Valley Creek Data Summary and Analysis Report

Through December 2013

Submitted June 2014

Report to

Valley Branch Watershed District (VBWD)

and

Metropolitan Council Environmental Services (MCES)

by

James E. Almendinger
St. Croix Watershed Research Station (SCWRS)
Science Museum of Minnesota

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Valley Branch Watershed District
established November 14, 1968

St. Croix Watershed Research Station

Contents

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Abstract

Valley Creek is a valued trout stream in the Twin Cities metropolitan area whose habitat quality is sustained by baseflow. To protect Valley Creek, resource managers need to know how much of the variation in baseflow is caused by interannual weather patterns and how much could be caused by pumping from nearby high-capacity wells. The purpose of this report is twofold. The first is to discuss recent data (2011-13) in the context of the database for the creek that has documented its hydrology and water quality over time. Recent data show that median flows and baseflows in the creek have largely recovered back to near-average values during 2011-13, following low flows during 2008-10. While suspended sediment and total phosphorus levels have remained low, nitrate concentrations have risen, perhaps reflecting decades-old groundwater pollution that is working its way to the creek.

The second purpose of the report is to examine the flows in the database for their possible relation to weather patterns and pumping. Two metrics of weather were used, Washington County precipitation and flow in a reference river, the nearby Apple River, which presumably is relatively unimpacted by human activities. Regional pumping was defined as that from all regulated (permitted) wells within 15 km of Valley Creek, and local pumping as that from the two wells (#15 and 16) in the Woodbury East well field. For the three monitoring sites on Valley Creek (main stem, North Branch, and South Branch), regression models of flow on precipitation lagged by two to five years gave good fits (R^2 = 0.49-0.74), whether for annual median flows (main stem) or for 12-month running mean monthly baseflows (all three sites). In all cases, adding local pumping to the equation improved the fit (R^2 = 0.63-0.81) and produced a significant coefficient for the pumping variable. Fits of Valley Creek flows to Apple River flows produced similar R^2 values (0.58-0.75), with less of the variance being explained by the pumping when added. Given amounts pumped and the regression-determined pumping coefficients, the pumping could have reduced baseflow by 0.7-1.9 cfs, depending the model and creek branch selected. Water levels in monitor well 3 (MW3) near the headwaters of South Branch Valley Creek were similarly related to precipitation (R^2 = 0.77), and to precipitation plus pumping (R^2 = 0.86), with pumping responsible for perhaps a one-foot drop in water level. In short, these different regression models generally suggest that while most of the flow variance can be explained by interannual precipitation differences, a small amount may be explained by pumping from the Woodbury East well field. Adding a pumping variable to the regression equation usually resulted in an improved R^2 and a significant parameter. However, it is important to note that the models generally suffered

from autocorrelation and hence the significances of the fit and the parameters were overestimated.

As an additional exercise, annual White Bear Lake levels were regressed on Washington County precipitation lagged by up to seven years with an R^2 value of 0.77. However the large number of parameters versus the relatively small number of data points implied that the model was overfit and hence quantitatively unreliable. A regression of annual lake levels on median flows in the Apple River, lagged by up to four years, produced a much tighter fit ($R^2 = 0.96$), demonstrating that White Bear Lake and the Apple River are responding in similar ways to regional hydrologic influences. While pumping was not needed as an explanatory variable, these analyses do not disprove the possible impact of pumping on the lake, because pumping may have already lowered aquifer heads and lake levels to a lower baseline, and interannual precipitation patterns are simply explaining the variation in levels around this reduced baseline.

Introduction

Valley Creek is one of the few remaining trout streams in the Minneapolis-St. Paul metropolitan area (Figure 1) and is thus a highly valued and protected resource. The viability of the trout population depends on continued groundwater discharge to the creek, which maintains cool, equable temperatures and a coarse stream bed required by spawning trout and their macroinvertebrate food base. The groundwater-fed baseflow of Valley Creek varies over time as a result of monthly and annual weather variability. In addition, baseflow might be reduced by municipal water-supply wells, because these wells tap the same aquifers that supply groundwater to the creek. Increases in impervious surfaces accompanying regional urbanization may also indirectly alter baseflow by changing the infiltration that recharges the aquifers, thus changing the amount of groundwater available. Management and protection of Valley Creek hinges on an adequate data set that documents baseline conditions and allows changes to be identified, which can provide clues as to how much of the variation in baseflow is due to weather variability, and how much is due to human activities in the study area. Hence the purpose of this report is two-fold: first, to maintain the monitoring data set that documents stream hydrology and water quality; and second, to examine this record for relations that could identify which factors most impact stream hydrology, specifically baseflow in this case.

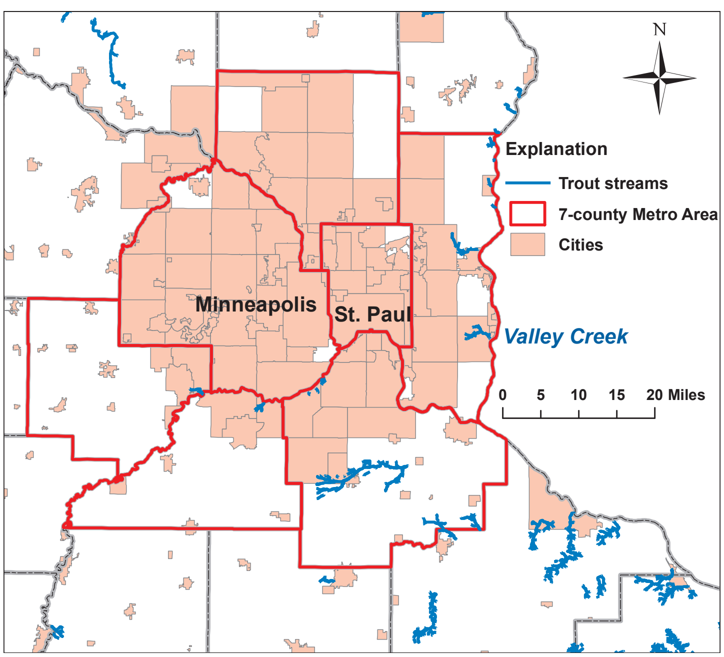


Figure 1. State-designated trout streams in and near the Minneapolis-St. Paul metropolitan area.

This report extends the summary and analysis of Valley Creek flow and water-quality data through 2013. The data summary focuses on the last three years, with reference to data extending back to 1998-99, when continuous flow monitoring stations were established on the creek. The data analysis portion of the report determines the relation of median flow and baseflow in Valley Creek to weather and human activities, specifically high-capacity well withdrawals. Weather variables included Washington County precipitation and flow in a nearby reference river (Apple River in western Wisconsin). High-capacity wells included both regional and local wells. Regional were are those within 15 km of the perennial reaches of Valley Creek, and local wells referred specifically to those in the Woodbury East well field, namely wells 15 and 16. The principal findings of the report are that flows in Valley Creek have rebounded back to near average values during 2011-13, following low flows during 2008-10. According to multiple regression models, most of the flow variation was explained by precipitation, lagged by up to five years. However, adding local pumping as a variable improved the statistical fit slightly in most models, indicating that pumping may be having a small effect on flow in Valley Creek. A similar analysis was done for White Bear Lake levels, where multiple regression models showed a strong relation between lake level and either precipitation (lagged up to seven years) or flow in the Apple River as a references system, although the effect of pumping could not be discounted.

Study Area

Valley Creek is tributary to the St. Croix River and lies in eastern Washington County, on the eastern fringe of the urbanizing Twin Cities metropolitan area (Figure 2). The watershed of Valley Creek remains largely rural, although the city of Woodbury to the west is developing rapidly and some development has occurred along the I-94 corridor to the north. Continuous (15-minute to hourly) flow monitoring has been done on the North Branch (NB) and South Branch (SB) since 1998 and on the main stem (MS) since 1999. Seasonal flow measurements on the main stem extend its record back to 1976. In 2003 Woodbury installed a new municipal well (#15) tapping the Jordan aquifer near the western edge of the watershed and a nest of monitoring wells (MW3) near the headwaters of the South Branch. This nest has piezometers screened in the water table, Prairie du Chien, and Jordan aquifers. In 2006 a second municipal well (#16) was completed nearby the first. In 2013, a third well (#18) was installed and is scheduled to begin pumping in 2014.

Although the surficial (directly contributing) watershed of Valley Creek is about 37 km^2, its groundwatershed is much larger (Figure 3). Earlier studies indicate that the contributing area is at least 60 km^2 for the Prairie du Chien aquifer, and about 80 km^2 for the Jordan aquifer (Almendinger and Grubb 1999). Water balance considerations suggest that the larger area is more representative. That is, for baseflow in Valley Creek to be sustainable, the aquifer

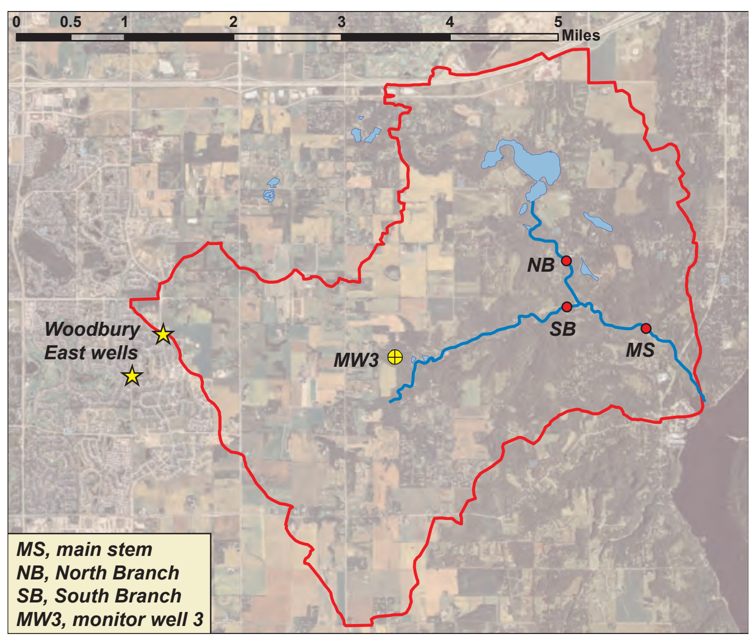


Figure 2. Surficial watershed of Valley Creek, monitoring sites, and Woodbury East wells.

that feeds Valley Creek must be replenished by the same amount as that baseflow each year, on average. Aquifers are replenished by recharge, the amount of water percolating down to the water table. Recharge is described as a depth of water, in inches or millimeters, just like precipitation. So the annual recharge (R) over the contributing area (A) to a stream (or a well) is the volume (R x A) of water available to that stream (or well) each year. If the contributing area is 80 km^2, then Valley Creek would need a recharge of 6.6 inches per year over that area to sustain its baseflow of about 15 cfs.

Within a radius of 15 km from the centroid of the perennial reaches of Valley Creek (red cross, Figure 3), there are 118 permitted (regulated) wells pumping a total of 8.4 billion gallons per year (BG/yr; 2007-11 average). This pumping rate is equivalent to 36 cfs, or about 2.4 Valley Creeks. Since Valley Creek requires a contributing area of at least 80 km^2, these wells would require a contributing area of about 190 km^2. The point is that these wells extract more water from the aquifer, and require a larger contributing area in aggregate, than does Valley Creek itself.

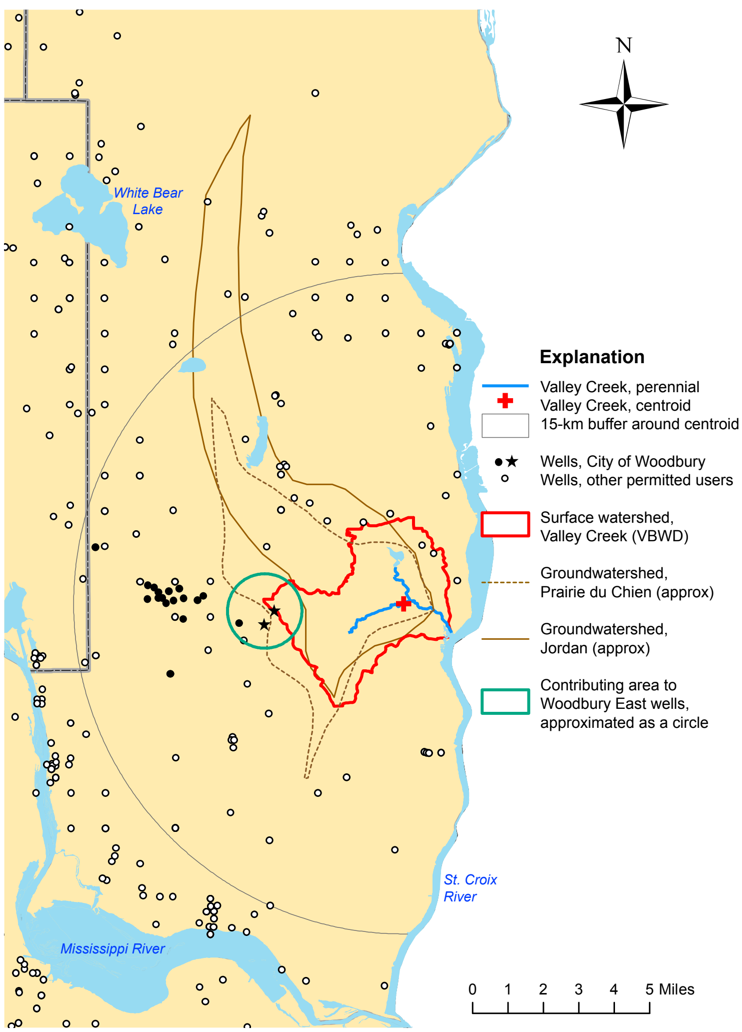


Figure 3. Eastern Twin Cities metropolitan area showing watersheds associated with Valley Creek, permitted (regulated) high-capacity wells, and 15-km radius around Valley Creek.

It is entirely prudent to investigate the degree to which pumping may be capturing water that otherwise would sustain valued and protected natural resources such as Valley Creek.

Woodbury is the single largest user within this data set, accounting for nearly one third (32.7%) of the water pumped each year (Table 1). The two Woodbury wells closest to Valley Creek (#15 and #16 in the Woodbury East well field; see stars in Figures 2 and 3) are two of the most highly pumped wells in the data set (at the 88th and 90th percentiles, respectively), and together they account for over 5% of the total pumping and about 16% of Woodbury's total. If one assumes a similar rate of recharge that supplies the groundwatershed of the creek, then the contributing area to these two wells would be about 10 km^2 (approximated by blue circle, Figure 3).

Data were also compiled for the Apple River watershed in western Wisconsin (Figure 4), about 50 km to the northeast of Valley Creek and the metropolitan area. The Apple River was selected for two reasons. First, it has a relatively long flow record (1914-present, with an unfortunate data gap from 1970-86). Second, its watershed is relatively unimpacted by urbanization and municipal well pumping, at least when compared to the urbanizing areas in Washington County. Furthermore, its watershed is on the Wisconsin (east) side of the St. Croix River, which is a regionally significant hydrologic boundary that effectively isolates the Apple River from human activities on the Minnesota (west) side. The working hypothesis is that flow in the Apple River represents a hydrologically integrated signal of how watersheds (including aquifers) respond to interannual weather variations in the absence of significant human activities. In other words, Apple River may be an excellent "reference river" whose flow provides a surrogate measure of climatic moisture supply to the east-central Minnesota/west-central Wisconsin area. Pumping for agricultural irrigation, which apparently has increased in recent years, may somewhat compromise the "reference" status of the Apple River.

Table 1. Groundwater permittees within 15 km of Valley Creek, ranked by annual average withdrawals, 2007-11.

Permittee	Mgal/yr	Percent
WOODBURY, CITY OF	2748	32.7%
3M COMPANY	1563	18.6%
COTTAGE GROVE, CITY OF	1140	13.6%
OAKDALE, CITY OF	804	9.6%
STILLWATER, CITY OF	371	4.4%
BAILEY NURSERIES INC	295	3.5%
OAK PARK HEIGHTS, CITY OF	235	2.8%
ANDERSEN CORPORATION	170	2.0%
All others (33 users, <2% each)	1072	12.8%
Total	***8398***	***100%***

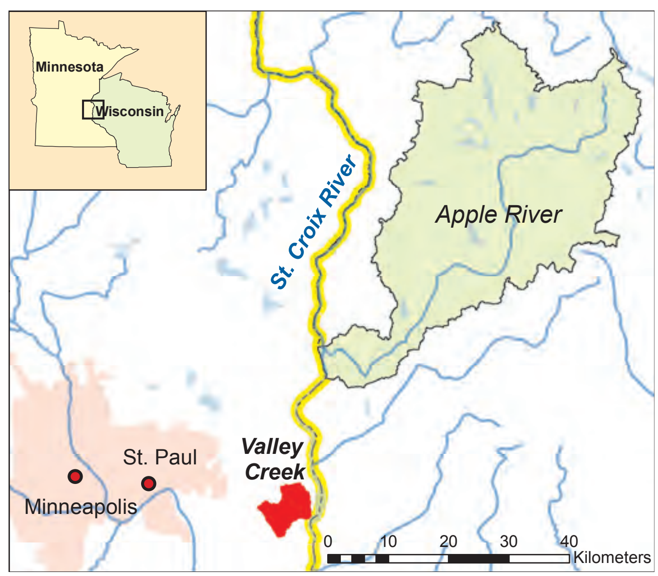


Figure 4. Location of the Apple River watersheds, western WI, in relation to Valley Creek and the Twin Cities metropolitan area.

Methods

Field and Laboratory Methods. Flows were measured by standard area-velocity methods by technicians for Barr Engineering (1976-1999), the St. Croix Watershed Research Station (1998-2011), and the Washington Conservation District (2011-present). Rating curves (stage-discharge relations) have been established at each of the three stations (MS, NB, and SB; Figure 2), although shifting stream beds have required that the curves be frequently modified over the years. Stages and field water-quality parameters (temperature and specific conductance) were measured hourly with battery-powered components on the two branch stations (NB and SB) and measured every 15 minutes at the main-stem station (MS), which has continuous power and telephone-line connectivity to allow remote monitoring. Grab samples to determine baseflow water quality were collected monthly at the MS site and semiannually (January and July) at the NB and SB stations. Storm samples were collected automatically at the MS site with a sampler triggered at equal stormflow-volume increments (e.g., as every 50,000 cubic feet pass the station). Water samples from the MS site were analyzed by the Metropolitan Council Environmental Services (MCES) laboratory according to standard methods for suspended solids, dissolved constituents (including nutrients), and microbiological activity. Samples from the NB and SB sites were analyzed by the SCWRS laboratory for suspended solids and nutrients. Annual loads (masses) of solids and nutrients at the MS site were calculated by MCES personnel using the program FLUX as applied to daily mean flows.

Statistical Methods. Multiple linear regression models were constructed with the R statistics package (R Core Development Team 2013) to relate selected dependent variables (annual median flow, monthly baseflow, or monthly monitor-well water level) to selected independent variables (measures of weather and pumping). In other words, equations were constructed to predict flow or groundwater levels (y variables) as functions of weather and pumping (x variables). Table 2 lists the sources of the data sets used as model variables. Model autocorrelation was tested with the Durbin-Watson statistic.

Table 2. Data sets used in statistical analysis of factors affecting Valley Creek flow.

Data Set	Units	Years	Source
Annual Data Analysis			
Dependent variable (y)			
Main stem flow (annual median)	cfs	1976-present	Barr Eng., SCWRS, WCD
Independent variables (x_i)			
Weather variables:			
Precipitation, Washington County, MN (annual mean)	inches	1976-present	MN State Climatologist
Precipitation, Amery, WI (annual mean)	inches	1976-present	NCDC
Apple River flow (annual median)	cfs	1986-present	USGS
Pumping variables:			
Regional pumping (annual total)	MG/yr	1988-present	MDNR
Local pumping (Woodbury East annual total)	MG/yr	2003-present	Woodbury
Monthly Data Analysis			
Dependent variable (y)			
Main stem baseflow	cfs	1998-present	SCWRS, WCD
North Branch baseflow	cfs	1998-present	SCWRS, WCD
South Branch baseflow (12-month running mean)	cfs	1998-present	SCWRS, WCD
MW3-Jordan water level (monthly average)	ft ASL	2003-present	Woodbury (Stantec)
Independent variables (x_i)			
Weather variables:			
Precipitation, Washington County, MN (monthly mean and 12-month running mean)	inches	1976-present	MN State Climatologist
Apple River baseflow (12-month running mean)	cfs	1986-present	USGS
Pumping variable:			
Local pumping (Woodbury East monthly total	MG/month	2003-present	Woodbury

ABBREVIATIONS: MW3, monitor-well nest #3; cfs, cubic feet per second; MG, million gallons; yr, year; ft ASL, feet above mean sea level; SCWRS, St. Croix Watershed Research Station; WCD, Washington (County) Conservation District; NCDC, National Climatic Data Center website; MDNR, Minnesota Department of Natural Resources; USGS, U.S. Geological Survey

Results and Discussion I: Flow and Water-Quality Data Summary, 2011-13

High flows, main stem

In 2011 as in 2010, no significant snowmelt peak occurred in Valley Creek (Figure 5), despite the relatively snowy winter and flooding of Minnesota's major rivers. A very gradual warming and snowmelt averted major flooding and the St. Croix crested well below originally predicted levels. (Even at the maximum predicted crest for the St. Croix, the monitoring station on Valley Creek would have remained above water.) The small peak in late March in Valley Creek occurred after several days of above-freezing temperatures plus an inch of rain. Through June 2011, peaks in response to rainstorm events were modest. However, significant rainstorm events produced large peak flows in July and August, the largest at 87 cfs on 16 July in response to a 3.34" rain fall event.

In 2012, snowmelt started on 29 February with nearly 1 inch of rain and slightly above freezing temperatures (Figure 6). The real melt came on 6 March, with a peak of about 57 cfs at 8 PM, on the first day with significant above freezing temperatures (7.1 deg C, or about 45 deg F), in the absence of rain. Subsequent peaks during the rest of the year were modest an in response to weeklong clusters of rainy days.

2013 continued the trend of relatively modest peak flows (Figure 7). No significant snowmelt peak occurred. The highest flow of the year occurred on 21 June, reaching 47.4 cfs, as a result of a 2.5-inch rainfall event, followed by another 0.5 inches the next day, as measured at MSP airport. These events were not recorded at the Valley Creek weather station at the Belwin Outdoor Science center, which was evidently not functioning properly at that time.

Median and low flows

Median (i.e., typical) flows have followed rainfall patterns with some delays (Tables 3a and 4). Since the lowest flow values in 2009, large rainfall totals in 2010 and early 2011 drove flows up during 2011. However, the latter half of 2011 was very dry, and 2012 had a similar pattern with a wet spring followed by a very dry August through December period nearly 8 inches below normal (Washington County averages, Table 4). Consequently median flows for the North Branch and main stem dropped from 2011 to 2012 to below average values. However, the South Branch was an exception to this pattern: despite the lower-than average precipitation during 2011-12, median and baseflows increased from 2011 to 2012, indicating that the spring-fed South Branch was still responding to the apparently large groundwater recharge total that resulted from earlier wet years (2010) and wet springs (2011 and 2012). 2013 continued the precipitation pattern of 2011-12, with a very wet first half of the year, followed by a very dry second half. The net result was a slightly above-average annual precipitation total in Washington County and at the MSP airport, and median and mean flows and baseflows in the main stem recovered to above-average values (Tables 3 and 4). The increase resulted from a nearly step-wise increase in flow that occurred mostly during April 2013 (Figure 7). In contrast, mean annual flows and baseflows in the North and South branches remained slightly below average during 2013 (Table 4), due mostly to low values in early 2013. Because of equipment failure and shifting streambed configurations, measuring streamflow on Valley Creek was challenging during 2013 (Leigh Harrod, Metropolitan Council Environmental Services, personal communication, April 2013).

Despite lower than average precipitation for 2011-12, the 7-day low flows for the main stem have remained above average during this time (Table 4). These low flows are sustained by groundwater discharge, which apparently has responded well to several years of wet springs,

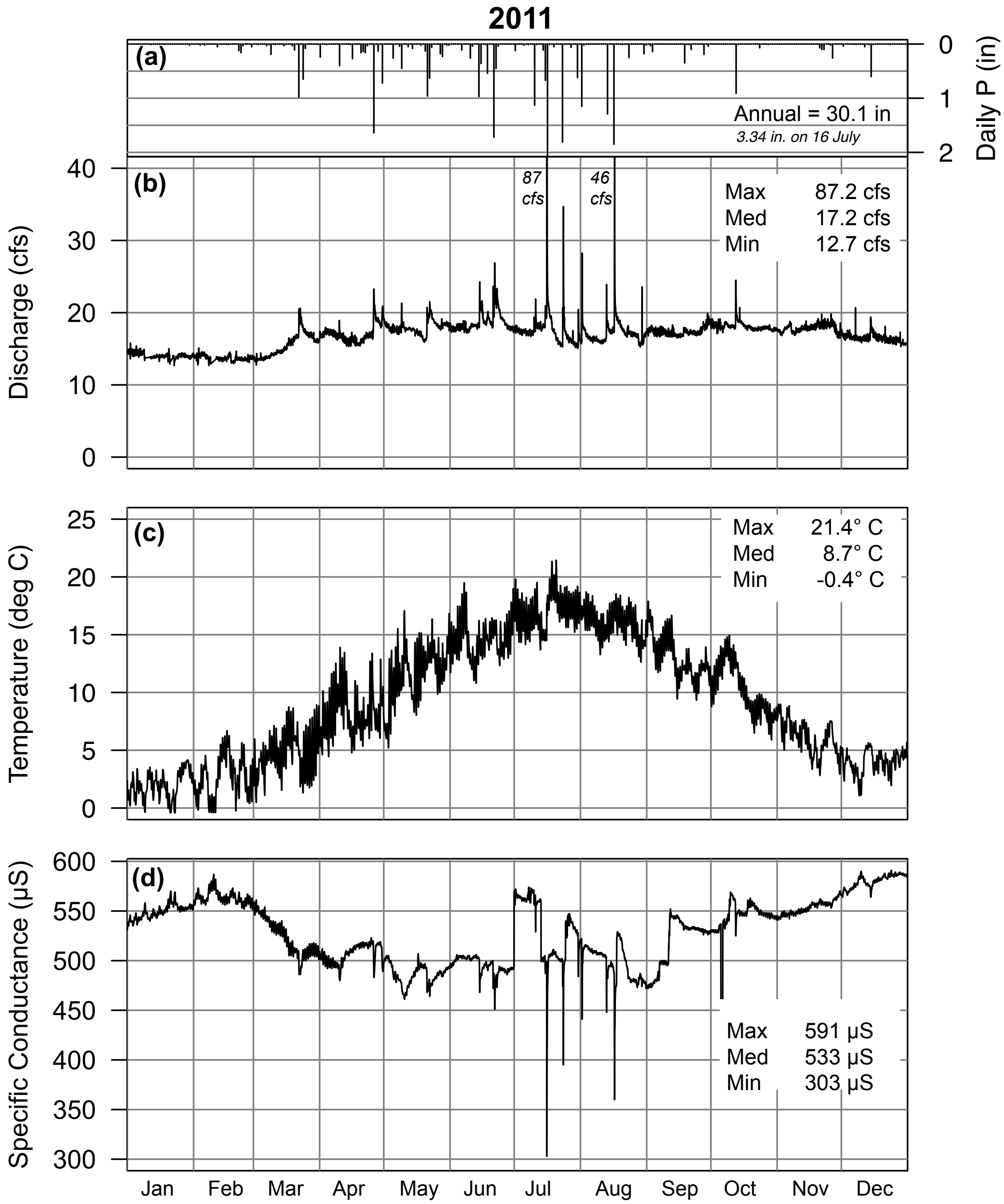


Figure 5. Hydrologic data for Valley Creek at Putnam Blvd., 2011
(a) daily precipitation, (b) hourly discharge, (c) hourly water temperature, and (d) hourly specific conductance.
NOTE: Annual total precipitation (P) is a minimum, because snowfall was not accurately collected by tipping-bucket gauge.

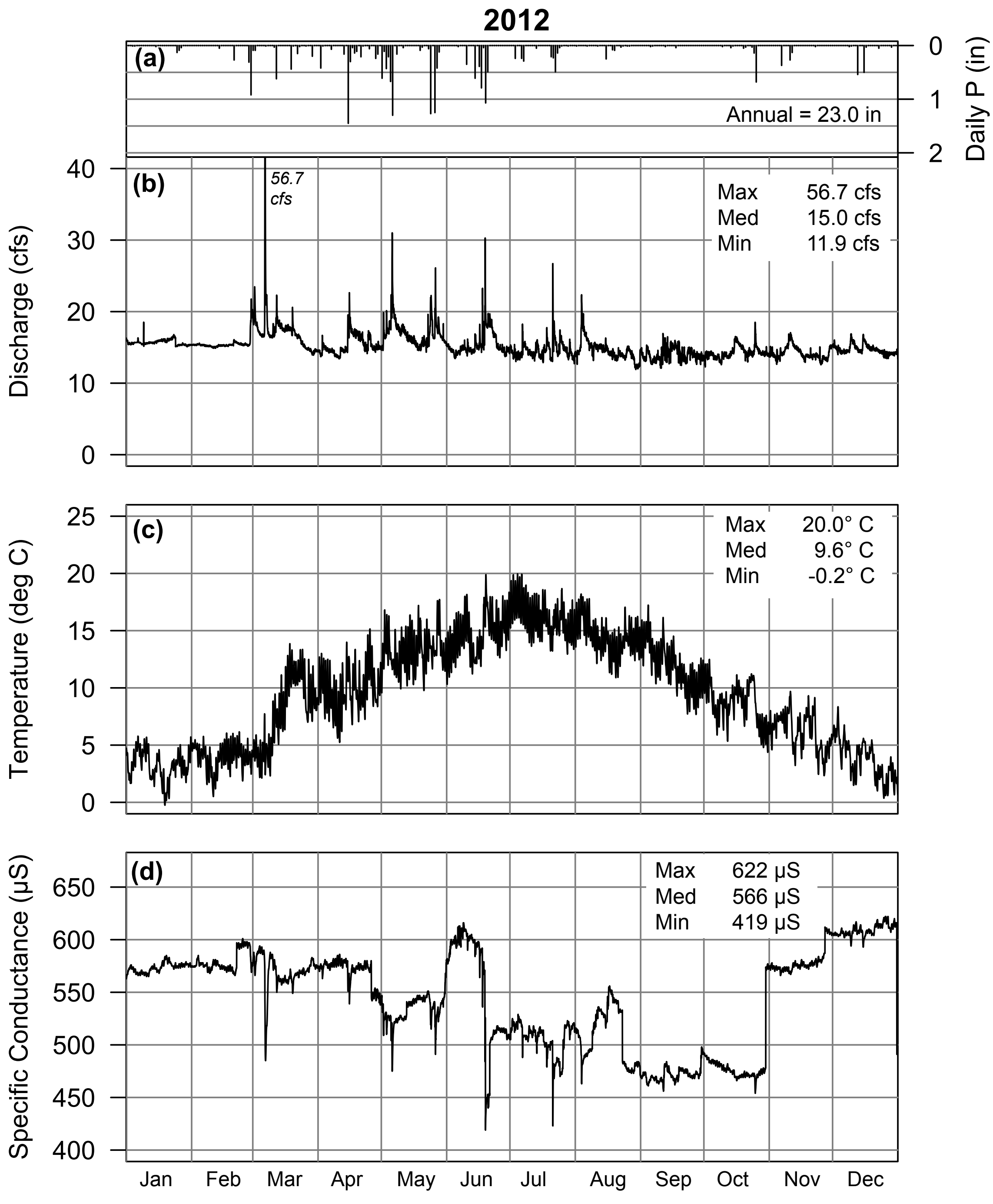


Figure 6. Hydrologic data for Valley Creek at Putnam Blvd., 2012 (a) daily precipitation, (b) hourly discharge, (c) hourly water temperature, and (d) hourly specific conductance.

NOTE: Annual total precipitation (P) is a minimum, because snowfall was not accurately collected by tipping-bucket gauge.

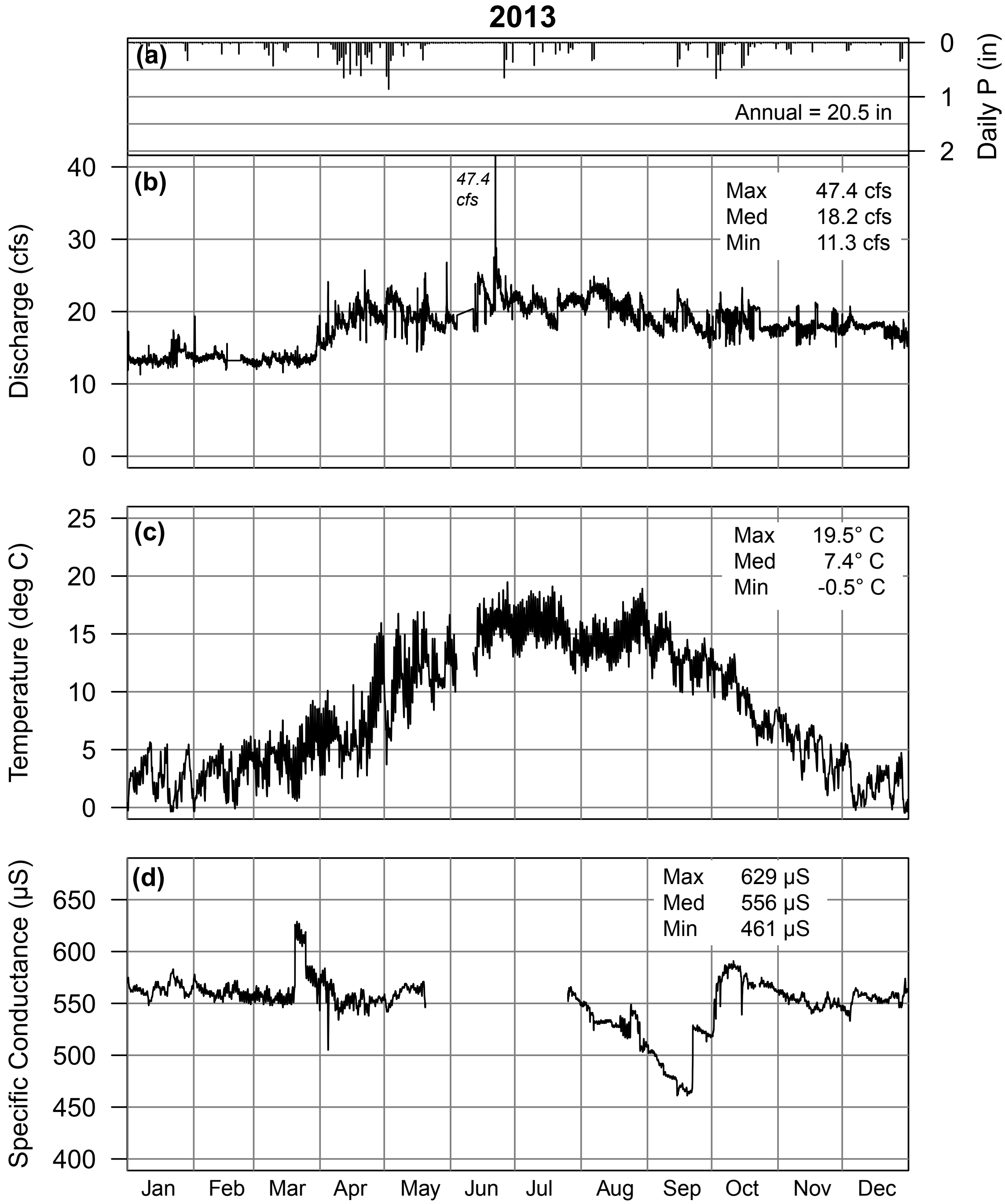


Figure 7. Hydrologic data for Valley Creek at Putnam Blvd., 2013 (a) daily precipitation, (b) hourly discharge, (c) hourly water temperature, and (d) hourly specific conductance.

NOTE: Annual total precipitation (P) is a minimum, because snowfall was not accurately collected by tipping-bucket gauge.

Table 3. Annual summaries of (a) hourly flow, (b) temperature, and (c) specific conductance for three stations on Valley Creek, 1998-2013.

(a) FLOW (cfs)

	North Branch			South Branch			Main Stem		
	Median	*Maximum*	*Minimum*	Median	*Maximum*	*Minimum*	Median	*Maximum*	*Minimum*
1998	8.7	*15.7*	*6.7*	9.9	*52.6*	*7.6*	na	*na*	*na*
1999	6.7	*11.4*	*4.4*	8.7	*124.9*	*6.2*	17.2	*97.0*	*13.8*
2000	5.6	*16.2*	*4.5*	9.9	*129.3*	*4.2*	16.9	*106.2*	*10.2*
2001	7.6	*13.2*	*5.9*	10.7	*25.1*	*4.0*	19.0	*46.6*	*11.8*
2002	7.3	*13.6*	*5.6*	9.8	*123.7*	*8.1*	20.9	*97.5*	*15.3*
2003	7.7	*20.4*	*4.6*	8.9	*117.6*	*7.2*	20.2	*158.2*	*14.8*
2004	6.1	*11.1*	*3.9*	8.4	*21.5*	*6.8*	17.1	*41.8*	*11.7*
2005	4.5	*12.3*	*1.8*	8.1	*133.2*	*6.7*	15.1	*153.9*	*8.5*
2006	5.0	*13.0*	*0.4*	7.9	*25.2*	*7.0*	16.0	*52.6*	*10.2*
2007	3.4	*33.5*	*0.8*	7.7	*145.1*	*6.8*	12.8	*292.1*	*11.9*
2008	3.1	*9.9*	*0.3*	7.0	*15.8*	*6.6*	12.9	*20.2*	*11.7*
2009	2.2	*53.5*	*0.7*	6.7	*106.7*	*5.7*	11.7	*147.9*	*9.5*
2010	2.7	*9.5*	*1.5*	7.0	*15.5*	*6.7*	12.1	*31.0*	*9.7*
2011	6.6	*23.3*	*2.6*	7.7	*26.0*	*6.8*	17.2	*87.2*	*12.7*
2012	4.1	*17.1*	*1.8*	8.1	*39.8*	*7.4*	15.0	*56.7*	*11.9*
2013	4.6	*14.0*	*2.2*	7.5	*11.1*	*7.2*	18.2	*47.4*	*11.3*
Statistics on the above values									
Mean	5.3	*18.0*	*3.0*	8.4	*69.6*	*6.6*	16.1	*95.8*	*11.7*
Median	5.3	*13.8*	*2.4*	8.1	*46.2*	*6.8*	16.9	*87.2*	*11.7*

(b) TEMPERATURE (°C)

	North Branch			South Branch			Main Stem		
	Median	*Maximum*	*Minimum*	Median	*Maximum*	*Minimum*	Median	*Maximum*	*Minimum*
1998	12.7	*26.2*	*0.5*	9.7	*16.8*	*0.6*	na	*na*	*na*
1999	10.0	*27.1*	*0.0*	8.9	*18.0*	*-0.1*	9.2	*21.3*	*-0.3*
2000	12.9	*26.1*	*-0.3*	9.5	*17.4*	*-0.2*	9.5	*20.5*	*-0.4*
2001	9.6	*28.1*	*-0.2*	9.4	*17.6*	*-0.2*	9.2	*21.7*	*-0.4*
2002	8.7	*26.5*	*0.5*	8.0	*18.0*	*0.5*	8.0	*21.3*	*-0.1*
2003	10.5	*25.9*	*-0.1*	8.6	*17.0*	*-0.1*	9.2	*20.3*	*-0.4*
2004	10.4	*24.5*	*-0.2*	8.9	*17.8*	*-0.2*	9.2	*20.4*	*-0.6*
2005	10.5	*22.6*	*-0.2*	9.0	*18.0*	*-0.2*	9.3	*20.0*	*-0.6*
2006	9.8	*25.3*	*-0.1*	8.8	*17.9*	*-0.2*	9.0	*20.3*	*-0.5*
2007	10.2	*20.4*	*-1.1*	9.5	*17.5*	*-0.1*	9.7	*19.3*	*-0.5*
2008	8.4	*21.4*	*-1.1*	8.7	*16.5*	*-0.1*	8.4	*17.9*	*-0.5*
2009	8.1	*21.6*	*-1.1*	8.8	*17.2*	*-0.1*	8.5	*18.6*	*-0.5*
2010	10.2	*24.2*	*-1.1*	9.4	*17.9*	*-0.1*	9.4	*18.7*	*-0.4*
2011	9.4	*29.4*	*-0.7*	9.0	*17.1*	*-0.2*	8.7	*21.5*	*-0.4*
2012	11.4	*26.2*	*0.2*	9.4	*17.1*	*-0.1*	9.6	*20.0*	*-0.2*
2013	*-- missing summer values --*			*-- missing summer values --*			7.4	*19.5*	*-0.5*
Statistics on the above values									
Mean	10.2	*25.0*	*-0.3*	9.0	*17.5*	*-0.1*	9.0	*20.1*	*-0.4*
Median	10.2	*25.9*	*-0.2*	9.0	*17.5*	*-0.1*	9.2	*20.3*	*-0.4*

(c) SPECIFIC CONDUCTANCE (µS)

	North Branch			South Branch			Main Stem		
	Median	*Maximum*	*Minimum*	Median	*Maximum*	*Minimum*	Median	*Maximum*	*Minimum*
1998	425	*576*	*343*	516	*654*	*395*	na	*na*	*na*
1999	446	*539*	*315*	530	*568*	*198*	489	*522*	*300*
2000	456	*516*	*300*	532	*571*	*208*	494	*568*	*344*
2001	430	*507*	*316*	525	*560*	*417*	484	*526*	*378*
2002	441	*512*	*300*	526	*576*	*171*	482	*547*	*256*
2003	431	*549*	*279*	525	*555*	*241*	492	*567*	*287*
2004	425	*561*	*318*	527	*586*	*335*	483	*543*	*342*
2005	433	*574*	*177*	535	*570*	*143*	496	*556*	*184*
2006	435	*527*	*307*	519	*569*	*407*	486	*548*	*338*
2007	449	*572*	*17*	509	*545*	*78*	491	*548*	*102*
2008	462	*551*	*300*	540	*585*	*369*	512	*564*	*395*
2009	464	*551*	*233*	540	*580*	*248*	515	*552*	*269*
2010	459	*557*	*239*	538	*583*	*369*	505	*566*	*335*
2011	457	*666*	*237*	564	*598*	*340*	533	*591*	*303*
2012	520	*1217*	*374*	593	*636*	*270*	566	*622*	*419*
2013	*-- missing summer values --*			*-- missing summer values --*			556	*629*	*461*
Statistics on the above values									
Mean	449	*598*	*270*	535	*582*	*279*	506	*563*	*314*
Median	446	*551*	*300*	530	*576*	*270*	494	*556*	*335*

Table 4. Annual mean flow, baseflow, and 7-day low flow for Valley Creek, and nearby precipitation, 1998-2013.

	Annual Mean Flow (cfs)			Annual Mean Baseflow (cfs)			Low Flow (cfs)	Annual Precipitation (inches)		
	North Branch	South Branch	Main Stem	North Branch	South Branch	Main Stem	Main Stem	Belwin Station	Washington County	MSP Int'l Airport
1998	8.86	10.29	*na*	8.24	9.50	*na*	*na*	33.00	34.31	33.39
1999	6.82	8.83	17.72	6.47	8.15	16.40	14.64	26.62	33.45	30.54
2000	5.82	10.28	17.16	5.51	9.48	15.05	12.56	28.60	32.01	30.48
2001	7.45	11.54	19.49	7.16	10.91	17.52	15.42	30.10	32.93	34.23
2002	7.47	11.07	21.08	7.09	10.33	18.85	16.51	35.60	40.32	38.45
2003	7.72	8.87	20.76	7.27	8.55	18.42	16.07	25.69	26.14	22.73
2004	5.79	8.30	16.89	5.27	8.00	15.19	13.22	25.99	32.57	27.39
2005	4.53	9.87	15.32	4.06	8.96	13.03	11.20	30.06	36.31	33.41
2006	5.25	7.90	16.76	4.79	7.70	14.56	12.23	28.77	27.88	27.57
2007	3.63	8.15	14.00	3.14	7.60	13.05	12.34	31.54	31.85	34.32
2008	3.18	7.04	12.79	2.72	6.97	12.54	12.00	24.93	27.18	22.38
2009	2.38	7.01	12.18	2.11	6.56	11.00	10.40	25.72	28.28	24.80
2010	2.86	7.11	12.45	2.59	6.99	11.51	10.40	36.40	37.17	32.89
2011	6.83	7.87	16.85	6.12	7.73	15.78	13.44	30.14	31.70	26.91
2012	4.95	8.17	15.23	4.62	8.02	13.93	13.32	22.95	29.98	29.59
2013	4.69	7.46	17.97	4.17	7.39	15.62	12.92	20.51	32.82	32.43
Avg	*5.51*	*8.74*	*16.44*	*5.08*	*8.30*	*14.83*	*13.11*	*28.54*	*32.18*	*30.09*

Notes: Annual mean flows calculated from hourly values. Baseflow calculated as the 7-day running minimum of hourly flows. Belwin weather station measures precipiation with an unheated tipping bucket rain gauge, which can underestimate intense rainfall rates and snow fall, thereby commonly underestimating annual totals by about 10%. Faulty rain-gauge function during 2012-13 appears to have caused substantial underestimation of actual rainfall totals at the Belwin station.

when most groundwater recharge is thought to occur. The main-stem low flows are sustained mostly by flow from the spring-fed South Branch, whose increasing baseflows over the last few years is evidence of the positive impact of wet springs on groundwater recharge. In 2013, the annual 7-day low flow actually dropped a small amount, occurring in early 2013 (4 March) before spring snowmelt and rains brought flows back above average.

Temperature and specific conductance

Temperature (Table 3b and Figures 5c, 6c, and 7c) is a critical variable in trout habitat, and the large baseflow component in Valley Creek tends to keep the water temperature in the range favored by trout (about 5-20° C). The spring-fed South Branch virtually never exceeds 20° C, whereas the lake-fed North Branch regularly exceeds 20° C during the summer, depending on how much of its flow is composed of warm lake water from Lake Edith. When Lake Edith outflow drops and reduces flow in the North Branch, then temperatures remain low, as during 2007-09 when temperatures only exceeded 20° C for less than 1% of the time. Temperatures increased as flows picked up during 2010-11, and the North Branch exceeded 20° C for 2% of the time in 2010 and all the way up to 20% of the time in 2011. In fact, the largest maximum temperature yet measured on the creek since 1998 was 29.4° C on 18 July 2011. But flows in the North Branch again declined during 2012, and percent time that temperatures exceeded 20° C dropped to 13%. During 2013, equipment failures resulted in unreliable temperature values during most of the summer for both the North and South branches, and hence annual means were not representative, being biased by the cold-weather values.

In the main stem, temperatures are driven by the mixture of flows from the South Branch, the North Branch, and other groundwater discharge along the channel. Generally, temperatures only exceed 20° C for a few hours in the years when Lake Edith outflow increases, e.g., for 0.2% of the time in 2011. Temperatures remained at or below 20° C during all of 2012-13.

The specific conductance of the water is a measure of its dissolved mineral content. The South Branch has a large specific conductance characteristic of groundwater, with its large mineral content. Because lake water can lose minerals by precipitation during the summertime, the North Branch has a lower specific conductance resulting from the influence of Lake Edith. The main stem has intermediate values from the mixing of the two branches (Table 3c). In general the annual pattern of specific conductance on the main stem (Figures 5d and 6d) shows higher values in the winter, and lower values in the summer when Lake Edith loses some mineral content and its outflow dilutes the stream. Dilute stormwater causes sharp, temporary drops in specific conductance during runoff events, which is evident in the figures as well. A number of large jumps in values during 2011-13 are probably not real and are likely due to probe instabilities. Data for much of May-July 2013 were discarded because of apparent data errors. These errors unfortunately add variability and decrease confidence in the data.

Trends in water quality, main stem, 1999-2012

Water quality is summarized here as annual median baseflow concentrations and annual loads of total suspended solids (TSS), total phosphorus (TP), and nitrate-nitrogen (NO3-N). Baseflow concentrations represent typical conditions in the creek, whereas loads capture all of the mass transported by the creek during both stormflow and baseflow conditions. Most data here are from the Metropolitan Council Environmental Services (MCES), based on samples collected at the main stem site (the WOMP station on Putnam Blvd). Water-quality data were not yet available for 2013 at the time this report was written.

Total Suspended Solids (TSS) -- Figure 8a: TSS concentrations (line, right axis) and loads (bars, left axis) remain generally low for Valley Creek. TSS tends to increase slightly during years with greater flow. Hence the low-flow years of 2008-10 have low TSS values, which increased during 2011 with increased flow. Loads dropped in 2012 in response to lower flows.

Total Phosphorus (TP) -- Figure 8b: TP follows essentially the same pattern as TSS, with larger values generally related to years with greater flows. Concentrations (line, right axis) and loads (bars, left axis) are similarly low compared to other creeks in the area (Almendinger 2003).

Nitrate-Nitrogen (NO3-N) -- Figure 8c: NO3-N is the most evident pollutant delivered by Valley Creek to downstream receiving waters (the St. Croix River). Concentrations (line, right axis) and loads (bars, left axis) are well above expected ambient levels and are derived from agricultural activity in the watershed that has contaminated the aquifer that feeds Valley Creek. The wetlands (Metcalf Marsh) that feed Lake Edith, and in-lake processes in Lake Edith, likely remove some NO3 via denitrification and algal uptake, and thus the North Branch tends to have lower NO3 values than the South Branch, which receives spring discharge directly (see Almendinger et al. 1999). The main stem (Figure 8c) has NO3 concentrations intermediate between the two branches. In general, years with lower flow correspond to higher concentrations because of less influence of Lake Edith outflow, and more influence of the higher-concentration South Branch. NO3 and total nitrogen (TN) concentrations in the South Branch have increased over the 1998-2011 period by about 1 mg/L (data not shown -- in SCWRS files), which further influences the concentrations at the main stem site. These concentration trends may reflect decades-old patterns of agricultural pollution that is gradually migrating through the aquifer.

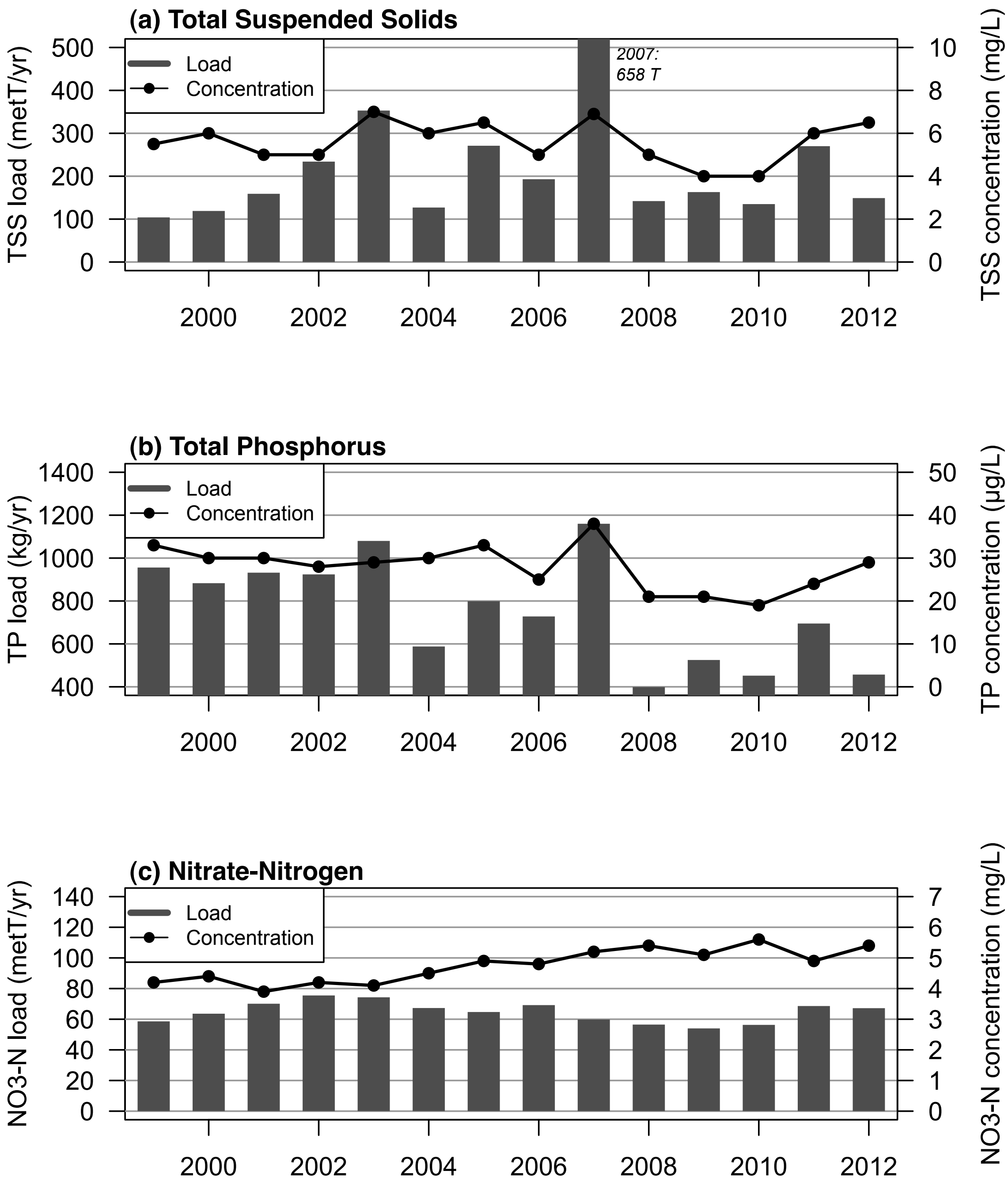


Figure 8. Annual loads and median baseflow concentrations for (a) total suspended solids (TSS), (b) total phosphorus (TP), and (c) nitrate-nitrogen (NO3-N) for Valley Creek, 1999-2012.

Load data from MCES using FLUX model; concentration data from MCES and SCWRS.

Results and Discussion II: Relation of Flow to Weather and Pumping

The health of Valley Creek as a trout stream depends on its strong baseflow component driven by groundwater discharge in its headwater springs and elsewhere along its channel. Baseflow could be negatively impacted by municipal well pumping. In particular, wells 15 and 16 in the Woodbury East wellfield extract water from the same interconnected aquifer system that feeds the baseflow of Valley Creek. The purpose of this analysis was to search for the possible impact of municipal well pumping on flow in Valley Creek.

The conceptual basis of the analysis assumes connectivity between weather-driven inputs of precipitation across the watershed surface, groundwater recharge to the aquifer system, and groundwater discharge to Valley Creek. Year-to-year variability in the precipitation inputs can cause substantial variability in groundwater discharge that constitutes the baseflow of Valley Creek, although time lags within the groundwater flow system greatly smooth the baseflow response to precipitation variability. Groundwater pumping by municipal wells can short-circuit the connectivity by removing groundwater that otherwise would have contributed to the baseflow of the creek. Can municipal well pumping be identified as a separate influence on baseflow, over and above any influence of weather-related variability? To answer this question, datasets were compiled on precipitation, baseflows, and water levels for Valley Creek and selected other features that may offer relevant comparisons or serve as reference systems for Valley Creek. Multiple regression analysis was used to relate flow or water level (dependent y variables) as functions of precipitation and pumping (independent x variables).

Data Compilation

Annual data compilation

The annual median flow of the main stem of Valley Creek from 1976-2013 was selected as the principal dependent (y) variable to be modeled at the annual time scale (Table 3; Figure 9a). Baseflows perhaps would have been preferable, but their calculation requires continuous (daily or more frequent) monitoring data, which was not available until 1999. However, because runoff events are short-lived in Valley Creek, annual baseflow may be reasonably represented by annual median flow, which is uninfluenced by extreme events and was easily calculable from existing data. Median flows were low during the 2007-10 period, similar to low flows during the mid-1970s and late 1980s, but have rebounded recently during the 2011-13 period (Figure 9a). Of the three monitoring sites on Valley Creek, only the main stem site at the Putnam bridge has a long enough record (about 38 years) for data analysis of annual values. The North Branch and South Branch records begin in only 1998–99, with therefore only 15–16 years of record.

The annual independent (x) variables chosen to represent the influence of weather (climate) were the annual average precipitation totals for Washington County and annual median flows in the Apple River (Figure 9b and c). Because baseflows in creeks are related to water levels in aquifers which are recharged over broad areas, a countywide average precipitation may be more representative of the general influence of weather on the creek flow, rather than precipitation measured locally at only a few stations. Previous reports had used the Palmer Hydrologic Drought Index (PHDI) rather than simple precipitation totals in an attempt to account for year-to-year storage in the watersheds and other factors causing time lags in response. However, the regression models used here in this report already allow for time lags, and the use of precipitation as the independent variable gave similar results as the use of PHDI. Further, the PHDI is a complicated variable whose construction is not fully explained by the National

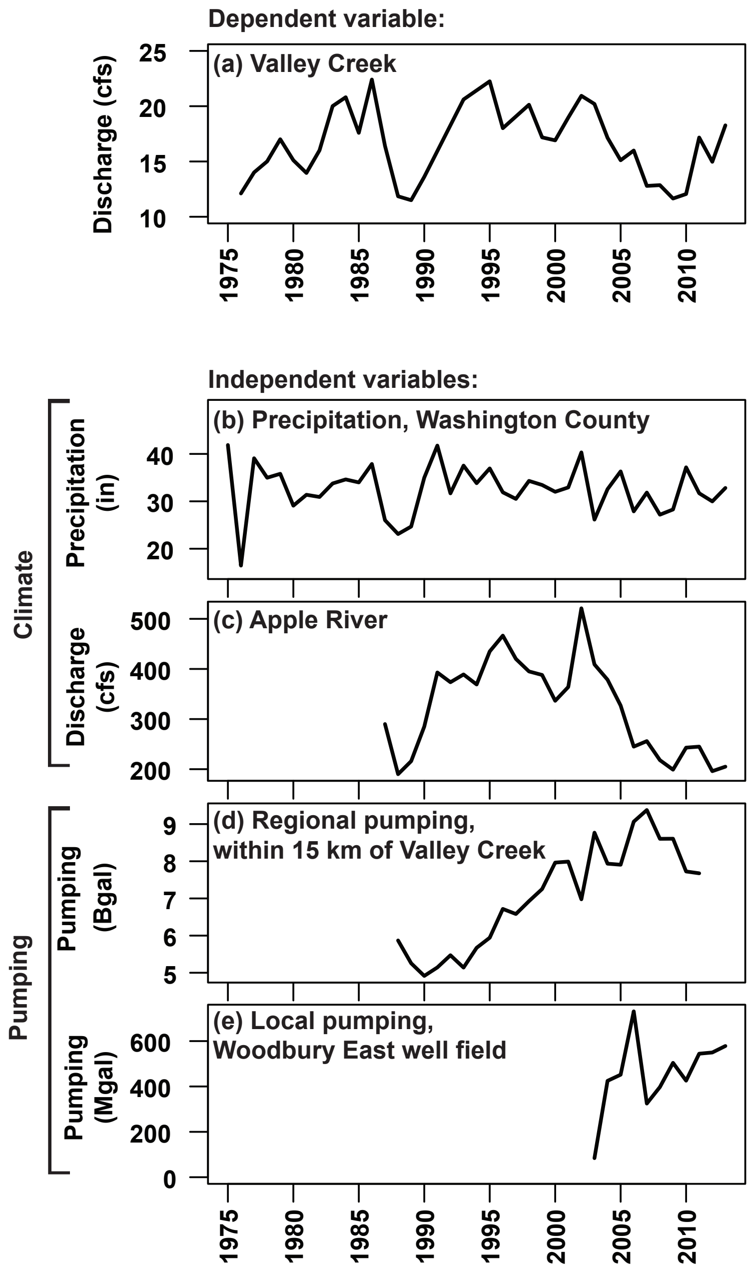


Figure 9. Annual dependent and independent data sets selected for analysis of Valley Creek flows.

Climatic Data Center. Hence the use of PHDI was abandoned in favor of the simpler and more robust countywide precipitation totals.

An alternative measure of climatic or weather-caused variability would be a record from a reference system, i.e., hydrologic data from a system responding purely (or nearly so) to weather variability in the absence of interference from human activities. The flows in the Apple River in western Wisconsin may provide such a measure. As at Valley Creek, annual median flow was chosen as the statistic to represent flow in the Apple River (Table 2). In general, the pattern of annual Apple River flows is broadly similar to the flows in Valley Creek, with low values in the late 1980s and again in the late 2000s. However, Apple River flows have not rebounded to the same degree as those in Valley Creek during the last three years (Figure 9a and c). To investigate the relation between Apple River flow and weather, daily precipitation values from the weather station in Amery, WI, were aggregated into monthly and annual totals.

Annual pumping was calculated at both regional and local scales. Regional annual pumping (1988-2011) was defined as the annual total from all permitted wells within a 15-km radius of Valley Creek, specifically from the centroid of the perennial reaches of the creek (Figures 3 and 9d). As noted earlier, these wells extract about 2.4 times as much groundwater from the aquifer as does Valley Creek. Regional pumping peaked in 2007 and has declined 18% as of 2011 (data were not yet posted for 2012-13). Local annual pumping was defined as the annual total pumping of the two wells in the Woodbury East well field (Figure 9e). These two wells are significant contributors to Woodbury's pumping, accounting for 16% of its total and 5% of all pumping within 15 km of Valley Creek (averaged over 2007-11).

Monthly data compilation

The three principal monthly data sets chosen as dependent variables were the monthly average baseflows for the three stations on Valley Creek, namely, the main stem, North Branch, and South Branch Figure 10 a, b, and c). Data were available through 2013 for the main stem, and through 2012 for the two branches. Baseflow is the component of flow most likely to be directly related to groundwater discharge in the creek, and hence the most likely to be impacted by groundwater withdrawals. Baseflows can really only be calculated from continuous data sets with daily or more frequent flows known, commonly from automated stations, which were installed at Valley Creek in 1997-98. For Valley Creek, hourly baseflow was defined as the hourly running minimum of the previous seven days, which screened out all storm-runoff events and succeeding interflow. Hourly baseflows were then aggregated into monthly means. For the North Branch, temporary drops in flow due to beaver activity were filtered out by first calculating an hourly 4-day centered running median flow. There was a subtle rise in baseflow in the South Branch from 2010-12, with a peak in baseflow in the North Branch in late 2011. Baseflow in the North Branch increased again during 2013 but remained nearly flat in the South Branch. Baseflow in the main stem appears to have rebounded substantially during 2013, more so than in the two tributary branches.

A fourth monthly data set chosen as a dependent-variable was monthly mean water level in the Jordan aquifer at MW3 (monitor well #3) near the headwater springs feeding the South Branch (Table 2; Figures 2 and 10d). Because the Woodbury East wells tap the Jordan aquifer, the Jordan piezometer at MW3 would be more likely to register the influence from this pumping than either the water-table or Prairie-du-Chien piezometer at the same location. Water levels followed the same general trend as baseflow in the main stem, with a decline through the 2000s and rises during 2011 and 2013.

The two data sets chosen as the independent variable (*x*) representing monthly weather were based on countywide precipitation totals and Apple River flows, just as was done for the annual analysis (Table 2). Monthly precipitation totals (Figure 11a) were aggregated into running means of selected numbers of prior months to account for lags in system response. Commonly the aggregations were for yearly increments, i.e., the current year (mean precipitation for the prior 1-12 months), the previous year (mean precipitation for the prior 13-24 months), and so forth. Monthly flows in the Apple

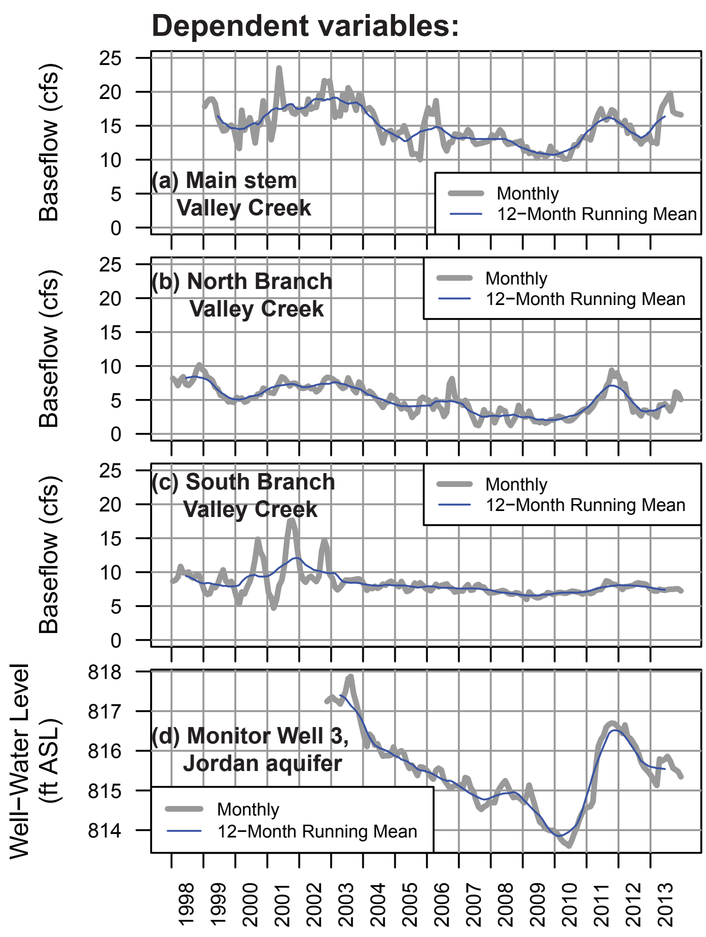


Figure 10. Monthly dependent data sets selected for analysis of Valley Creek flows.

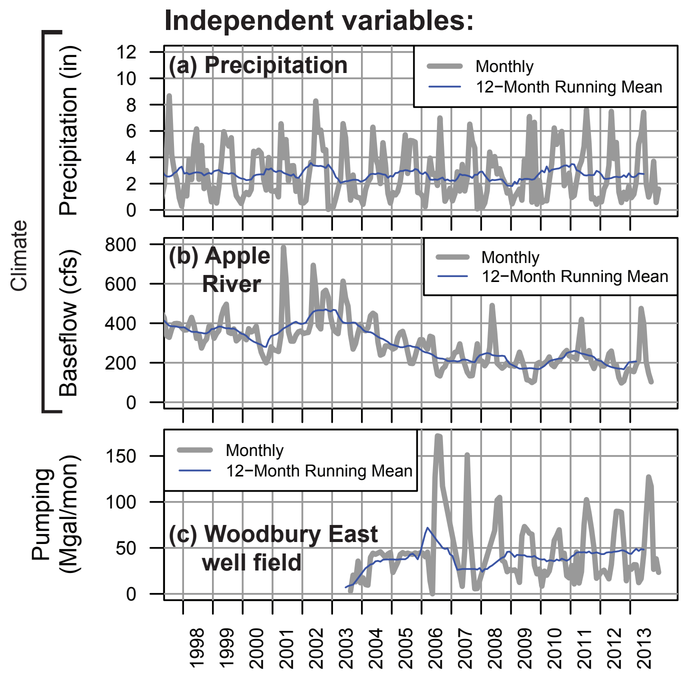


Figure 11. Monthly independent data sets selected for analysis of Valley Creek flows.

River (Figure 11b) were likewise aggregated into running means based on yearly increments. For the Apple River, baseflow was defined as the 30-day running minimum of the previous daily flows, in contrast to 7-day window used for the much smaller Valley Creek. Flow manipulation above the Apple gauging station for power generation resulted in anomalous (non-weather related) low flows which were first filtered out of the data set by taking 15-day centered running median flows prior to calculating baseflows.

The monthly independent-variable data set for local pumping was the monthly total from the two Woodbury East wells (Figure 11c). Twelve-month running mean values were calculated in order to be consistent with the target flow-data sets from Valley Creek. Pumping was rather steady as the wells were tested in 2004-05, with large seasonal variation in the years that followed. No monthly data set was compiled for regional pumping, because it seemed unlikely that regional pumping would have an influence that was distinct from, and larger than, that of local pumping at that relatively short time scale.

Precipitation data and groundwater recharge comments

Because of the relation between stream baseflow, aquifer water levels, and groundwater recharge, we assume that the baseflow record from any given stream is a convolved record of the time series of groundwater recharge in the watershed. Because of the importance of groundwater recharge in supplying water for both drinking water supplies as well as natural features such as trout streams, it would be good to know which weather patterns induce the most recharge. This relation would give managers a tool to predict groundwater recharge given recent weather patterns, or to predict future recharge under a changed climate.

Recharge is driven largely by precipitation as modified by losses to evapotranspiration. Patterns of surface runoff also play a role, as recharge is reduced when runoff is shunted out of the system into storm sewers and receiving streams, whereas recharge is enhanced when runoff is captured in depressions that allow infiltration. Nonetheless, one would think that changes in recharge from year to year would be driven largely by the balance between precipitation and evapotranspiration, and that recharge would be enhanced by precipitation falling in months when evapotranspiration is low, namely during the time of the year when leaf area is minimal, from about November to April or May.

Consequently, substantial effort was put into finding a seasonally weighted measure of precipitation, giving greater weight to precipitation during the low-evapotranspiration months, that would correlate significantly with records of baseflow in Valley Creek and the Apple River. That is, annual baseflows should be better explained by seasonally weighted annual total precipitation than to simple unweighted precipitation. Years with large winter and spring precipitation should allow more recharge than years where the precipitation fell in July and August, when plants transpire available soil moisture and little percolates below the soil zone. Nonetheless, no seasonally weighted precipitation scheme gave a better fit than simple unweighted precipitation totals. There may still be an optimal weighting of seasonal precipitation, perhaps in combination with temperatures that determine frost depth in winter and evaporative intensity in summer, that is highly correlated to groundwater recharge, but it was not discovered here.

Apple River as a Reference Hydrologic System

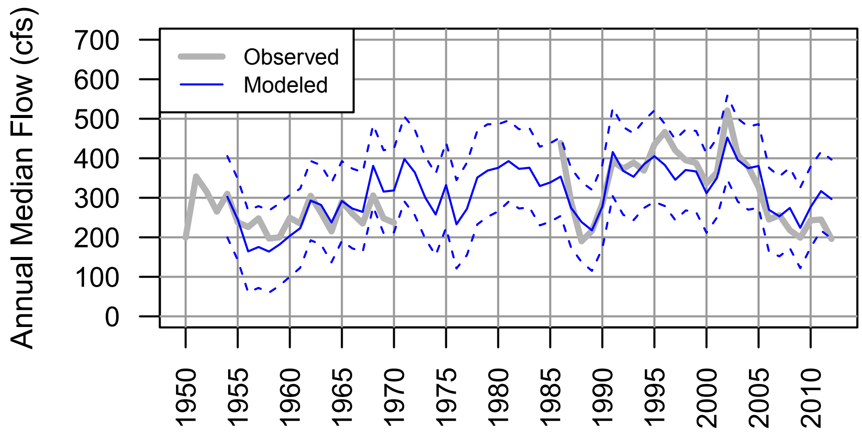
Although our main concern here is Valley Creek, the relation of Apple River flows to weather should be explored in order to justify the use of the Apple River as a reference hydrologic system for comparison with Valley Creek. Consequently Apple River flows were fit to both annual and monthly precipitation values at Amery, WI, which lies near the center of the watershed and has a precipitation record extending back to at least 1950.

Annual median flows were fit to annual total precipitation lagged by up to four years with an R^2 value of 0.72, indicating that 72% of the variance was explained by the regression model (Figure 12). Annual median flows were chosen as the dependent (y) variable as a reasonable surrogate for baseflow and to be consistent with data from Valley Creek. Significant coefficients were attained for annual precipitation totals lagged by up to four prior years, indicating that median flows in any one year were a result of precipitation from five years (that year plus the prior four). The model was fit to a long time series based on the 1950-2013 precipitation record and the 1914-2012 flow record. Note the gap in observed flows from 1970-86.

Twelve-month running mean baseflow was fit to 12-month running monthly total precipitation lagged by up to eight years with an R^2 of 0.85 (Figure 13). This model was fit based on just the Apple flow data set since 1987 to avoid the missing data from 1986 and before, and to remain relatively consistent with monthly data set from Valley Creek, which extends back to only 1998.

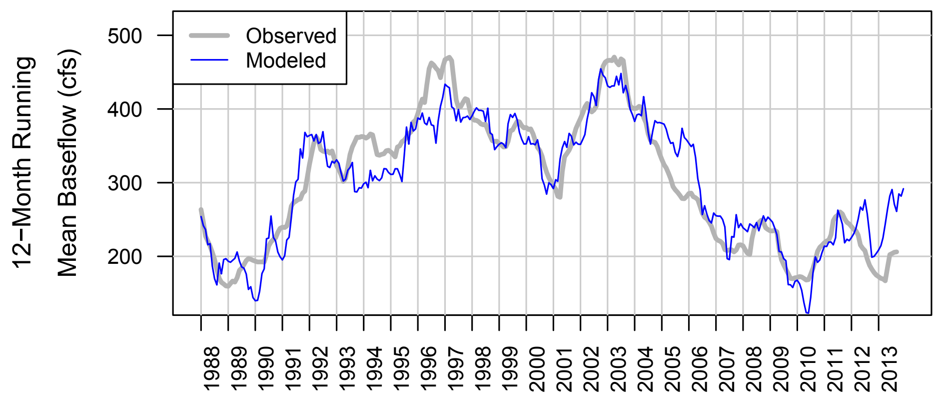
Both the annual and monthly regressions showed a strong relationship between Apple River flow and precipitation. Reasons were unclear as to why the monthly regression needed more lagged years (nine total) than the annual regression (five total). Both models suffered from serious autocorrelation, and so significance of parameters was overestimated. Both models also showed a consistent progression of coefficient values, which generally got smaller as the lag got larger, which indicated that flow was more related to recent precipitation than to precipitation in distant earlier years, as one might expect. Finally, both models also showed a deviation from observed values in the last two or three years, with observed flows below model predicted flows.

In short, the Apple River appears to be well-related to precipitation and could thus serve as a good reference system for other flow or water-level records. The deviation of observed flows below modeled flows during recent years is cause for concern that human activities may be impacting the system since about 2011, at least in ways different than before, although it seems just as likely that the deviations are due simply to model error.




```
Dependent variable =
Apple River annual median flow (Qmed_apple)

Independent variables =
Amery WI annual precipitation totals, lagged by 0 to 4 years
(PCP_am_L0 to 4)

Residuals:
     Min       1Q   Median       3Q      Max
-100.724  -24.588    4.463   24.711   84.869

Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -496.914     86.265  -5.760 1.21e-06 ***
PCP_am_L0      7.340      1.272   5.769 1.18e-06 ***
PCP_am_L1      7.050      1.262   5.585 2.11e-06 ***
PCP_am_L2      4.162      1.264   3.293  0.00215 **
PCP_am_L3      4.358      1.332   3.272  0.00228 **
PCP_am_L4      3.097      1.344   2.303  0.02682 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 48.02 on 38 degrees of freedom
  (19 observations deleted due to missingness)
Multiple R-squared:  0.7221,  Adjusted R-squared:  0.6856
F-statistic: 19.75 on 5 and 38 DF,  p-value: 1.171e-09

------------------------------------------------
Durbin-Watson test for autocorrelation
DW = 0.9445, p-value = 0.000109
Autocorrelation significant.
```

Figure 12. Apple River annual median flow as a function of annual precipitation at Amery, WI.




```
Dependent variable =
Apple River monthly baseflow, 12-month running mean (Qbase_apple_rm12)

Independent variables =
Amery WI monthly precipitation totals, 12-month running means,
lagged by 0 to 9 years
(P1t12, P13t24, P25t36, ..., where P1t12 indicates the average
precipitation from previous months 1 to 12, P13t24 indicates the average
precipitation from previous months 13 to 24, and so forth)

Residuals:
    Min      1Q  Median      3Q     Max
-95.257 -20.628   3.695  20.976 101.753

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -1215.300     46.632 -26.061  < 2e-16 ***
P1t12          96.968      4.400  22.041  < 2e-16 ***
P13t24        108.916      4.206  25.897  < 2e-16 ***
P25t36         87.207      4.270  20.421  < 2e-16 ***
P37t48         76.708      4.283  17.911  < 2e-16 ***
P49t60         68.245      4.475  15.250  < 2e-16 ***
P61t72         41.956      4.501   9.320  < 2e-16 ***
P73t84         56.409      4.498  12.541  < 2e-16 ***
P85t96         19.209      4.680   4.104 5.23e-05 ***
P97t108        13.599      4.829   2.816  0.00518 **
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 34.26 on 299 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.8546,  Adjusted R-squared:  0.8502
F-statistic: 195.2 on 9 and 299 DF,  p-value: < 2.2e-16

       Durbin-Watson test
data:  myMod1
DW = 0.1973, p-value < 2.2e-16
alternative hypothesis: true autocorrelation is greater than 0
```

Figure 13. Apple River 12-month running average baseflow as a function of 12-month running average monthly precipitation at Amery, WI.

Valley Creek Main Stem

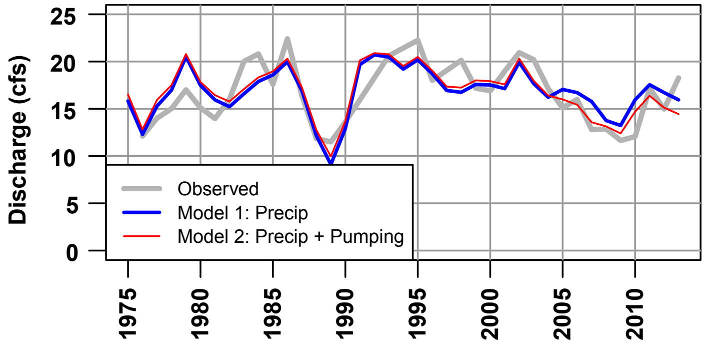
Valley Creek main stem flow was investigated with regard to both annual (Figure 9) and monthly (Figures 10-11) data sets. For the annual data sets (1975-2013), median annual flow was well explained by annual precipitation, lagged by up to 2 prior years, with an R^2 value of 0.61 (Figure 14: model 1, blue line). Adding regional pumping to the equation improved the fit to an R^2 of 0.75, but reduced the number of degrees of freedom (DFs) from 31 to 18 resulting in a model that was "overfit" and quantitatively unreliable. Nonetheless, the model qualitatively supported the hypothesis that regional pumping has reduced stream flow. When local pumping at the Woodbury East well field was lagged by one year and added to the model, the R^2 value increased to 0.68 (Figure 14: model 2, red line). The resulting coefficient (-0.0037 cfs / Mgal) times the average annual pumping since 2010 (506 Mgal/yr) suggested that the pumping has reduced the annual median flows in Valley Creek by 1.87 cfs. This value seems large compared to the pumping of the two wells (#15 and 16) in Woodbury's East well field (about 2.14 cfs) but could be an aggregate effect when combined with other pumping in the area. The value of the coefficient is uncertain and its statistical significance is questionable given some minor autocorrelation. However, it provides some evidence of a small impact on the flow in the creek as a result of pumping.

Annual median flows were also fit to those for the Apple River, without any lags being required (Figure 15). The fit was moderately good ($R^2 = 0.66$), but the modeled flows diverged from observed flows especially since 2010. Apparently the Apple River has not rebounded from its late 2000s low flows to the same degree that Valley Creek has. Adding pumping to the regression model did not improve the fit.

For the monthly data sets (1999-2013), the 12-month running mean of monthly baseflow was fit to 12-month running means of monthly precipitation, lagged back to 60 months (5 years) (Figure 16). The running means smooth both the input (precipitation) and output (baseflow) data sets, thereby avoiding large seasonal signals that add variability that would be difficult to match via regression analysis. The model fit the data rather well ($R^2 = 0.69$; Figure 16: model 1, blue line) and the fit improved when pumping from Woodbury East was added ($R^2 = 0.76$; Figure 16: model 2, red line). The coefficient of the pumping parameter (-0.036 cfs / Mgal) and average monthly pumping since 2010 (42.5 Mgal/mon) suggested a reduction of 1.52 cfs as a result of the pumping. Again, the coefficient value is uncertain and its significance is likely overestimated by autocorrelation. Still, the calculated flow reduction was similar to that calculated from the annual data analysis and added further evidence of impact on the creek.

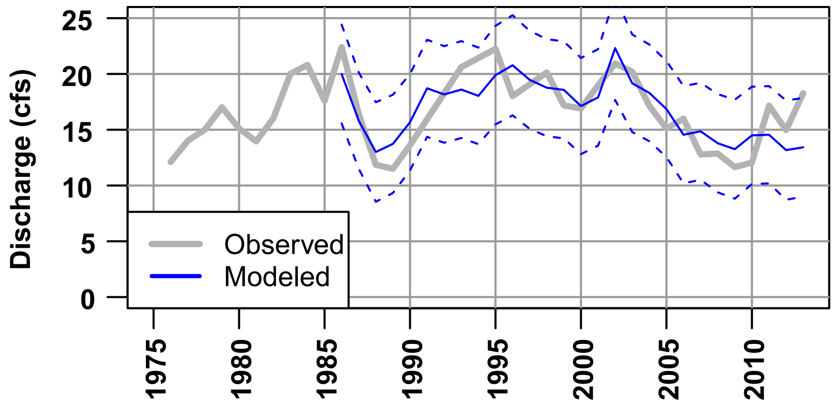
Monthly baseflows (12-month running averages) were also fit to those at the Apple River, with no lags required and with a good R^2 value of 0.75 (Figure 17). However, the fit was worst during the last four years, given that the flow in Valley Creek has rebounded proportionally more than in the Apple River. It may be that the smaller Valley Creek responds on a faster time scale than does the Apple River, and hence data from Valley Creek itself needs to be lagged or smoothed over a longer time window to better match flows in the Apple. Adding pumping from the Woodbury East well field to the regression equation did not improve the statistical fit.

Taken together, the regressions of flow in the main stem of Valley Creek show good relations with precipitation, at both annual and monthly scales. The flow relations between Valley Creek and the Apple River were significant, but have diverged in recent years. The regressions of flow on precipitation were improved by adding pumping from the Woodbury East well field as a variable, suggesting an impact from these wells on the creek on the order of 1.5 to 1.9 cfs, although these values seem large relative to the pumping rate in the well field of about 2.1 cfs over the past four years. The data are at least qualitatively consistent in indicating a slight impact on the creek. Nonetheless, in all four models shown, the observed flow in the creek was above model estimates, and the suggested impact is within the 95% prediction intervals in the regression models, plus or minus about 4.2 cfs in the annual model and 2.3 cfs in the monthly model.



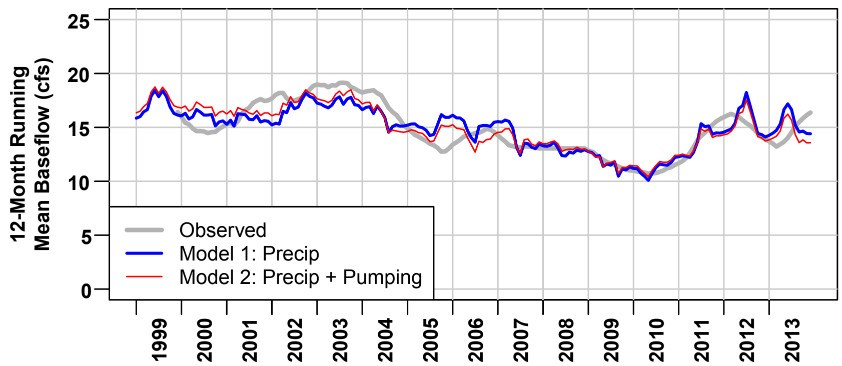

```
Dependent variable =
Valley Creek main stem annual median flow (Qmed_vc_ms)

Independent variables =
Model 1:
Washington County annual precipitation totals,
lagged by 0 to 2 years (PCP_L0 to 2)
Model 2:
As above, plus Woodbury East annual total pumping (Mgal),
lagged by 1 year (PMPWeL1)

------------------------------------------------
Model 1

Residuals:
    Min      1Q  Median      3Q     Max
-3.8974 -1.4285 -0.3784  1.9512  3.4182

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -14.35469    4.47390  -3.209  0.00310 **
PCP_L0        0.37059    0.07591   4.882 3.01e-05 ***
PCP_L1        0.38052    0.07485   5.084 1.69e-05 ***
PCP_L2        0.21243    0.06809   3.120  0.00389 **
---
Residual standard error: 2.087 on 31 degrees of freedom
  (4 observations deleted due to missingness)
Multiple R-squared:  0.6137,  Adjusted R-squared:  0.5763
F-statistic: 16.41 on 3 and 31 DF,  p-value: 1.439e-06

       Durbin-Watson test
DW = 1.254, p-value = 0.01296

------------------------------------------------
Model 2
Residuals:
    Min      1Q  Median      3Q     Max
-3.7790 -0.9595 -0.1578  1.4656  3.8250

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
(Intercept) -12.322400   4.242884  -2.904  0.00685 **
PCP_L0        0.362990   0.070639   5.139 1.57e-05 ***
PCP_L1        0.355588   0.070337   5.055 1.99e-05 ***
PCP_L2        0.196324   0.063644   3.085  0.00435 **
PMPWeL1      -0.003697   0.001526  -2.423  0.02165 *
---
Residual standard error: 1.94 on 30 degrees of freedom
  (4 observations deleted due to missingness)
Multiple R-squared:  0.6769,  Adjusted R-squared:  0.6338
F-statistic: 15.71 on 4 and 30 DF,  p-value: 4.874e-07

       Durbin-Watson test
DW = 1.3107, p-value = 0.01298
```

Figure 14. Valley Creek main stem annual median flow as a function of Washington County annual precipitation and Woodbury East well-field pumping.



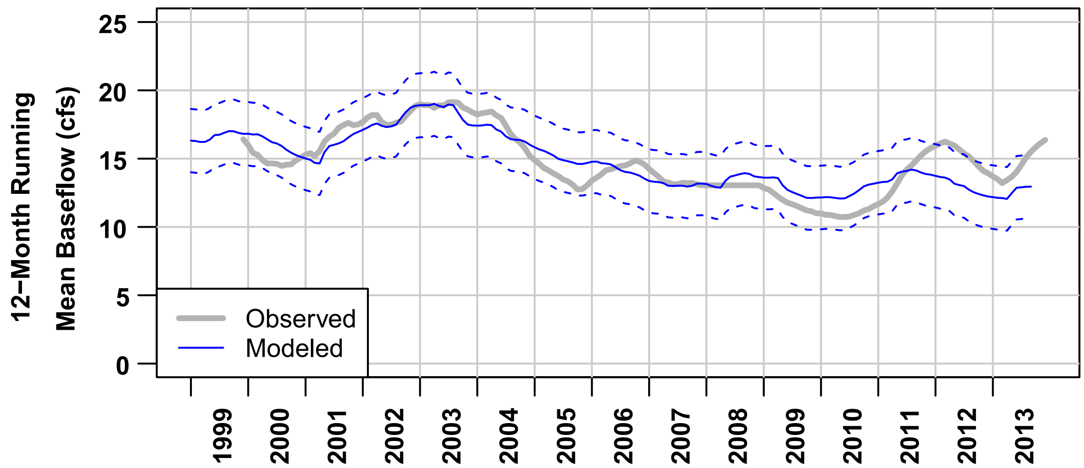

```
Dependent variable =
Valley Creek main stem annual median flow (Qmed_vc_ms)

Independent variables =
Apple River annual median flow (Qmed_apple)

------------------------------------------------
Regression summary:
Residuals:
    Min      1Q  Median      3Q     Max
-2.7689 -1.6055 -0.4013  1.4399  4.8425

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        7.660445   1.424267   5.379 1.83e-05 ***
Qmed_apple         0.028121   0.004234   6.641 8.94e-07 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.041 on 23 degrees of freedom
  (14 observations deleted due to missingness)
Multiple R-squared:  0.6572,  Adjusted R-squared:  0.6423
F-statistic:  44.1 on 1 and 23 DF,  p-value: 8.936e-07

       Durbin-Watson test
DW = 1.5365, p-value = 0.08716
```

Figure 15. Valley Creek main stem annual median flow as a function of Apple River annual median flow.




```
Dependent variable =
Valley Creek main stem monthly baseflow, 12-month running mean (Qbase_vcms_rm12)

Independent variables =
Model 1:
Washington County monthly precipitation totals, 12-month running means,
lagged by 0 to 5 years
(P1t12, P13t24, P25t36, ..., where P1t12 indicates the average
precipitation from previous months 1 to 12, P13t24 indicates the average
precipitation from previous months 13 to 24, and so forth)
Model 2:
As above, plus Woodbury East monthly total pumping (Mgal), 12-month running mean
------------------------------------------------
Model 1
Residuals:
    Min      1Q  Median      3Q     Max
-3.4430 -0.6998  0.0020  0.9304  2.8905
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -28.5182     2.4918 -11.445  < 2e-16 ***
P1t12         3.0796     0.2944  10.459  < 2e-16 ***
P13t24        4.9910     0.2989  16.700  < 2e-16 ***
P25t36        3.8106     0.3075  12.393  < 2e-16 ***
P37t48        2.5253     0.3215   7.855 5.09e-13 ***
P49t60        1.7535     0.3067   5.717 5.05e-08 ***
---
Residual standard error: 1.296 on 163 degrees of freedom
  (11 observations deleted due to missingness)
Multiple R-squared:  0.6949,  Adjusted R-squared:  0.6856
F-statistic: 74.26 on 5 and 163 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.2111, p-value < 2.2e-16

------------------------------------------------
Model 2
Residuals:
     Min       1Q   Median       3Q      Max
-2.69616 -0.65425 -0.06326  0.86414  2.79599
Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)    -18.108729   2.709221  -6.684 3.56e-10 ***
P1t12            2.417276   0.279862   8.637 5.20e-15 ***
P13t24           4.331076   0.283403  15.282  < 2e-16 ***
P25t36           2.988170   0.299759   9.969  < 2e-16 ***
P37t48           1.646197   0.314636   5.232 5.13e-07 ***
P49t60           1.260397   0.282396   4.463 1.51e-05 ***
PMP_weMon_1t12  -0.035743   0.005361  -6.667 3.90e-10 ***
---
Residual standard error: 1.151 on 162 degrees of freedom
  (11 observations deleted due to missingness)
Multiple R-squared:  0.7606,  Adjusted R-squared:  0.7517
F-statistic: 85.79 on 6 and 162 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.2155, p-value < 2.2e-16
```

Figure 16. Valley Creek main stem monthly average baseflow (12-month running average) as a function of Washington County monthly precipitation (12-month running averages).

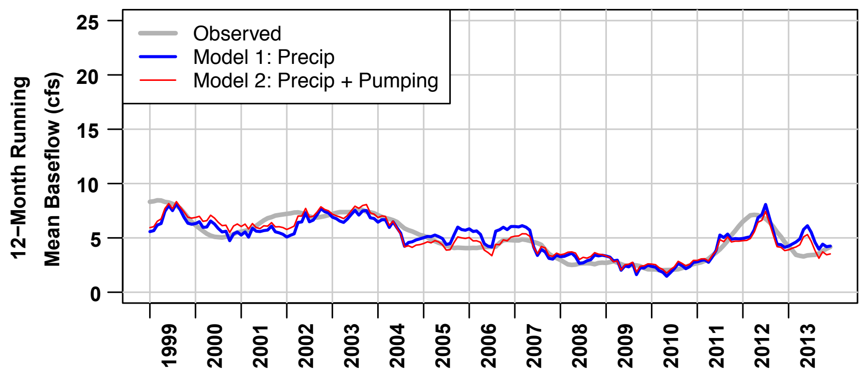



```
Dependent variable =
Valley Creek main stem monthly baseflow, 12-month running mean

Independent variable =
Apple River monthly baseflow, 12-month running mean; no lags needed
(BF_apple_mon_1t12)
------------------------------------------------
Regression summary:

Residuals:
     Min       1Q   Median       3Q      Max
-1.87724 -0.94007  0.04213  0.80134  2.79345

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       8.227685   0.307973   26.72   <2e-16 ***
BF_apple_mon_1t12 0.022939   0.001038   22.10   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.169 on 164 degrees of freedom
  (14 observations deleted due to missingness)
Multiple R-squared:  0.7486,  Adjusted R-squared:  0.7471
F-statistic: 488.4 on 1 and 164 DF,  p-value: < 2.2e-16

       Durbin-Watson test
DW = 0.0361, p-value < 2.2e-16
```

Figure 17. Valley Creek main stem monthly average baseflow (12-month running average) as a function of Apple River monthly average baseflow (12-month running average).

North Branch Valley Creek

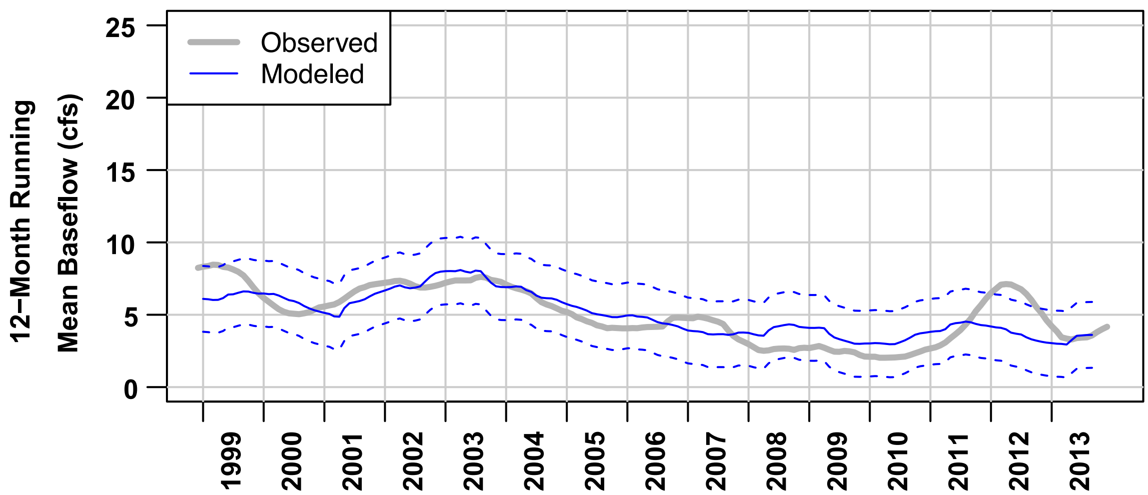
As for the main stem, the 12-month running mean baseflow for North Branch Valley Creek was fit against the 12-month running mean precipitation in Washington County, lagged back to 60 months, or five years (Figure 18). The fit to precipitation was quite good with an R^2 of 0.74. Adding the 12-month running mean of pumping from the Woodbury East well field improved the R^2 to 0.81. Autocorrelation may cause overestimation of the significance of the pumping coefficient, but at current pumping rates (2010-13), the coefficient indicated a possible baseflow reduction of about 1.3 cfs due to pumping.




```
Dependent variable =
North Branch Valley Creek monthly baseflow, 12-month running mean

Independent variables =
Model 1:
Washington County monthly precipitation totals, 12-month running means,
lagged by 0 to 5 years
(P1t12, P13t24, P25t36, ..., where P1t12 indicates the average
precipitation from previous months 1 to 12, P13t24 indicates the average
precipitation from previous months 13 to 24, and so forth)
Model 2:
As above, plus Woodbury East monthly total pumping (Mgal), 12-month running mean
------------------------------------------------
Model 1
Residuals:
     Min       1Q   Median       3Q      Max
-2.72920 -0.54796 -0.02623  0.50637  2.74282
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -29.3261     1.7315 -16.937  < 2e-16 ***
P1t12         2.4340     0.2116  11.500  < 2e-16 ***
P13t24        4.0300     0.2155  18.700  < 2e-16 ***
P25t36        2.7378     0.2206  12.411  < 2e-16 ***
P37t48        1.6065     0.2275   7.062 3.78e-11 ***
P49t60        1.9627     0.2171   9.042 2.94e-16 ***
---
Residual standard error: 0.9574 on 174 degrees of freedom
Multiple R-squared:  0.7421,  Adjusted R-squared:  0.7347
F-statistic: 100.2 on 5 and 174 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.2589, p-value < 2.2e-16

------------------------------------------------
Model 2
Residuals:
     Min       1Q   Median       3Q      Max
-1.91441 -0.49059 -0.09674  0.46113  2.37776
Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)    -19.842738   1.888862 -10.505  < 2e-16 ***
P1t12            1.827585   0.195830   9.333  < 2e-16 ***
P13t24           3.429463   0.198605  17.268  < 2e-16 ***
P25t36           1.994816   0.209770   9.510  < 2e-16 ***
P37t48           0.807666   0.218111   3.703 0.000286 ***
P49t60           1.474557   0.195083   7.559 2.28e-12 ***
PMP_weMon_1t12  -0.030201   0.003739  -8.078 1.08e-13 ***
---
Residual standard error: 0.8182 on 173 degrees of freedom
Multiple R-squared:  0.8128,  Adjusted R-squared:  0.8063
F-statistic: 125.2 on 6 and 173 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.2766, p-value < 2.2e-16
```

Figure 18. North Branch Valley Creek monthly average baseflow (12-month running average) as a function of Washington County monthly precipitation (12-month running averages) and Woodbury East well field pumping (12-month running average).

Likewise, the 12-month running mean baseflow for the North Branch was fit to the same variable for the Apple River, our presumed reference river (Figure 19). The fit was reasonable ($R^2 = 0.63$) but not as good as the fit based on precipitation. As for the same attempted fit on the main stem, the relation between flows in the North Branch and Apple tended to diverge over the past three years or so as flows in Valley Creek rebounded more than did those of the Apple River in response to increased available moisture. Adding pumping to the equation was non-significant.

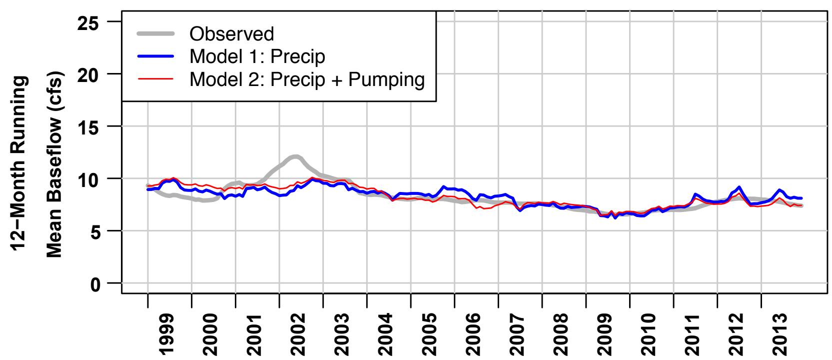



```
Dependent variable =
North Branch Valley Creek monthly average baseflow, 12-month running mean

Independent variables =
Apple River monthly average baseflow, 12-month running mean
(BF_apple_mon_1t12)
------------------------------------------------
Regression summary:
Residuals:
    Min      1Q  Median      3Q     Max
-1.7266 -0.8414 -0.3098  0.6146  3.3248

Coefficients:
                  Estimate Std. Error t value Pr(>|t|)
(Intercept)       0.1143008  0.2987758   0.383    0.703
BF_apple_mon_1t12 0.0169570  0.0009911  17.109   <2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 1.147 on 175 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.6258,  Adjusted R-squared:  0.6237
F-statistic: 292.7 on 1 and 175 DF,  p-value: < 2.2e-16

       Durbin-Watson test
DW = 0.0299, p-value < 2.2e-16
```

Figure 19. North Branch Valley Creek monthly average baseflow (12-month running average) as a function of Apple River monthly average baseflow (12-month running average).

South Branch Valley Creek

The 12-month running mean baseflow for South Branch Valley Creek was fit to the 12-month running mean precipitation for Washington County, again lagged up to 60 months (Figure 20). The statistical fit was reasonable ($R^2 = 0.49$) but not as good as at the main stem and North Branch, mostly because of differences between observed and modeled flows prior to about 2003. The observed flows at that time were likely not as accurate as later ones. Interestingly, all three sites on Valley Creek required lags in the precipitation values up to 60 months (5 years). Adding the 12-month running mean pumping from the Woodbury East well field further improved the fit to $R^2 = 0.63$, and the coefficient implied a baseflow reduction of about 1.2 cfs due to pumping at current rates (2010-13, 42.5 Mgal/mon).

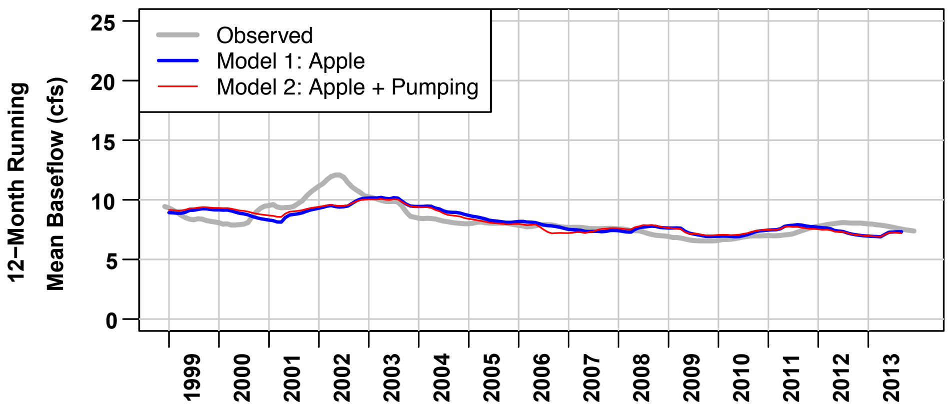



```
Dependent variable =
South Branch Valley Creek monthly baseflow, 12-month running mean

Independent variables =
Model 1:
Washington County monthly precipitation totals, 12-month running means,
lagged by 0 to 5 years
(P1t12, P13t24, P25t36, ..., where P1t12 indicates the average
precipitation from previous months 1 to 12, P13t24 indicates the average
precipitation from previous months 13 to 24, and so forth)
Model 2:
As above, plus Woodbury East monthly total pumping (Mgal), 12-month running mean
------------------------------------------------
Model 1
Residuals:
    Min      1Q  Median      3Q     Max
-1.4782 -0.5358 -0.1608  0.2867  3.2708
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) -12.2467     1.6319  -7.505 3.05e-12 ***
P1t12         1.6795     0.1995   8.420 1.35e-14 ***
P13t24        1.7914     0.2031   8.820 1.17e-15 ***
P25t36        1.6474     0.2079   7.923 2.64e-13 ***
P37t48        1.3913     0.2144   6.489 8.67e-10 ***
P49t60        1.1069     0.2046   5.411 2.05e-07 ***
---
Residual standard error: 0.9023 on 174 degrees of freedom
Multiple R-squared:  0.4898,  Adjusted R-squared:  0.4751
F-statistic:  33.4 on 5 and 174 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.1015, p-value < 2.2e-16

------------------------------------------------
Model 2
Residuals:
     Min       1Q   Median       3Q      Max
-1.64882 -0.35910 -0.05734  0.29481  2.73959
Coefficients:
                Estimate Std. Error t value Pr(>|t|)
(Intercept)    -3.320605   1.781113  -1.864 0.063968 .
P1t12           1.108712   0.184659   6.004 1.10e-08 ***
P13t24          1.226128   0.187276   6.547 6.43e-10 ***
P25t36          0.948069   0.197804   4.793 3.52e-06 ***
P37t48          0.639412   0.205669   3.109 0.002196 **
P49t60          0.647431   0.183955   3.520 0.000553 ***
PMP_weMon_1t12 -0.028427   0.003525  -8.063 1.18e-13 ***
---
Residual standard error: 0.7715 on 173 degrees of freedom
Multiple R-squared:  0.6291,  Adjusted R-squared:  0.6163
F-statistic: 48.91 on 6 and 173 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.0831, p-value < 2.2e-16
```

Figure 20. South Branch Valley Creek monthly average baseflow (12-month running average) as a function of Washington County monthly precipitation (12-month running averages) and Woodbury East well field pumping (12-month running average).

The regression fit to the 12-month running mean baseflow of the Apple River (Figure 21) also produced a reasonable fit with an $R^2 = 0.58$, and adding pumping slightly improved the fit to $R^2 = 0.60$, very similar to the pattern in the fit to precipitation. In this case, the baseflow reduction due to pumping was estimated at 0.7 cfs.

The baseflow in South Branch Valley Creek is perhaps the most important benchmark to be watched, since it provides the principal flow that sustains trout in the creek and is perhaps most likely to show an impact from the Woodbury East well field because of proximity. The modeled impact of pumping (1.2 cfs) is within the 95% prediction interval of 1.6 cfs, meaning that the possible effect of pumping is less than the expected error in the model. This does not mean that pumping is not having an effect; it demonstrates the difficulty of distinguishing the effect of pumping from error alone.

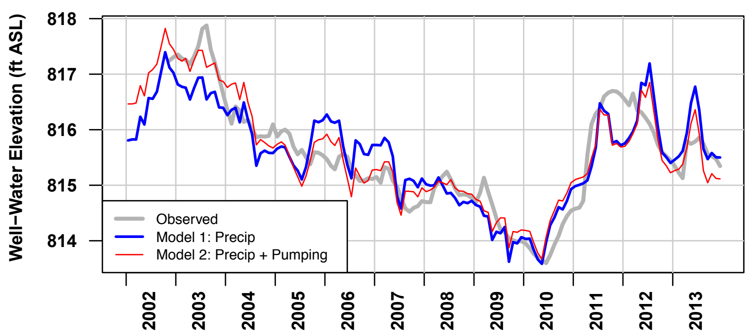



```
Dependent variable =
South Branch Valley Creek monthly average baseflow, 12-month running mean

Independent variables =
Model 1:
Apple River monthly average baseflow, 12-month running mean (BF_apple_mon_1t12)
Model 2:
As above, plus Woodbury East monthly total pumping (Mgal), 12-month running mean
------------------------------------------------
Model 1:
Residuals:
    Min      1Q  Median      3Q     Max
-1.1857 -0.5745 -0.1709  0.2926  2.6965
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)       5.0788187  0.2129017   23.86   <2e-16 ***
BF_apple_mon_1t12 0.0108916  0.0007063   15.42   <2e-16 ***
---
Residual standard error: 0.8174 on 175 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.5761,  Adjusted R-squared:  0.5737
F-statistic: 237.8 on 1 and 175 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.0345, p-value < 2.2e-16
------------------------------------------------
Model 2:
Residuals:
    Min      1Q  Median      3Q     Max
-1.3678 -0.5696 -0.1211  0.4428  2.6016
Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)        6.341527   0.438562  14.460  < 2e-16 ***
BF_apple_mon_1t12  0.007943   0.001135   7.000 5.33e-11 ***
PMP_weMon_1t12    -0.015936   0.004878  -3.267  0.00131 **
---
Residual standard error: 0.7957 on 174 degrees of freedom
  (3 observations deleted due to missingness)
Multiple R-squared:  0.6006,  Adjusted R-squared:  0.596
F-statistic: 130.8 on 2 and 174 DF,  p-value: < 2.2e-16
       Durbin-Watson test
DW = 0.0342, p-value < 2.2e-16
```

Figure 21. South Branch Valley Creek monthly average baseflow (12-month running average) as a function of Apple River monthly average baseflow (12-month running average).

Monitor Well MW3-Jordan

The water elevation in monitor well MW3-Jordan (Figure 2) was likewise fit to the 12-month running mean precipitation for Washington County, lagged back to 60 months (Figure 22). The well-water level itself already apparently smoothed its response to monthly weather, and so it was not smoothed further by taking running means. The model fit was quite good ($R^2 = 0.77$) and improved by adding a 24-month running mean of pumping from the Woodbury East well field ($R^2 = 0.86$). The 2010-13 24-month running mean pumping was 41.8 Mgal/mon and the coefficient of the pumping term in the regression model was 0.023 ft/Mgal. Multiplying these two values suggests that pumping reduced water levels in MW3-Jordan by about one foot (0.96 ft more exactly) during this time. This effect was the same as the 95% prediction interval (model error) of plus or minus 0.96 ft. In last year's report, a regression equation was developed to relate the water level in MW3 to baseflow in the South Branch: $Q_{bf,SB} = -426.24 + 0.532*H_{MW3-J}$. A 0.96-ft drop in water level, multiplied by the coefficient 0.532 cfs/ft, would then imply a 0.5 cfs drop in the baseflow of the South Branch due to pumping, based on the drop in MW3 water level.




```
Dependent variable =
Monitor well MW3-Jordan monthly mean water elevation in ft above mean sea level

Independent variables =
Model 1:
Washington County monthly precipitation totals, 12-month running means,
lagged by 0 to 5 years
(P1t12, P13t24, P25t36, ..., where P1t12 indicates the average
precipitation from previous months 1 to 12, P13t24 indicates the average
precipitation from previous months 13 to 24, and so forth)
Model 2:
As above, plus Woodbury East monthly total pumping (Mgal), 12-month running mean
-----------------------------------------------
Model 1
Residuals:
     Min       1Q   Median       3Q      Max
-1.08682 -0.40129  0.03322  0.30357  1.33177
Coefficients:
            Estimate Std. Error t value Pr(>|t|)
(Intercept) 798.8362     1.0346 772.084  < 2e-16 ***
P1t12         1.6237     0.1193  13.610  < 2e-16 ***
P13t24        2.1296     0.1161  18.335  < 2e-16 ***
P25t36        1.3235     0.1198  11.045  < 2e-16 ***
P37t48        0.7896     0.1290   6.120 1.06e-08 ***
P49t60        0.4055     0.1286   3.153  0.00201 **
---
Residual standard error: 0.4768 on 128 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.7688,  Adjusted R-squared:  0.7598
F-statistic: 85.15 on 5 and 128 DF,  p-value: < 2.2e-16
        Durbin-Watson test
DW = 0.3574, p-value < 2.2e-16

-----------------------------------------------
Model 2
Residuals:
     Min       1Q   Median       3Q      Max
-0.74444 -0.23854 -0.02505  0.23323  0.97810
Coefficients:
                 Estimate Std. Error t value Pr(>|t|)
(Intercept)    804.188965   1.015061 792.257  < 2e-16 ***
P1t12            1.372385   0.098287  13.963  < 2e-16 ***
P13t24           1.792031   0.099217  18.062  < 2e-16 ***
P25t36           0.923288   0.104737   8.815 7.73e-15 ***
P37t48           0.356343   0.112894   3.156    0.002 **
P49t60           0.096311   0.107272   0.898    0.371
PMP_weMon_1t24  -0.022924   0.002584  -8.870 5.70e-15 ***
---
Residual standard error: 0.3761 on 127 degrees of freedom
  (10 observations deleted due to missingness)
Multiple R-squared:  0.8573,  Adjusted R-squared:  0.8505
F-statistic: 127.1 on 6 and 127 DF,  p-value: < 2.2e-16
        Durbin-Watson test
DW = 0.4664, p-value < 2.2e-16
```

Figure 22. Monitor well MW3-Jordan monthly average water elevation as a function of Washington County monthly precipitation (12-month running averages) and Woodbury East well field pumping (12-month running average).

Addendum: White Bear Lake

Water levels in White Bear Lake were compiled as an alternative data set because they might be a good proxy for the combined effects of regional climate, urbanization, and pumping on the groundwater hydrology of the Washington County area. This signal could provide a regional context on which local factors might be superimposed in determining what factors affect flow in Valley Creek. This approach might be useful but was not pursued further because the regression analysis with precipitation and local pumping was a more direct way to explain flow variation in Valley Creek.

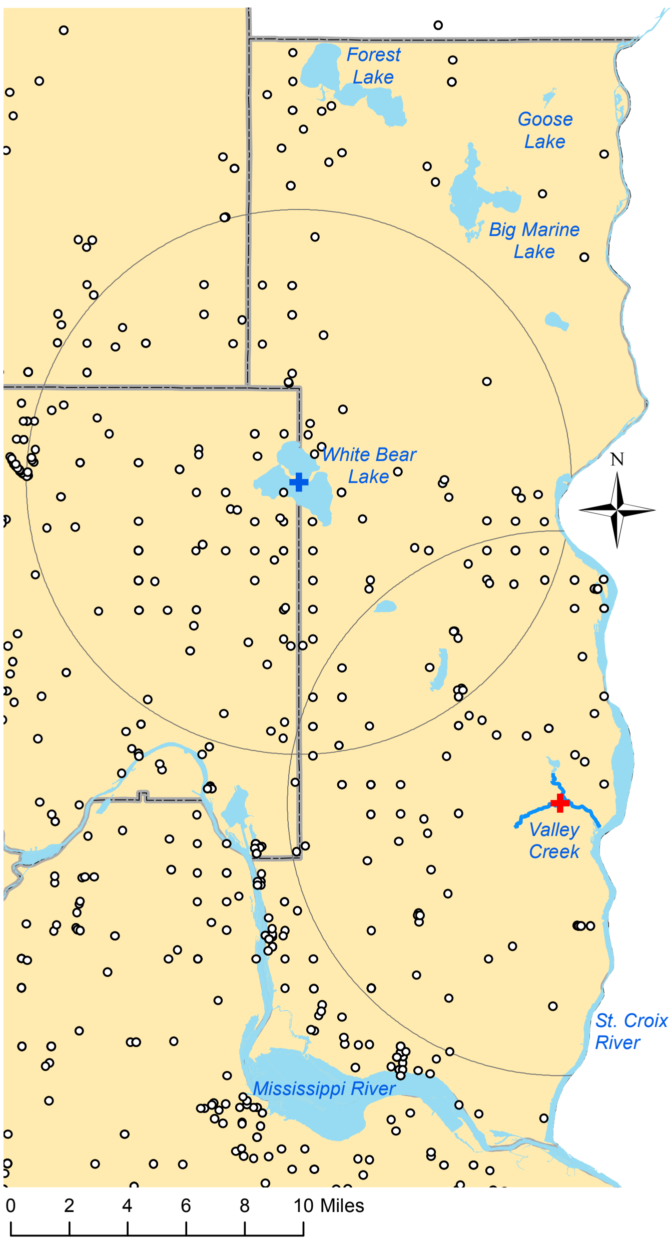


Figure 23. Eastern Twin Cities metropolitan area showing permitted (regulated) high-capacity wells and 15-km radii around White Bear Lake and Valley Creek.

Nonetheless, because of the recent interest in the levels of White Bear Lake, regressions were constructed relating lake level to selected independent variables, which was easily done because most of the relevant data sets had already been compiled for the analysis of Valley Creek. Figure 23 shows the region surrounding White Bear Lake with selected other lakes, and Figure 24 shows the dependent and independent variables used in the analysis. The annual average lake level for White Bear Lake (Figure 24a, gray line) was calculated as the simple unweighted arithmetic mean of lake-level readings posted by the MDNR on the web. For comparison, average annual levels of Goose Lake (Figure 24a, blue line), from northeastern Washington County (Figure 23), are plotted on the same graph, demonstrating that the changes in White Bear Lake were not unique but indicative of a larger regional pattern. Independent variables included countywide annual precipitation in Washington County, annual median flow of the Apple River, and permitted groundwater withdrawals within 15 km of the centroid of White Bear Lake (Figure 24b, c, and d). Of these records, only the Apple River flow has a visual similarity to White Bear Lake levels. There was substantial annual variability in the pumping record, swinging from 7.3 Bgal in 2002 up to nearly 10.8 Bgal in 2006 (Figure 24d), but without an obvious trend. This is in contrast to the findings of the USGS (Jones et al. 2013), who examined a longer record (1980 to 2007) for a smaller subset of wells closer to the lake, where they found an increase in pumping from 2.6 Bgal in 1980 to 6 Bgal in 2007. The cities of Shoreview, Oakdale, St. Paul, and White Bear Lake were the largest users of groundwater in the 15-km radius area (Table 5).

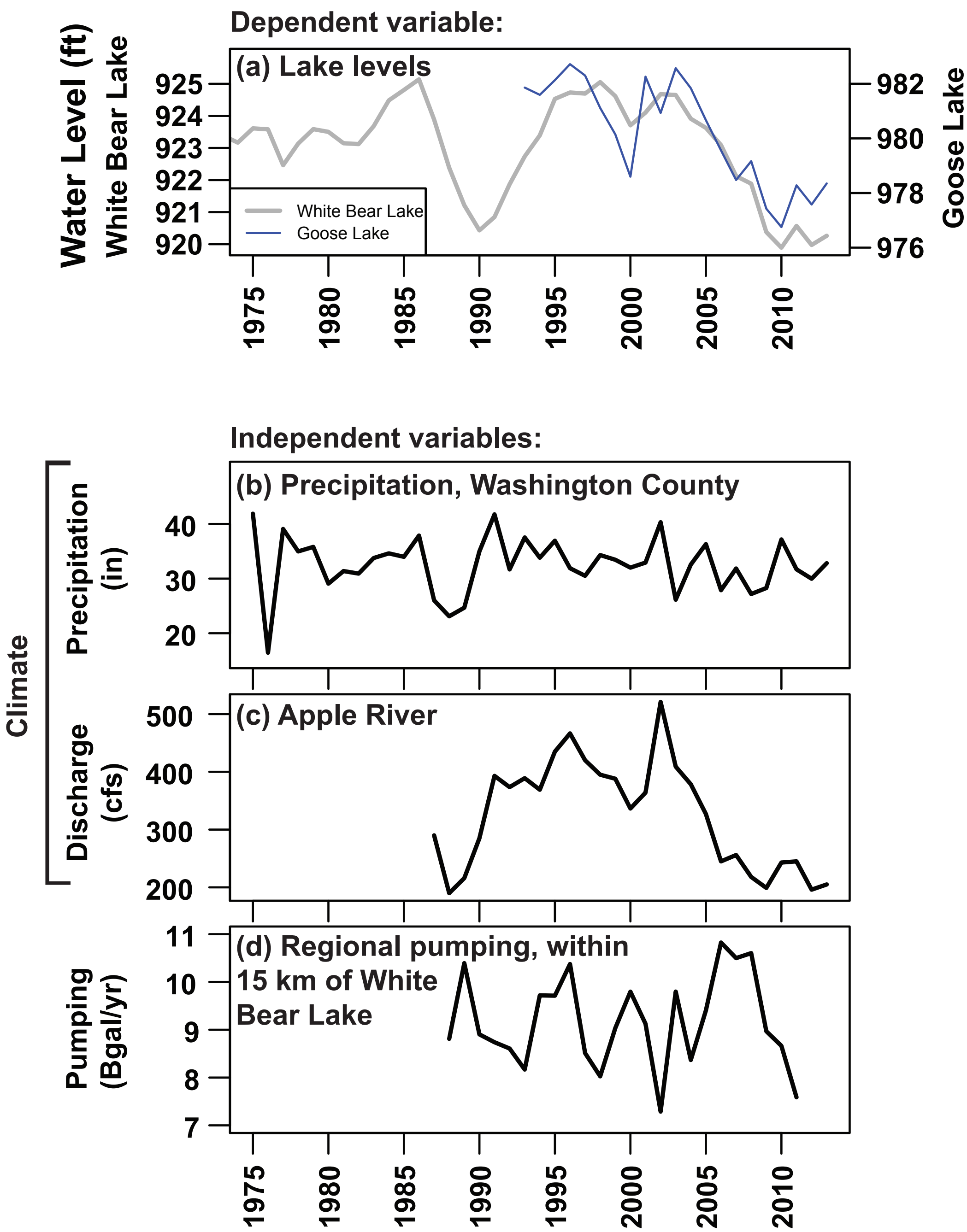


Figure 24. Annual dependent and independent data sets selected for analysis of White Bear Lake levels.

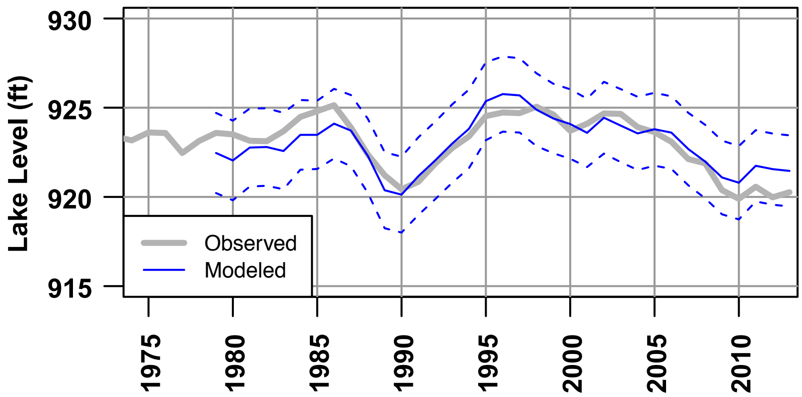
Table 5. Groundwater permittees within 15 km of White Bear Lake, ranked by average annual withdrawals, 2007-11.

Permittee	Mgal/yr	Percent
SHOREVIEW, CITY OF	1140	12.3%
OAKDALE, CITY OF	1009	10.9%
ST PAUL REGIONAL WATER SERVICES	992	10.7%
WHITE BEAR LAKE, CITY OF	962	10.4%
STILLWATER, CITY OF	759	8.2%
WHITE BEAR TOWNSHIP	563	6.1%
LINO LAKES, CITY OF	541	5.8%
VADNAIS HEIGHTS, CITY OF	528	5.7%
NORTH ST PAUL, CITY OF	457	4.9%
HUGO, CITY OF	375	4.1%
MAHTOMEDI, CITY OF	286	3.1%
OAK PARK HEIGHTS, CITY OF	235	2.5%
US ARMY	185	2.0%
All others (57 users, <2% each)	1233	13.3%
Total	***9264***	***100%***

NOTES: Distance was measured from the centroid of White Bear Lake.

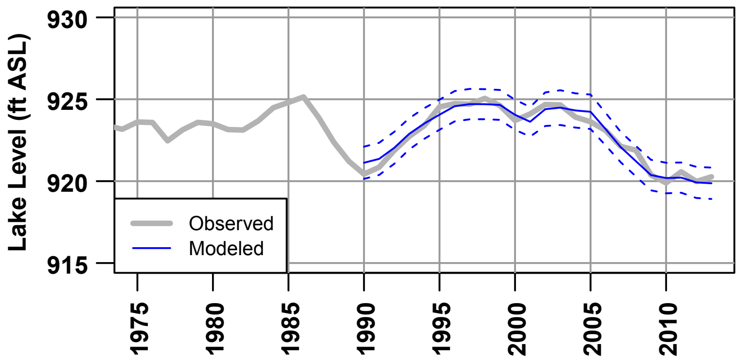
White Bear Lake levels were first fit to annual precipitation in Washington County, lagged by up to seven years (Figure 25), and the fit was quite good ($R^2 = 0.77$). The regression model tended to underestimate lake levels in the early part of the record, and overestimate levels near the end of the record, which is what would be expected to occur if pumping were continuously increasing during this time but not included directly in the model. However, even though pumping was not explicitly included here, it may still have an indirect effect, because Jones et al. (2013) demonstrated a relation between pumping and precipitation. Hence the effect of pumping may be hidden within the regression to precipitation alone.

However, this model has several inherent problems. First, there are too many model parameters given the few degrees of freedom (DFs), only about three DFs per parameter. This implies that the model is "overfit," meaning that the large number of parameters is artificially forcing a large R^2 value. For example, a linear regression with two parameters [slope and intercept] fit through two points would give a perfect statistical fit, but its significance cannot really be trusted from the perfect R^2 value. The "adjusted" R^2 value is supposed to account for this problem, but still the values given here seem large (adj $R^2 = 0.70$). The second problem is that the model has significant autocorrelation, implying that many of its data points are redundant and generating overestimated significance. Removing the redundant data points would further erode the available DFs of the model. Adding regional pumping (with a lag of one year) as an independent parameter did produce a significant coefficient, which, when applied to recent pumping rates, implied an effect of several feet of lake level due to pumping. However, adding yet another parameter to an already-overfit model is dangerous. In short, the model fit of White Bear Lake levels to precipitation and regional pumping is interesting, suggesting that the lake has a "memory" extending back at least seven years of previous weather inputs, and that pumping may have an effect. The coefficient values suggest that lake level is most sensitive to precipitation lagged by two years, with lessening influence by precipitation from earlier and later years. While these conclusions seem qualitatively sensible and useful from the standpoint of generating viable hypotheses, they should be regarded as quantitatively unreliable.




```
Dependent variable =
White Bear Lake level, annual average, in feet above mean
sea level (ft ASL)
Independent variables =
Washington County annual precipitation totals,
lagged by 0 to 7 years (PCP_L0 to 7)

-----------------------------------------------
Regression summary:
Residuals:
     Min       1Q   Median       3Q      Max
-1.58131 -0.53669  0.08179  0.44682  1.45992

Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) 885.08542    4.33273 204.279  < 2e-16 ***
PCP_L0        0.12129    0.03787   3.203 0.003579 **
PCP_L1        0.19923    0.03789   5.258 1.70e-05 ***
PCP_L2        0.20755    0.03802   5.459 1.00e-05 ***
PCP_L3        0.17592    0.03259   5.398 1.18e-05 ***
PCP_L4        0.17958    0.03185   5.638 6.29e-06 ***
PCP_L5        0.12423    0.03093   4.017 0.000447 ***
PCP_L6        0.09688    0.03080   3.146 0.004118 **
PCP_L7        0.06311    0.02963   2.130 0.042763 *
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Residual standard error: 0.8993 on 26 degrees of freedom
  (84 observations deleted due to missingness)
Multiple R-squared:  0.7735,  Adjusted R-squared:  0.7038
F-statistic:  11.1 on 8 and 26 DF,  p-value: 1.139e-06

       Durbin-Watson test
DW = 0.4099, p-value = 2.181e-08
```

Figure 25. White Bear Lake annual average lake level as a function of Washington County annual precipitation.




```
Dependent variable =
White Bear Lake level, annual average, in feet above mean
sea level (ft ASL)
Independent variables =
Apple River annual median flows,
lagged by 0 to 4 years (Qmed_apple_annLag0 to 4)

------------------------------------------------
Regression summary:
Residuals:
     Min       1Q   Median       3Q      Max
-0.69104 -0.19725  0.00034  0.30213  0.66629

Coefficients:
                    Estimate Std. Error  t value Pr(>|t|)
(Intercept)        9.147e+02  4.248e-01 2153.068  < 2e-16 ***
Qmed_apple_annLag0 5.909e-03  1.507e-03    3.921  0.00100 **
Qmed_apple_annLag1 5.886e-03  2.018e-03    2.917  0.00921 **
Qmed_apple_annLag2 4.246e-03  2.006e-03    2.117  0.04845 *
Qmed_apple_annLag3 5.118e-03  1.965e-03    2.604  0.01794 *
Qmed_apple_annLag4 2.736e-03  1.385e-03    1.976  0.06368 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1

Residual standard error: 0.4081 on 18 degrees of freedom
  (15 observations deleted due to missingness)
Multiple R-squared:  0.9604,  Adjusted R-squared:  0.9494
F-statistic: 87.35 on 5 and 18 DF,  p-value: 5.573e-12

        Durbin-Watson test
DW = 1.318, p-value = 0.02647
```

Figure 26. White Bear Lake annual average lake level as a function of Apple River annual median flow.

An alternative model was constructed by fitting annual White Bear Lake levels to the annual median flow of the Apple River, lagged by up to four years (Figure 26). The fit is excellent ($R^2 = 0.96$; adjusted $R^2 = 0.95$). This model is also overfit with six parameters and only 18 DFs, but both the overfitting and autocorrelation are less than in the regression fit to precipitation. The Apple River appears to be an excellent proxy for the White Bear Lake system, meaning that the hydrologic processes within the Apple River watershed respond similarly to variations in weather-related inputs as does the aquifer system supporting White Bear Lake levels. Adding regional pumping to the regression model did not improve the fit. Note that both Apple River flows (Figure 12) and White Bear Lake levels (Figure 25) were reasonably well-fit to precipitation alone, until about the last three years when flows and lake levels remained low while precipitation increased. Perhaps the Apple River is being impacted by irrigation pumping, which anecdotally has increased in recent years. In contrast, pumping within 15-km of White Bear Lake (Figure 24d) does not appear to have increased recently. In short, White Bear Lake levels and Apple River flow are well-correlated with each other, but the cause of their similar mismatch with recent precipitation may or may not be related to pumping, and may simply be due to model error.

Summary and Conclusions

Protecting Valley Creek as a valued trout habitat requires protecting baseflow and the water quality in the creek. Valley Creek is geographically vulnerable because of its position at the urbanizing fringe of the Twin Cities metropolitan area. Urbanization is known to generally impact both stream hydrology and water quality. Municipal well withdrawals from the same aquifer system feeding Valley Creek could reduce baseflow, resource managers in charge of regulating these withdrawals need to know if they are in fact impacting the creek. In particular, managers are concerned that two new municipal wells in the Woodbury East well field may be impacting the creek. However, interannual weather variability also affects aquifer water levels and baseflow, and these effects need to be accounted for before being able to identify residual effects due to pumping. Protection of Valley Creek hinges on an adequate data set that documents baseline conditions and allows changes to be identified. Hence the purpose of this report is two-fold: first, to maintain the data set that documents the stream's hydrology and water quality; and second, to examine this record to identify the factors that most impact stream hydrology, specifically baseflow in this case.

To maintain the current data set, this report first summarized recent data from 2011-13. High flows have been modest, but median and average flows of Valley Creek have rebounded to near average values, after low values during 2008-10. Temperatures remained in the range favored by trout (below 20° C) nearly all the time in the main stem and South Branch, but exceeded that temperature for up to 20% of the year (2011) in the North Branch. Both suspended sediment and total phosphorus are low in Valley Creek relative to most streams in the lower St. Croix basin, but nitrate concentrations are large, between 5-6 mg/L NO3-N in the main stem, and these concentrations have increased since about 2001. This increase could be the result of decades-old patterns of agricultural pollution that is gradually migrating through the aquifer and reaching the creek.

In examining the flow records to identify factors impacting hydrology, a significant effort was made to relate flow in Valley Creek to weather inputs (precipitation), reference systems (Apple River), and pumping (local and regional). Multiple regressions of median flows or baseflows of Valley Creek main stem, North Branch, and South Branch to lagged precipitation values, whether for annual or monthly values, could explain 49-74% of the variance (R^2 = 0.490.74). Adding pumping from the Woodbury East well field improved the fits (R^2 = 0.63-0.81) in most cases. Fits of Valley Creek flows to Apple River flows produced similar R^2 values (0.580.75), with less of the variance being explained by the pumping when added. Given amounts pumped and the regression-determined pumping coefficients, the pumping could have reduced baseflow by 0.7-1.9 cfs, depending on which model for which creek branch was selected. Water levels in monitor well 3 (MW3) near the headwaters of South Branch Valley Creek were similarly related to precipitation (R^2 = 0.77), and to precipitation plus pumping (R^2 = 0.86), with pumping responsible for perhaps a one-foot drop in water level. This foot of water-level drop would translate into a baseflow reduction of about 0.5 cfs in the South Branch, according to relations between flow and MW3 water levels. In short, these different regression models generally suggest that while most of the flow variance can be explained by interannual precipitation differences, a small amount may be explained by pumping from the Woodbury East well field. Adding a pumping variable to the regression equation usually resulted in an improved R^2 and a significant parameter. However, it is important to keep in mind that the models generally suffered from autocorrelation and hence the significances of the fit and the parameters were overestimated.

As an additional exercise, annual White Bear Lake levels were fit to precipitation lagged by up to seven years with an R^2 value of 0.77. However the large number of parameters given the relatively small number of data points implied that the model was overfit and hence quantitatively unreliable. A regression of annual lake levels on median flows in the Apple River, lagged by up to four years, produced a much tighter fit ($R^2 = 0.96$), demonstrating that White Bear Lake and the Apple River are responding in similar ways to regional hydrologic influences, whether these influences are precipitation patterns or groundwater withdrawals. In this case, regional precipitation patterns seem more likely to be the major driver of the similarity in the variation in White Bear Lake level and Apple River flow, because it seems unlikely that groundwater pumping in the two systems would be very similar. That is, White Bear Lake has been in an urbanizing setting with municipal well pumping for many years, whereas the Apple River watershed is largely rural, but with pumping for irrigation ramping up recently. None of these analyses disprove the possible impact of pumping on the lake, because pumping may have lowered aquifer heads and water tables to a new, lower baseline, and interannual precipitation patterns are simply explaining the variation in levels around this reduced baseline.

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