommes, 1999). Flow during storm events had a much larger interquartile range, because storm events vary in intensity. Overall, the South Branch of Valley Creek was characterized by extremely stable baseflow conditions; only 3% of the total annual flow volume was delivered during runoff events. The upstream intermittent branches (west of VC-3, south of VC-4; Figure 1) were observed with running water only three times in the past 4 years: one storm event (1 July 1997) and two snowmelt events (17 March 1999 and 25 February 2000). In 2001, no snowmelt runoff event occurred despite exceptionally heavy snowfall that winter and wet conditions the previous fall. Apparently, the underlying soil was largely unfrozen and a cool, gradual snowmelt allowed water to infiltrate rather than run off, demonstrating the high infiltration capacity of the Valley Creek watershed.

Figure 2b shows total suspended solids (TSS) boxplots for both baseflow and stormflow conditions for South Branch Valley Creek in 1999. The median TSS concentration at baseflow was low, only 4.2 mg/L; however, stormflow TSS values could be several orders of magnitude greater. These very low baseflow TSS values in 1999-2000 were consistent with those found in Valley Creek during 1997-98 by the SCWRS (Almendinger, Schottler, and Thommes, 1999) and were similar to TSS values found in streams draining undisturbed or forested watersheds (Perry and Vanderklein, 1996).

Figure 2c and 2d show total nitrogen (TN) and total phosphorus (TP) concentrations boxplots for both baseflow and stormflow conditions for the South Branch in 1999. The median TN concentration at baseflow was 6.8 mg-N/L, similar to the measured median from 1997-98 (6.7 mg-N/L) (Almendinger, Schottler, and Thommes, 1999). The vast majority (97%) of this nitrogen occurred in the dissolved form of nitrate. The baseflow TN concentrations measured at VC-1 are similar to those found in watersheds dominated by row-crop agriculture (Miller and others, 1997; Spahr and Wynn, 1997). Nitrate concentrations in undisturbed watersheds are often found in concentrations of less than 1 mg/L (Clark, Mueller, and Mast, 2000). The South Branch median stormflow TN concentration (5.8 mg-N/L) was lower than the baseflow median, indicating that nitrogen was diluted during stormflow events.

Total phosphorus concentrations during baseflow were very low (median = 19.3 μg-P/L), but increased by over an order of magnitude during runoff events (median stormflow TP = 409.20 μg-P/L). Baseflow TP concentrations were similar to those found in 1997-1998 by the SCWRS (Almendinger, Schottler, and Thommes, 1999). As with TSS values, the low TP baseflow concentrations found in South Branch Valley Creek were similar to those found in undisturbed or forested watersheds (Clark, Mueller, and Mast, 2000).

Output Loads

A load is either an input to, or an output from, a system such as South Branch Valley Creek. Loads are measured as the total volume (for water) or mass (for constituents such as phosphorus or suspended solids) entering or exiting the system during a selected time period. Loads of such constituents are calculated as the product of flow (volume/time) and concentration (mass/volume). Annual output loads of nutrients and suspended solids were calculated for South Branch Valley Creek by measuring both flow and constituent concentrations at VC-1 for the 1999 calendar year. The annual output load of TP was 226 kilograms (kg), that of TN was 50.1 metric tons, and that of TSS was 114 metric tons (one metric ton equals 1000 kg, or 2,200 pounds).

Loads were similarly calculated at VC-5 for Valley Creek as a whole during 1999. Comparison of loads between stations VC-1 and VC-5 allowed estimates of changes in the creek between the two stations, as well as determining the relative contribution of the South Branch to the total output load from Valley Creek entering the St. Croix River. At VC-5, the annual output load of TP was 684 kg, 33% of which came from the South Branch, and the annual output load of TN was 73.2 metric tons, 68% of which came from the South Branch. In contrast, the annual output load of TSS at VC-5 was only 106 metric tons, less than the 114 metric tons leaving the South Branch. Apparently, at least 8 metric tons of fine-grained sediment was trapped in pools and slow-moving water between the South Branch outlet and the mouth of Valley Creek. Contributions of sediment from North Branch Valley Creek were not included in this calculation and would make this deposition of sediment even greater, as would contributions from bedload.

The TSS annual output load for the South Branch (114 metric tons) was less than 1% of the total annual soil loss of about 14,000 metric tons (15,400 short tons) estimated by the SWCD (1982). However, the soil loss equation used by the SWCD did not address the transport or deposition of the soil, and our data suggest that only a small fraction of upland soil lost each year finds its way to the creek. Also, the TSS loads calculated in our report are certainly a significant underestimate of the total sediment load of the creek, because no measures of bedload movement along the channel bottom were taken during the study period. Such bedload appeared to consist primarily of sand-sized particles and formed visible deltas in slack water sections of the creek, especially after major flow events.

The form of nutrients delivered to a stream is important; particulate and dissolved forms of nutrients differ in their transport and bioavailibility. Figure 3a shows particulate and dissolved forms of both phosphorus and nitrogen as a percentage of their annual output loads from South Branch Valley Creek. Approximately 42% (95.4 kg) of the annual TP output load moved in particulate form, attached to sediment particles that either washed into the creek or eroded from the channel or stream bottom itself. Particulate phosphorus can be deposited into pools or other slow moving water sites along the creek, essentially building a reservoir of sediment-bound phosphorus in the creek. In contrast, nearly 97% (48.8 metric tons) of the TN output load for 1999 moved in dissolved form (Figure 3a) and the majority (97%) of dissolved nitrogen in the creek was in the form of nitrate, which is bioavailable. As is commonly found, the nitrogen-to-phosphorus ratio in the creek was very high, making phosphorus a limiting nutrient for plant growth.

Understanding flow conditions when the constituents move through the system is also important. The contribution of baseflow, storm events, and annual snowmelt runoff to annual phosphorus and nitrogen output loads is shown in Figure 3b. These results indicate that runoff events (snowmelt and rainfall events) accounted for a large amount of the TP output load from the stream annually. In fact, 37% of the annual phosphorus output load in 1999 occurred during the annual snowmelt event alone, which lasted about a day. Rain events during the rest of the year contributed only another 3% of the annual TP load, making snowmelt and storm events responsible for 40% of the annual output of phosphorus from the South Branch. In contrast, Figure 3c shows that the vast majority (97%) of the nitrogen output load from the stream occurred throughout the year during baseflow conditions. Runoff events (snowmelt and rainfall events) contributed only 3% to the annual total nitrogen output load from the system.

Nutrient sources and pathways

This study aimed to determine the general source of nutrients to South Branch Valley Creek, namely from regional non-point sources, or from point sources or other near-channel sources such as local septic tank leakage or bank erosion.

Nitrogen**:** No evidence for significant local sources of nitrate was found along the creek. Nitrate concentrations in surface water along the length of the creek did not increase in the downstream direction (Figure 4). The minimum value was 5.6 mg/L from surface water in the headwater reservoir. The maximum value along the creek was found to be 7.9 mg/L at the main pond near the headwaters of the creek. The interquartile range for nitrate values along the creek was only 0.8 mg/L. This small variability in stream-water nitrate concentrations along the length of the stream made it unlikely that there were point sources (such as septic systems or near-channel agricultural activity) entering along the South Branch, and indicated instead a regional, non-point source that enters the creek by groundwater discharge.

To investigate the possible regional source of nitrate to Valley Creek, nitrate concentrations of groundwater from wells in the watershed were plotted (Figure 5). The nitrate database was compiled by the Minnesota Department of Health (MDH) and most of the samples were taken in 1990 (Sheila Growe, MDH, personal communication, 1998). Also included were wells and groundwater sources sampled in 1999 by the SCWRS. Groundwater sampled from piezometers near the headwaters of the South Branch had concentrations of nitrate reaching 9.7 mg/L. High concentrations of nitrate were found in the headwater area of the creek where much of the flow to the South Branch originates. These groundwater concentrations confirmed that a regional, non-point groundwater source was most likely responsible for high baseflow loads of total nitrogen in the South Branch Valley Creek. Groundwater travel times over most of the groundwatershed have been estimated to be 30 to 40 years or even longer (Almendinger and Grubb, 1999). Therefore, it may take decades for this nitrate to flush through the aquifer system.

The majority of nitrogen both entering and exiting the South Branch during 1999 was in dissolved form. However, unlike at baseflow where the dissolved portion of nitrogen is almost entirely nitrate, snowmelt runoff contained both nitrate and ammonia. Ammonia nitrogen (NH_3 plus NH_4) is produced by microbial activity in saturated soils, manure, or sewage. Elevated levels of ammonia nitrogen measured in surface waters can be an indicator of agricultural and urban pollution. Ammonia nitrogen was not detected during baseflow in the South Branch. However, during snowmelt, up to 10% of the total nitrogen concentration at VC-1 was in the form of ammonia nitrogen. Waters entering the creek from intermittent branches (VC-3 and VC-4) had ammonia concentrations measured as high as 1.49 mg/L. Un-ionized ammonia (NH_3) is the toxic form of ammonia and is temperature and pH dependant. It was calculated on available samples using the temperature and pH of sampled water. Un-ionized ammonia was found to be between 0.1 and 0.3 μg/L, well below the Minnesota Pollution Control Agency (MPCA) chronic water standard (16 μg /L).

Phosphorus: As noted earlier, total phosphorus (TP) concentrations in Valley Creek were relatively low at baseflow, indicating no significant regional or local source of TP under these conditions. These low TP concentrations were at least in part related to low total suspended solids (TSS) concentrations at baseflow, as suspended particles tend to have adsorbed phosphorus, and there was a resulting positive relation between TP and TSS (Figure 6). Even so, at baseflow about two-thirds of the TP moved in the dissolved form (median 12.8 μg-P/L) rather than the particulate form (median 6.3 μg-P/L). Thus, of the 60% TP annual output load attributable to baseflow conditions, two-thirds apparently came from seeps and springs of potentially regional source, and one-third came from local sources of particulates, such as forest debris, algal productivity, and bank erosion.

During high flows, especially snowmelt, concentrations of TP rose dramatically (Figure 7) and were clearly related to TSS (Figure 6). Yet even under these conditions, dissolved phosphorus constituted the majority (51% in 1999 and 80% in 2000) of the TP in the overland runoff flowing into the South Branch from the intermittent channels.

The plots of TP as functions of TSS (Figure 6) and flow (Figure 7) suggest that two separate populations of samples were collected, one clustering at baseflow and the other at higher values during snowmelt runoff periods. Indeed, at snowmelt, Valley Creek is dominated by different water (runoff rather than groundwater discharge) and essentially becomes a different creek, with different relations (slopes) between TP, TSS, and flow. Consequently, fitting separate relationships for baseflow and snowmelt conditions would seem justified. As a simpler compromise, we fit a second-order curve to the data, which allows different slopes under the different conditions while creating a smooth transition (however artificial) between them. While conceptually useful, the second order curves do not appear to fit the data substantially better than the simple linear regressions, based on R^2 values.

The large contribution of dissolved phosphorus (DP) during the 1999 and 2000 snowmelt events was unanticipated. Initially, we expected the vast majority of phosphorus carried through the system during this high-energy event would be attached to particulates. Yet, almost half (44%) of the TP output load leaving VC-1 during the 1999 snowmelt event was in dissolved form. A main source of DP in runoff is soils with high phosphorus levels (Pote and others, 1999). Fertilization and manure spreading can contribute to high levels of soil phosphorus. McDowell and Sharpley (2001) found that concentrations of dissolved reactive phosphorus in drainage waters were related to soil-phosphorus concentrations of topsoils in the U.K. and Pennsylvania. Water running over fields of dead plant material can also carry significant DP into streams. Breakdown of plant cells by freezing and thawing allows dead plant material to release P from its tissues as water runs over fields (Randall and others, 1998). Agricultural watersheds in southcentral Minnesota contained DP percentages during snowmelt similar to those in South Branch Valley Creek; 52 to 83% of TP during snowmelt in these watershed was in dissolved form and attributed to water running over crop residue (Ginting, Moncrief, and Gupta, 2000).

Stream Inventory Survey

Valley Creek was surveyed in partnership with the Minnesota Department of Natural Resources (DNR) and the SWCD. Global positioning system units allowed the creation of a geographic information system (GIS) map of the stream. This initial GIS database was prepared by Jeff Berg of the SWCD and was distributed on a CD titled Valley Creek Natural Resources Inventory. Locations of macrophyte beds, gullies, springs, and the general stream outline are shown in Figure 8.

Sediment from the stream-channel and near-channel sources along the entire extent of Valley Creek were surveyed for phosphorus content to identify possible spatial patterns. Sediment-phosphorus concentrations and other lab data were added to the GIS database and all location data were converted to universal transverse Mercator (UTM) coordinates for ease of calculations. Locations of sediment samples and their total phosphorus concentrations (sediment-TP) are shown in Figure 9. The average sediment-TP concentration for all sediments sampled in the stream was 55 micrograms of phosphorus per gram of dry sediment (µg-P/g). Macrophyte beds averaged 46 µg-P/g, but variability within macrophyte patches was fairly large, ranging from 20 to 73 µg-P/g. For comparison, the Kinnickinnick, another trout-stream tributary of the St. Croix River, averaged 140 µg-P/g as sediment-TP within macrophyte patches (Szalay and Perry, 1999). The maximum sediment-TP concentration found in Valley Creek was 180 µg-P/g in a pool where fine-grained sediment deposition takes place. For comparison, the maximum concentration of sediment-TP in the St. Croix River was found to be 220 µg-P/g (Kroening and Andrews, 1997). The minimum sediment-TP concentration found in Valley Creek was 11 µg-P/g from sediments sampled outside of macrophyte patches where there was little fine-grained sediment. Overall, higher sediment total phosphorus samples were located in pools and large macrophyte patches, the majority of which were in the upper reaches of the South Branch or near the confluence with the North Branch (VC-2).

In an effort to identify sediment and phosphorus sources to the creek from within the watershed, we sampled source sediments such as upland soils, intermittent tributary sediments, streambanks, and gully sediments. Soils from fields in the watershed ranged from 33 to 210 µg-P/g. Sediment from intermittent branches ranged from 48 to 117 µg-P/g. Gully wall and floor sediments ranged from 37 to 95 μg-P/g. Eroding bank sediments had the lowest average total phosphorus concentration of all suspected source sediments (30 μg-P/g); their concentrations ranged from 21 to 42 μg-P/g.

Note that phosphorus was measured for these samples only on sediment that was 2 mm in diameter or smaller, which includes sand, silt, and clay. Generally, only the clay and silt fractions (termed fines here) have a significant amount of phosphorus adsorbed to them; conversely, sands carry little adsorbed phosphorus. Samples with lesser amounts of fines relative to sands would therefore contain less phosphorus. The different percentage among samples of fines versus sands, which was not measured, might explain much of the variability of phosphorus concentrations.

In order to determine the amount of sediment-bound P that is bioavailable for plant growth, a sequential phosphorus extraction method was employed. In this method, sediment was shaken first for one hour with NH_4Cl, then 16 hours with NaOH, and finally for 20 hours with HCl. After each extraction sequence, an aliquot of solution was taken and the amount of phosphorus released from the sediment to this solution was measured. A separate sample of sediment was extracted for sediment-TP with a H_2O_2/HCl hot digestion. Figure 10 is a diagram of this phosphorus fractionation scheme. The first extraction was for loosely-bound P (NH_4Cl-P), a fraction that is readily bioavailable. Next, iron- and aluminum-bound P (NaOH-P) was removed from the sediment. This fraction is also considered bioavailable; it has been related to algal-available portions in several studies (Hegemann, Johnson, and Keenan, 1983; Bostruom, Persson, and Broberg, 1988). Apatite-P (HCl-P) was the final extraction. HCl-P is associated with calcium carbonate minerals such as apatite and is non-reactive and not bioavailable. Residual phosphorus was found by subtracting the sum of inorganic fractions (NH_4CL-P, NaOH-P, and HCL-P) from sediment-TP. The residual fraction is composed mainly of organic phosphorus, which is associated with organic detritus. This fraction may eventually become available, but on the temporal scale of our concern (the summer growing season) it is primarily unavailable for growing plants.

Of the stream-channel sediments, samples from outside of macrophyte patches had the smallest phosphorus concentrations and, on average, 81% of their sediment-TP was present as HCl-P, which is unavailable (Figure 11). These samples contained very little fine-grained material, unlike patches and pools which tend to trap finer grained sediments. Sediment from pools and backwater areas had the highest concentrations of sediment-TP in the stream, but the majority of their phosphorus (77%) was HCl-P and residual-P, both of which are not readily bioavailable (Figure 11). Macrophyte patches had intermediate total phosphorus concentrations, but they had the highest percentage (31%) of bioavailable-P of all samples in the stream (Figure 11). Both pools and macrophyte patches averaged nearly half of their sediment-TP as residual-P (organic-P). Pools and patches can slow down water and cause fine-grained particles (some of which are organic) to settle out. Pool sediments had an average 6.7% organic material in the sediment, while macrophyte patches were more variable; different patches ranged from an average of 1.8% to 9.5% organic matter.

Figure 12 compares average phosphorus fractionations from sources of sediment including eroding banks, gullies, and soil/tributary sediments outside of the stream. Eroding bank sediments contained the least amount of phosphorus of all samples analyzed. Of this small amount, the majority (80%) of the phosphorus in eroding bank sediments was HCl-P and residual-P, which are generally unavailable to macrophytes. Upland soils and intermittent branch sediments had the highest sediment-TP concentrations of all sediment sampled; however, the majority (76%) of this phosphorus is not bioavailable (residual-P and HCl-P). In general, as overall phosphorus concentrations increased, the residual (or organic) phosphorus was the fraction of phosphorus that increased the most.

Soil and other source sediments in the watershed contained a high percentage of residual-P, similar to that in pool sediments (Figure 12). This similarity in phosphorus fractions suggests that the source of sediment being trapped in pools was from upland soils and gullies (which had higher organic matter and sediment-TP) rather than bank sediments (which had lower organic matter and sediment-TP), but we cannot be sure. Macrophyte patches had a greater range of variability in P-fractionation, which we presume to be a result of variability in grain size. Macrophyte patch sediments were apparently a spatially variable mixture of fines deposited in slow water and sand trapped by the macrophytes obstructing the movement of bedload.

The total sediment-bound phosphorus reservoir within the South Branch was estimated with stream data from the Valley Creek Natural Resources Inventory and our initial stream survey. Data from the GIS database were used to find the length (3.2 km) and average width (5.9 m) of the South Branch; we assumed an arbitrary depth of sediment (10 cm) for the purposes of calculation. The bulk density of dry sand (about 1500 kg/m^3) was used to convert sediment volume to mass because the vast majority of samples were dominated by sand. An average sediment-TP concentration of all stream samples (54.6 μg-P/g; std. dev. = 39 μg-P/g; n = 64) was used to determine the amount of phosphorus stored in the sediments. Using these assumptions, we estimated that the reservoir of sediment-bound phosphorus in the South Branch was about 155 kg. Of this amount, only 12% (about 18 kg) is bioavailable. We feel that these numbers are probably an overestimate of the actual amount of sediment-bound phosphorus in the South Branch because we specifically targeted fine-grained patches while sampling. Even so, this reservoir of sediment-bound phosphorus seemed quite small, and was even less than the amount of phosphorus leaving the system on an annual basis (226 kg in 1999). While this reservoir may be locally important to patches of rooted macrophytes, it does not appear to be a significant source of internal phosphorus loading to the stream.

Vegetation Study

Three selected reaches were chosen for a more detailed study of the relationships between sediment phosphorus content and rooted aquatic vegetation (macrophytes). Reach site locations are shown in Figure 1. All sites were sampled within a week of each other in mid-August of 1999. Sediment and plant samples were collected from patches within each reach, along with measurements of the patch size, macrophyte density, and rooted depth. Relative availability of sunlight was determined by visually estimating the coverage of forest canopy over each reach. Macrophyte plant samples from each of the selected reaches were dried and weighed to determine biomass and extracted for total phosphorus (Table 1). Sediment samples, from within and outside of macrophyte patches, were extracted for all fractions of phosphorus (Table 2).

The creek substrate was physically different among the three reaches. At the Smith (upstream) reach, the substrate was very sandy and fairly homogenous. The Hornickel (downstream) reach was dominated by sand and gravel. The plentiful sand and gravel indicated that the major mechanism of sediment-trapping was by the obstruction of particles rolling along the streambed by macrophytes. In contrast, fine particles were much more plentiful at the Milano (middle) reach than the other sites, both inside and outside of macrophyte patches, suggesting that lower water velocities allowed more fine-grained sediments to collect. As is commonly found in macrophyte patches, the Milano reach had a statistically higher percentage of sediment organic matter inside patches than outside inside ($\alpha = 0.10$).

Reaches differed in the diversity of plants. Elodea (*Elodea canadensis)* is common in calcareous streams such as Valley Creek; in other streams it has been shown to be dominant in the late season (Field and Graczyk, 1989). The Milano and Smith reaches contained only elodea. However, the Hornickel reach did not have any elodea; it contained a much greater variety of macrophyte species including watercress (*Nasturtium officinale)*, forget-me-not (*Myosotis scorpioides*) and one unidentified plant. Aquatic moss (*Fontinalis* sp.*)* was found in both Milano and Hornickel reaches, but not in the Smith Reach. Thick mats of algae were draped on elodea plants in the Smith reach, but only small amounts of algae were found in the Milano and Hornickel reaches.

Macrophytes at the Milano reach had the highest average plant total phosphorus (plant-TP) concentrations at 3.7 milligrams of phosphorus per gram of dry plant material (mg-P/g). The maximum plant concentrations in this reach (5.9 mg-P/g) were comparable to plant phosphorus concentrations in agricultural drainage ditches in southern Wisconsin (Field and Graczyk, 1989). The Milano reach had the sparsest macrophyte biomass density, with an average density of 9.9 grams dry-weight plant material per square meter (g-dw/m^2) within patches. It also had the highest percentage of forest canopy coverage, which limits light availability and ultimately plant growth. With less dense patches, macrophytes at the Milano reach may be able to take up higher levels of plant-TP because of less competition from other macrophytes.

In contrast, the Smith reach had virtually no canopy coverage, so light was not a limiting factor for plant growth at this site. Macrophyte coverage in the Smith reach was highest, with 92% of the ~100-foot-long reach covered in vegetation. Plant-TP concentrations were fairly similar within this reach and averaged only 2.2 mg-P/g. Macrophyte density and rooted depth within patches was greatest in the Smith reach, with a maximum density of 145 g-dw/m^2. This density is similar to that found in Black Earth Creek, a highly productive trout stream in southern Wisconsin (Field and Graczyk, 1989).

The Hornickel reach had intermediate measures of macrophyte coverage, canopy coverage, macrophyte density, plant-TP, and rooted depth.

Table 2 shows sediment-TP concentrations within and outside of macrophyte patches in each reach. The Milano reach contained the highest sediment-TP concentrations on average, both within and outside of macrophyte patches. This reach had statistically higher sediment-TP concentrations than the other reaches, most likely because it contained the most fine-grained material. The Hornickel reach contained the least amount of sediment-bound phosphorus, both within and outside of patches. The Smith reach had intermediate sediment-phosphorus concentrations. Overall, the amount of loosely-bound phosphorus (NH_4Cl-P) was statistically higher inside patches than outside ($\alpha = 0.10$). The concentrations of iron- and aluminum-bound phosphorus (NaOH-P), apatite-P (HCl-P), and organic-P were all generally lower outside of patches than inside, but this difference was not statistically different. Again, it is important to note that sediment less then 2 mm in diameter was used for the phosphorus extractions. The percent of clay and silt in each sample was not measured, so variability within the reaches was fairly high.

The major factor in the density and percent macrophyte coverage within each reach appears to be the distribution of canopy coverage. Even with higher sediment-phosphorus concentrations, the Milano reach did not have as dense macrophyte growth as the Smith reach. It is likely that both the sediment and water are supplying P to macrophytes in South Branch Valley Creek. Elodea has been shown to have no strong preference for taking up phosphorus from the water column or sediment (Eugelink, 1998). The importance of macrophyte uptake of phosphorus from the water-column (by leaves and stems) and sediment (via roots) is still debated by researchers. Robach and others (1995) found no relationship between sediment-TP and plant-TP, but they did find a relationship between water-column phosphorus concentrations and plant-TP, suggesting that macrophytes take up phosphorus most efficiently from the water column. In contrast, others have found good relationships between sediment-TP and plant-TP (Carr and Chambers, 1998). In either case, it appears as though light availability (not phosphorus concentrations in sediment or water) was most likely the limiting growth factor for macrophytes in the South Branch.

Overall, plant-TP concentrations indicated that macrophyte patches were providing some minor short-term phosphorus storage in the stream, at least during the growing season. In addition, sediment within patches had generally higher sediment-TP concentrations than sediment found outside of patches, indicating that sediment and phosphorus was being physically trapped by macrophytes. These patches can be nearly entirely washed away during high-flow events, at which time the phosphorus in the biomass and sediment in theory can become available to the rest of the stream. However, the total mass of phosphorus stored in aquatic macrophyte biomass is only on the order of a kilogram for the entire South Branch, much too small for these plants to be a significant source or sink of phosphorus.

Mass Budgets

The mass budget for a component (such as TP) in any system, including aquatic ecosystems, is determined by subtracting output loads from input loads:

input load — output load = storage

If inputs exceed outputs, then storage is positive and the system is accumulating mass of the selected component. If outputs exceed inputs, then storage is negative and the system has lost some of the component. For the purposes of this report, we define the system as being the primary channels of the South Branch Valley Creek and their stream beds and banks, extending upstream from station VC-1 to stations VC-3 and VC-4 (see Figure 1). By this definition, all movements of sediment and nutrients to or from the stream beds or banks is considered a change in storage rather than an input or output, and the only output from the system occurs at VC-1, the mouth of the South Branch s subwatershed. In other words, deposition of sediment in the channel or on the banks is considered a gain in storage; channel scour or bank erosion is considered a reduction in storage.

The small reservoir at the headwater of the South Branch, which receives flow from the South Fork intermittent branch, creates some complications in the definition of the system boundaries. As the South Fork enters the reservoir, the water slows down, and sediment and its associated phosphorus can settle out. In this way, the reservoir is probably acting as a sink of sediment and phosphorus. However, because of a lack of data on the reservoir s response during storm events, we cannot say what effect it has on the overall loadings of water, sediment, and nutrients downstream to the main channel of the South Branch. Consequently, we defined two different system boundaries as possible end-case scenarios: either scenario *A*, in which VC-4 is included as a system input contributing in real time to outputs measured at VC-1, which assumes that the reservoir captures nothing; or scenario *B*, in which VC-4 is excluded from the system as an input, which assumes that the reservoir captures all flow, sediment, and nutrients that enter it during runoff events. The actual response must lie between these two extremes. Data from below the reservoir suggest that some of the sediment and nutrients from VC-4 are passing through the reservoir and contributing to the stormflow inputs. Even so, we will present our annual loading results using the both scenarios, giving us an overestimate and underestimate of input loadings from intermittent branches. This gives us a conservative (minimal) and generous (maximal) estimate of other inputs (gully and overland flow) as explained later in this report.

As demonstrated in the previous section, calculation of output loads was a relatively simple task conceptually, as it involved measurement of flow and water chemistry at a single point (VC-1 in our system). However, calculating input loads (and therefore mass budgets) was difficult because of the many different input sources to the creek, some of which were difficult or impossible to measure fully. These input sources included the following: direct precipitation, groundwater, intermittent tributaries, gullies, and overland runoff (sheet flow and rill erosion, where applicable). As noted above, channel or bank erosion was considered a reduction in storage rather than a separate input source.

Some of these input loads could be measured or estimated. We assumed that precipitation was not a significant source of nutrients or suspended sediment. We further assumed that contributions from groundwater at all times (including during snowmelt and stormflow events) could be approximated by flows and concentrations measured at the output (VC-1) during baseflow conditions. Input loads from intermittent tributaries (VC-3 and VC-4) were measured to the degree possible with data loggers and automated sampling equipment, which were unfortunately not always installed and operational in time for a complete record of episodic events.

The high infiltration rate of the watershed minimized overland runoff under most conditions. During approximately four years of monitoring (1997-2001), only three runoff events occurred that produced flow in the intermittent tributaries and gullies. One was a heavy rainstorm that occurred in July 1997 before monitoring equipment was installed. No other rainstorm since then produced significant runoff, though rainfall intensities exceeded 25 mm (1 inch) per hour at times. The other two events were both snowmelt events that lasted about a day each, one on 17 March 1999 and the other on 25 February 2000. Consequently, input loading data from the intermittent tributaries came from just these two events.

There were several significant unknowns in the budget equation. A major unknown was the input load from gully erosion; while we analyzed a few samples from gullies for sediment and nutrient content, the quantity of flow contributed was unknown. Another unknown was the contribution (loss from storage as defined above) from channel scour and stream bank erosion. Bank erosion did not appear to be a major problem in South Branch Valley Creek, as determined by the Natural Resource Inventory undertaken in the spring of 1999 and as indicated by extremely low TSS values at VC-1 under baseflow conditions. However, the amount of channel scour and bank erosion during snowmelt or large storm flows was not really known and might be a significant source of sediment passing out of the system. A third unknown was the input load from overland runoff directly into the stream from riparian areas; we assumed this input was small, as most of the stream valley is well vegetated and analysis of rain storm events indicated that the area contributing direct runoff was extremely small, not much wider than the creek itself.

Because of these unknowns, we could only calculate a partial mass budget with the hope that it indicates the gross possible significance of these unknowns. That is, are gully inputs likely to be a major, or minor, source of sediment or nutrients to the creek, in comparison to known inputs and outputs?

The annual measured inputs and outputs of nutrients and sediment for 1999 are shown in Table 3. Inputs are given as a range; minimum values represent calculations based on scenario *A* described above and maximum values represent calculations based on scenario *B*. In 1999, the measured outputs of total phosphorus (TP) were matched fairly closely by measured inputs from baseflow and intermittent branches. Between 164 and 210 kg of TP entered the South Branch from baseflow and intermittent branch inputs. Table 4 shows percentage contributions supplied by unmeasured inputs in 1999. Only 7 to 27% of the annual TP budget entered the stream from unmeasured inputs. It is interesting to note that the dissolved portion of the phosphorus load (DP) was almost entirely accounted for by measured inputs, probably because of the high measured inputs of DP from intermittent branches. Only between 1 and 12% of the annual DP load went unmeasured in 1999. Therefore, the majority of unmeasured phosphorus must be entering the stream attached to sediment particles.

Almost the entire measured nitrogen output load (both total and dissolved) was matched by baseflow and intermittent branch inputs. Only between 1,267 and 1,507 kg of the annual TN output load (50,118 kg) was contributed by unmeasured inputs (gully inputs, overland flow, changes in storage). This unmeasured nitrogen input is only a small portion (3%) of the total annual output load (Table 4).

Unlike nutrients, however, the annual budget for total suspended solids showed that much of the suspended sediment leaving the stream each year was not measured entering the stream from intermittent branch inputs and therefore came from unmeasured sources. In 1999, only between 31,043 and 41,115 kg of the annual TSS load (114,462 kg) entered the stream from measured sources (Table 3). This indicated that the majority (between 64 and 73%) of TSS entered the stream from unmeasured sources (Table 4). As discussed above, overland runoff was minimal and bank erosion was not found to be common; therefore, gully erosion and changes in stream sediment storage (streambed scouring) appear to be the most likely sources of this large unmeasured sediment input into the South Branch.

One major gully input, Bahneman s Gully, was sampled during both 1999 and 2000 events. These grab samples reveal total suspended solids concentrations as high as 1,035 mg/L and total phosphorus concentrations as high as 1,144 μg-P/L. However, because flows in the gully were not measured, the total loading from the gully could not be calculated. Again, we remind the reader that when measuring TSS we are only measuring suspended sediment (fines) and not the bedload of the creek. Bedload is composed of coarser fractions (sand and gravel) that travel by rolling along on the streambed itself. Gullies, because of their steepness, are a probably a prime source of bedload material. The dominance of sand in the creek implies that bedload is probably a substantial part of the entire sediment load in the creek. This sand becomes trapped in pools and macrophyte patches in the creek. One pond, near VC-1 on the Belwin property, fills in just a few years.

In summary, during 1999 only a small percentage of the TN (3%) and TP (7 to 27%) input loads went unmeasured. However, the majority of sediment (64 to 73%) did not enter the stream from intermittent branches or baseflow inputs. Our budget calculations strongly suggest that unmeasured inputs of sediment (gullies and channel scouring) were important contributors of sediment to the creek.

Stream Sediment and Phosphorus Storage

Because there were inputs to the creek that we could not measure, changes in the stream sediment storage were unknown. We could only estimate the amount of sediment delivered to the stream from unknown sources. We may have underestimated or overestimated gully and overland flow inputs to the system. If the change in stream sediment storage was zero, then the unmeasured inputs (gullies and channel scour) made up 81% and 93% of the total suspended solids load during 1999 and 2000. However, it is possible that even more material than this was delivered to the stream channel from the gullies and stored there, and that not all of it passed by station VC-1 by the end of the runoff event. Observations from the day after the 2000 snowmelt event showed that some of the pools (especially the pond at VC-1) collected sediment during the event. In contrast, it is also possible that scouring of streambed sediments supplied some of the sediment load during the snowmelt events, and that input from the gullies may be overestimated. During the 2000 snowmelt event, many of the macrophyte patches were stripped of both sediment and decaying plant material, which were either flushed out of the stream or deposited in downstream pools during the event.

Sediment storage in the South Branch of Valley Creek in the past was probably much greater. From studying old aerial photographs, we found evidence for greater sediment storage in the creek in the past. In the 1930s, the stream appeared almost choked with sediment; many braided channels were present. During the 1950s and 1960s, we saw a reduction in agriculture activities near the stream and more forested riparian areas along the stream. Also, more homes were being built in 1970s and a more mixed land use was created: rural residential and agriculture. The recovery of wooded riparian areas and the building of the headwater reservoir were likely important factors in reducing the amount of sediment delivery and storage in South Branch Valley Creek.

IV. SUMMARY AND CONCLUSIONS

We found that high nitrogen loads in the creek were attributable to the regional groundwater source during baseflow in South Branch Valley Creek. There was no evidence found for point sources contributing large inputs of nitrogen along creek. Considering groundwater flow rates in the watershed, it may take decades for the nitrate-rich groundwater to flush through the system.

Dissolved phosphorus (DP) was a larger component of the total phosphorus load for the South Branch than previously thought. Intermittent branches supplied the majority of this DP load during runoff events. The source of this DP could be from water running over dead plant tissue and/or soils with excessive phosphorus levels from fertilizer or manure applications.

Most of the annual suspended sediment load did not enter the South Branch from intermittent branches, as we had originally expected. The majority of suspended sediment came from unmeasured sources. Because banks were fairly stable and overland runoff was minimal, gully inputs and streambed scouring were most likely responsible for these large unmeasured inputs.

Macrophyte coverage and density were greatest in reaches with highest light availability, not those with highest water-column or sediment-phosphorus concentrations. Overall, the macrophytes in the stream provided a small, short-term reservoir of phosphorus, both as plant biomass and as sediment within macrophyte patches. These patches appear to be reduced significantly by high-energy, flushing flow that occur during snowmelt runoff events.

Compared to the annual output of total phosphorus, the estimated inventory of sediment-bound phosphorus stored in the stream channel was quite small. Furthermore, much of this inventory was of a form not available to plants. This small inventory sediment-TP may be a result of Valley Creek s substantial baseflow, which was apparently large enough to minimize the deposition of phosphorus-rich, fine-grained particles in the stream channel.

V. FUTURE RECOMMENDATIONS

Our data suggest that gully erosion could be a large contributor to sediment inputs during runoff events. This hypothesis should be investigated further by directly measuring gully inputs to the degree possible. Nonetheless, data presented here, together with field observations of the severity of gully erosion, indicate that gully erosion-control structures may be a valuable investment in keeping sediment from the stream.

A large baseflow contribution to Valley Creek should be maintained, for at least two reasons. First, large baseflows keep the stream within the temperature range preferred by trout (Almendinger, Schottler, and Thommes, 1999). But second, as indicated by our report here, large baseflows have been instrumental in preventing the build-up of fine-grained sediments in most of the stream channel, thereby maintaining the coarse stream substrate favored by trout for spawning while also limiting the area occupied by aquatic macrophytes that in turn physically trap even more of this phosphorus-rich sediment. Baseflow conditions should continue to be monitored to identify trends in flow, sediment, and nutrients.

Another issue that may affect the health of Valley Creek concerns the headwater reservoir dam. The dam, completed in 1956, has allowed the headwater reservoir to retain an estimated 14,000 metric tons of sediment over the past 45 years. A decision on the future of the dam will probably need to be made in the next decade. The existing reservoir, incidentally, does not appear to alter downstream water temperatures significantly. In the summer, the South Branch maintains cool temperatures, preferred by trout, because the creek is fed primarily by springs below the reservoir.

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Table 1. Selected vegetation variables for reach sites on South Branch Valley Creek, 1999

Reach Site (see Figure 1)	**Estimate of Canopy Coverage in Reach** (%)	**Macrophyte Coverage in Reach** (%)	**Avg. Density of Macrophytes in Patches** (g-dw/m^2)	**Average Plant TP** *(mg-P/g dry plant material)*	**Rooted Depth of Macrophytes** (cm)
Smith (upstream)	5%	92%	88.5 (n=9, sd=30.3)	2.2 (n=6, sd=0.41)	8-20 cm
Milano (middle)	75%	22%	9.9 (n=10, sd=6.3)	3.7 (n=6, sd=1.29)	3-8 cm
Hornickel (downstream)	35%	26%	30.6 (n=11, sd=20.2)	2.2 (n=6, sd=0.44)	3-15 cm

Table 2. Sediment-P concentrations for reach sites on South Branch Valley Creek, 1999

Reach Site (see Figure 1)	**Avg. Sediment-TP Within Patches** *(µg-P/g dry sediment)*	**Bioavailable Sediment-TP Within Patches** (%)	**Avg. Sediment-TP Outside Patches** *(µg-P/g dry sediment)*	**Bioavailable Sediment-TP Outside Patches** (%)
Smith (upstream)	33 (n=6, sd=27.5)	10%	20 (n=3, sd=12.7)	8%
Milano (middle)	90 (n=5, sd=67)	22%	42 (n=3, sd=1.4)	15%
Hornickel (downstream)	14 (n=7, sd=11.6)	11%	14 (n=3, sd=0.8)	10%

Table 3. Annual measured inputs vs. outputs of nutrients and sediment for South Branch Valley Creek, 1999

	Measured Inputs (from baseflow inputs, VC-03, and VC-04)	**Measured Output** (at VC-01)
TP (kg)	164 - 210	226
TN (kg)	48,610 — 48,851	50,118
DP (kg)	115 - 129	131
DN (kg)	47,550 — 47,714	48,845
TSS (kg)	31,043 — 41,115	114,462

ABBREVIATIONS:
TP = total phosphorus
TN = total nitrogen
DP = dissolved phosphorus
DN = dissolved nitrogen
TSS = total suspended solids

Table 4. Estimated contribution of unmeasured inputs to annual budgets for South Branch Valley Creek, 1999

(Unmeasured inputs = Gully flow and stream-channel scour; measured as difference between measured output and measured input)

	Scenario *A*: If reservoir trapped **none** of the flow/ constituents from VC4 and VC4a	**Scenario *B*:** If reservoir trapped **all** of the flow/ constituents from VC4 and VC4a
	Unmeasured inputs supply **at least:**	Unmeasured inputs supply **at most:**
TP	7%	27%
TN	3%	3%
DP	1%	12%
DN	2%	3%
TSS	64%	73%

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