Prepared in cooperation with Johnson County Wastewater

Effects of Wastewater Effluent Discharge and Treatment Facility Upgrades on Environmental and Biological Conditions of Indian Creek, Johnson County, Kansas, June 2004 through June 2013

Scientific Investigations Report 2014–5187

U.S. Department of the Interior
U.S. Geological Survey

Cover. Background photograph: Indian Creek near College Boulevard in Johnson County, Kansas, March 2012.
Front cover photographs: *A*, U.S. Geological Survey monitoring station on Indian Creek at Indian Creek Parkway in Johnson County, Kansas. *B*, Middle Basin Wastewater Treatment Facility in Johnson County, Kansas. *C*, Tomahawk Creek in Johnson County, Kansas, February 2012. *D*, Water-quality monitoring instrumentation on Indian Creek at State Line Road in Johnson County, Kansas.

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http://pubs.usgs.gov/sir/2014/5187/downloads/sir2014-5187_appendixes.xlsx

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Tables

Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
micrometer (µm)	0.001	millimeter (mm)
meter (m)	1.094	yard (yd)
nanometer (nm)	0.001	micrometer (µm)
	Area	
square meter (m^2)	10.76	square feet (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
milliliter (mL)	0.0338	ounce, fluid (oz)
gallon (gal)	3.785	liter (L)
million gallons (Mgal)	3,785	cubic meter (m^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Concentration	
milligrams per liter (mg/L)	1	parts per billion (ppb)
micrograms per liter (µg/L)	1	parts per million (ppm)
micrograms per kilogram (µg/kg)	1	parts per billion (ppb)
milligrams per kilogram (mg/kg)	1	parts per million (ppm)
milligrams per square meter (mg/m^2)	0.000001	kilogram per square meter (kg/m^2)
	Mass	
kilogram (kg)	2.204	pounds (lb)
milligram (mg)	0.001	gram (g)
microgram (µg)	0.000001	gram (g)
metric ton per year	1.102	ton per year (ton/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Abbreviations

ADAS	Algal Data Analysis System
ANOVA	analysis of variance
billion cells/m^2	billion cells per square meter
BNR	biological nutrient removal
BOD	biological oxygen demand
CEPT	chemically enhanced primary treatment
COD	chemical oxygen demand
CR	community respiration
CV	coefficient of determination
DEET	N,N-Diethyl-m-toluamide
DOC	dissolved organic carbon
EPA	U.S. Environmental Protection Agency
EPT	Ephemeroptera, Plecoptera, and Trichoptera
F	F-statistic
FNU	formazin nephelometric units
g O_2/m^2/d	grams of oxygen per meter squared per day
GPP	gross primary production
IDAS	Invertebrate Data Analysis System
KBI	Kansas Biotic Index
KDHE	Kansas Department of Health and Environment
lm/m^2	lumens per square meter
ln	natural logarithm
log10	common logarithm
MBI	Macroinvertebrate Biotic Index
n	number of measurements
NAWQA	National Water-Quality Assessment
NEET	Nutrient Enrichment Effects Team
NEP	net ecosystem production
NPDES	national pollutant discharge elimination system
NWQL	National Water Quality Laboratory
OWC	organic wastewater indicator compound

P/R	production to respiration ratio
PAH	polyaromatic hydrocarbon
PEC	probable effect concentration
p-value	probability value
R^2	coefficient of determination
RBP	Rapid Bioassessment Protocols
rho value	Spearman rank-correlation coefficient
RPD	relative percentage difference
SSC	suspended-sediment concentration
TAN	total ammonia nitrogen
TMDL	total maximum daily load
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
USGS	U.S. Geological Survey
UV	ultraviolet radiation
WWTF	wastewater treatment facility
YSI	Yellow Springs Instruments

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By Jennifer L. Graham, Mandy L. Stone, Teresa J. Rasmussen, Guy M. Foster, Barry C. Poulton, Chelsea R. Paxson, and Theodore D. Harris

Abstract

Indian Creek is one of the most urban drainage basins in Johnson County, Kansas, and environmental and biological conditions of the creek are affected by contaminants from point and other urban sources. The Johnson County Douglas L. Smith Middle Basin (hereafter referred to as the "Middle Basin") and Tomahawk Creek Wastewater Treatment Facilities (WWTFs) discharge to Indian Creek. In summer 2010, upgrades were completed to increase capacity and include biological nutrient removal at the Middle Basin facility. There have been no recent infrastructure changes at the Tomahawk Creek facility; however, during 2009, chemically enhanced primary treatment was added to the treatment process for better process settling before disinfection and discharge with the added effect of enhanced phosphorus removal. The U.S. Geological Survey, in cooperation with Johnson County Wastewater, assessed the effects of wastewater effluent on environmental and biological conditions of Indian Creek by comparing two upstream sites to four sites located downstream from the WWTFs using data collected during June 2004 through June 2013. Environmental conditions were evaluated using previously and newly collected discrete and continuous data and were compared with an assessment of biological community composition and ecosystem function along the upstream-downstream gradient. This study improves the understanding of the effects of wastewater effluent on stream-water and streambed sediment quality, biological community composition, and ecosystem function in urban areas.

After the addition of biological nutrient removal to the Middle Basin WWTF in 2010, annual mean total nitrogen concentrations in effluent decreased by 46 percent, but still exceeded the National Pollutant Discharge Elimination System (NPDES) wastewater effluent permit concentration goal of 8.0 milligrams per liter (mg/L); however, the NPDES wastewater effluent permit total phosphorus concentration goal of 1.5 mg/L or less was achieved at the Middle Basin WWTF. At the Tomahawk Creek WWTF, after the addition of chemically enhanced primary treatment in 2009, effluent discharges also had total phosphorus concentrations below 1.5 mg/L. After the addition of biological nutrient removal, annual total nitrogen and phosphorus loads from the Middle Basin WWTF decreased by 42 and 54 percent, respectively, even though effluent volume increased by 11 percent. Annual total phosphorus loads from the Tomahawk Creek WWTF after the addition of chemically enhanced primary treatment decreased by 54 percent despite a 33-percent increase in effluent volume.

Total nitrogen and phosphorus from the WWTFs contributed between 30 and nearly 100 percent to annual nutrient loads in Indian Creek depending on streamflow conditions. In-stream total nitrogen primarily came from wastewater effluent except during years with the highest streamflows. Most of the in-stream total phosphorus typically came from effluent during dry years and from other urban sources during wet years. During 2010 through 2013, annual mean discharge from the Middle Basin WWTF was about 75 percent of permitted design capacity. Annual nutrient loads likely will increase when the facility is operated at permitted design capacity; however, estimated maximum annual nutrient loads from the Middle Basin WWTF were 27 to 38 percent lower than before capacity upgrades and the addition of biological nutrient removal to treatment processes. Thus, the addition of biological nutrient removal to the Middle Basin wastewater treatment process should reduce overall nutrient loads from the facility even when the facility is operated at permitted design capacity.

The effects of wastewater effluent on the water quality of Indian Creek were most evident during below-normal and normal streamflows (about 75 percent of the time) when wastewater effluent represented about 24 percent or more of total streamflow. Wastewater effluent had the most substantial effect on nutrient concentrations in Indian Creek. Total and inorganic nutrient concentrations at the downstream sites during below-normal and normal streamflows were 10 to 100 times higher than at the upstream sites, even after changes in treatment practices at the WWTFs. Median total phosphorus concentrations during below-normal and normal streamflows at a downstream site were 43 percent lower following improvements in wastewater treatment processes. Similar decreases in total nitrogen were not observed, likely because total nitrogen concentrations only decreased in Middle Basin effluent and wastewater contributed a higher percentage to streamflows when nutrient samples were collected during the after-upgrade period.

The wastewater effluent discharges to Indian Creek caused changes in stream-water quality that may affect biological community structure and ecosystem processes, including higher concentrations of bioavailable nutrients (nitrate and orthophosphorus) and warmer water temperatures during winter months. Other urban sources of contaminants also caused changes in stream-water quality that may affect biological community structure and ecosystem processes, including higher turbidities downstream from construction areas and higher specific conductance and chloride concentrations during winter months. Chloride concentrations exceeded acute and chronic exposure criteria at all Indian Creek study sites, regardless of wastewater influence, for weeks or months during winter. Streambed sediment chemistry was affected by wastewater (elevated nutrient and organic wastewater-indicator compound concentrations) and other contaminants from urban sources (elevated polyaromatic hydrocarbon concentrations). Overall habitat conditions were suboptimal or marginal at all sites; general decline in habitat conditions along the upstream-downstream gradient likely was caused by the cumulative effects of urbanization with increasing drainage basin size.

Wastewater effluent likely affected algal periphyton biomass and community composition, primary production, and community respiration in Indian Creek. Functional stream health, evaluated using a preliminary framework based on primary production and community respiration, was mildly or severely impaired at most downstream sites relative to an urban upstream Indian Creek site. The mechanistic cause of the changes in these biological variables are unclear, though elevated nutrient concentrations were positively correlated with algal biomass, primary production, and community respiration. Macroinvertebrate communities indicated impairment at all sites, and Kansas Department of Health and Environment aquatic life support scores indicated conditions nonsupporting of aquatic life, regardless of wastewater influences. Urban influences, other than wastewater effluent discharge, likely control macroinvertebrate community structure in Indian Creek.

Changes in treatment processes at the Middle Basin and Tomahawk Creek WWTFs improved wastewater effluent quality and decreased nutrient loads, but wastewater effluent discharges still had negative effects on the environmental and biological conditions at downstream Indian Creek sites. Wastewater effluent discharge into Indian Creek likely contributed to changes in measures of ecosystem structure (streamflow, water and streambed-sediment chemistry, algal biomass, and algal periphyton community composition) and function (primary production and community respiration) along the upstream-downstream gradient. Wastewater effluent discharges maintained streamflows and increased nutrient concentrations, algal biomass, primary production, and community respiration at the downstream sites. Functional stream health was severely impaired downstream from the Middle Basin WWTF and mildly impaired downstream from the Tomahawk WWTF relative to the urban upstream site. As distance from the Middle Basin WWTF increased, nutrient concentrations, algal biomass, primary production, and community respiration decreased, and functional stream health was no longer impaired 9.5 kilometers downstream from the discharge relative to the urban upstream site. Therefore, although wastewater effluent caused persistent changes in environmental and biological conditions and functional stream health at sites located immediately downstream from WWTF effluent discharges, some recovery to conditions more similar to the urban upstream site occurred within a relatively short distance.

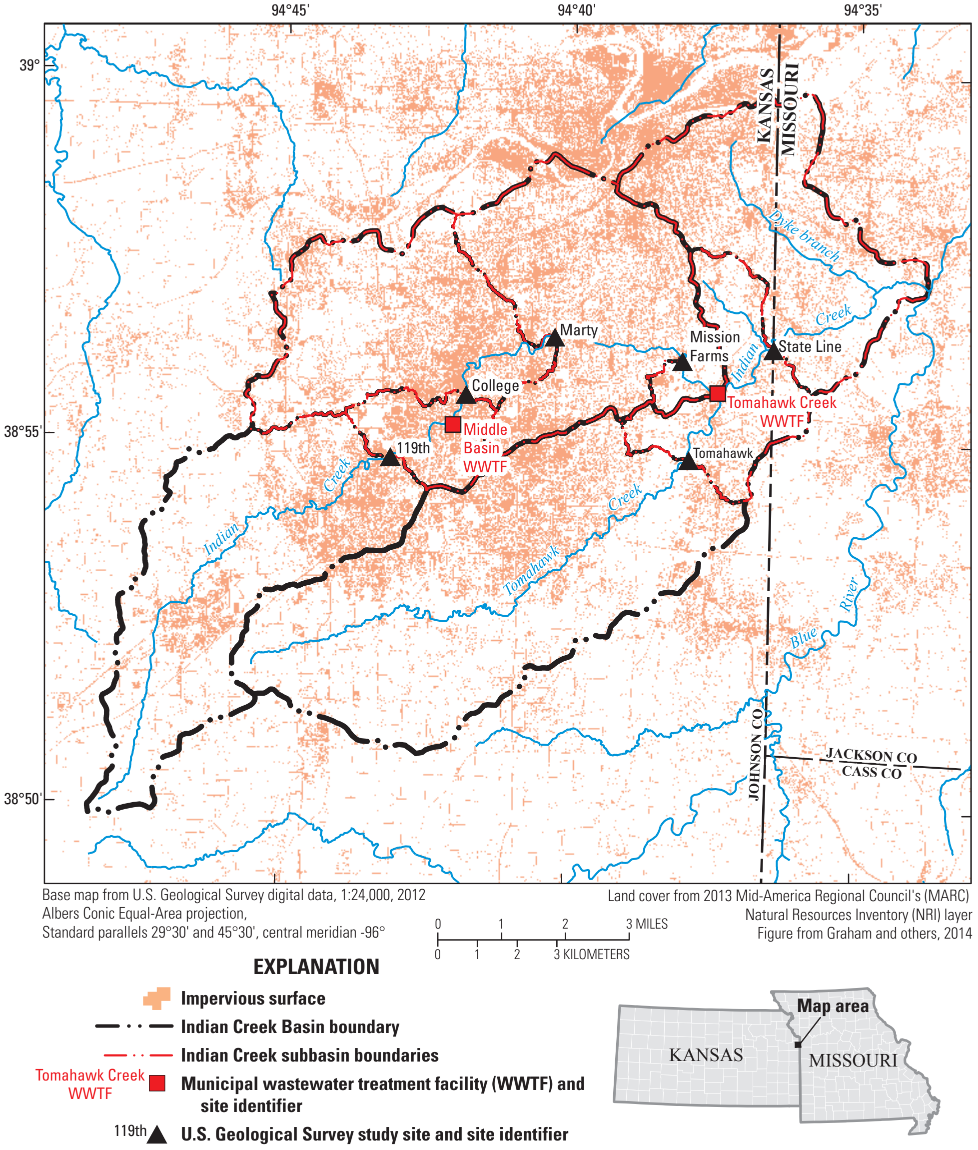
Introduction

Johnson County is the fastest growing county in Kansas, with a population of about 560,000 people in 2012. The population in Johnson County has increased by approximately 20 percent every decade, a growth trajectory that is expected to continue for at least the next 20 years (U.S. Census Bureau, 2013). Infrastructure needs will continue to increase with ongoing population growth and urban development. Urban growth and development can have substantial effects on water quality (Walsh and others, 2005), and streams in Johnson County are affected by nonpoint-source and urban-source contaminants from stormwater runoff and point-source discharges such as municipal wastewater effluent (Lee and others, 2005). Understanding of current (2014) water-quality conditions and the effects of urbanization is critical for the protection and remediation of aquatic resources in Johnson County, Kansas, and farther downstream.

Nutrients, particularly nitrogen and phosphorus, are considered leading causes of water-quality impairment in Kansas and throughout the nation (Kansas Department of Health and Environment, 2004; U.S. Environmental Protection Agency, 2009). Nutrients are essential for the growth of all organisms; however, excessive concentrations in aquatic environments may cause adverse human health and ecological effects including nuisance algal growth. Overly abundant algal growth causes aesthetic concerns, degrades habitats, and decreases dissolved oxygen stability. There are nonpoint, point, and urban sources of nutrient pollution, but point sources, such as wastewater effluent discharges, are easily identified and provide targeted opportunities to decrease nutrient loads in the environment (Kansas Department of Health and Environment, 2004).

Indian Creek (fig. 1) is one of the most urban drainage basins in Johnson County, Kans., and environmental and biological conditions are affected by contaminants from point and other urban sources (Rasmussen and others, 2009b, 2012; Rasmussen and Gatotho, 2014). The Johnson County Douglas L. Smith Middle Basin (hereafter referred to as the “Middle Basin”) Wastewater Treatment Facility (WWTF) is the largest point-source discharge on Indian Creek (fig. 1). A second WWTF, the Tomahawk Creek WWTF, discharges into Indian Creek about 11 kilometers (km) downstream from the Middle Basin WWTF (fig. 1).

Upgrades to increase capacity and include biological nutrient removal at the Middle Basin WWTF were completed in summer 2010 (Johnson County Wastewater, written commun., 2013). Biological nutrient removal is a modification of traditional biological treatment processes that further enhances nitrogen and phosphorus removal by selecting for specific wastewater microorganisms (Tchobanoglous and others, 2003). Wastewater treatment is subject to local, State, and Federal regulations to help protect water quality and aquatic life. The National Pollutant Discharge Elimination System (NPDES) permit for the expansion of, and upgrades to, the Middle Basin WWTF required an evaluation of wastewater effluent effects on Indian Creek after upgrades were complete (NPDES permit number KS0119601; Kansas permit number M-MO28-OO01). The NPDES permit also includes annual mean concentration goals for total nitrogen and phosphorus (TN and TP, respectively) of less than 8.0 and 1.5 milligrams per liter (mg/L), respectively, in wastewater effluent (NPDES permit number KS0119601). These goals were established by



Base map from U.S. Geological Survey digital data, 1:24,000, 2012
Albers Conic Equal-Area projection,
Standard parallels 29°30' and 45°30', central meridian -96°

Land cover from 2013 Mid-America Regional Council's (MARC)
Natural Resources Inventory (NRI) layer
Figure from Graham and others, 2014

Figure 1. Location of municipal wastewater treatment facilities and study sites in the Indian Creek Basin.

the Kansas Department of Health and Environment (KDHE) based on typical removal efficiencies for nutrients by biological nutrient removal processes as part of the Kansas Surface Water Nutrient Reduction Plan (Kansas Department of Health and Environment, 2004).

There have been no recent infrastructure changes at the Tomahawk Creek WWTF (NPDES permit number KS0055484; Kansas permit number M-MO27-OO01). The Tomahawk Creek WWTF currently (2014) is operating under an administratively extended permit while Johnson County Wastewater negotiates a new permit and implements recommended improvements (Johnson County Wastewater, written commun., 2014). During 2009, chemically enhanced primary treatment (CEPT) was added to the treatment process for better process settling before disinfection and discharge with the added effect of enhanced phosphorus removal. Through the CEPT process, ferric chloride was added to precipitate solids from the effluent (Johnson County Wastewater, written commun., 2014; Tchobanoglous and others, 2003).

Indian Creek also is affected by urban factors other than point-source wastewater discharges. Urban development can alter stream hydrology, channel and riparian habitat, water chemistry, and biological communities (U.S. Environmental Protection Agency, 1997; Paul and Meyer, 2001; Cuffney and others, 2010; Poff and others, 2010). As stormwater from rainfall and snowmelt moves across the urban landscape, it often carries trash, sediment, nutrients, metals, pesticides, household chemicals, and other contaminants into streams. In the urban drainage basins of Johnson County, the largest loads of sediment, fecal bacteria, and nutrients have originated from urban sources transported to streams during stormwater runoff (Rasmussen and others, 2008; Rasmussen and Gatotho, 2014). The complexity of altered stream systems, biological processes, contaminant sources and transport, and biological responses in urban drainage basins can make it difficult to separate individual effects, such as wastewater discharges.

The U.S. Geological Survey, in cooperation with Johnson County Wastewater, assessed the effects of wastewater effluent on environmental and biological conditions of Indian Creek by comparing two upstream sites to four sites located downstream from the WWTFs using data collected during June 2004 through June 2013. Water-quality and biological data were collected to allow assessment of chemical and resulting ecological effects of wastewater effluent discharge before and after Middle Basin WWTF upgrades. This study improves the understanding of the effects of wastewater effluent on stream-water and streambed sediment quality, biological community composition, and ecosystem function in urban areas. In addition, this information helps to fulfill the NPDES-permit required post-upgrade evaluation of Middle Basin WWTF effluent effects on Indian Creek.

Purpose and Scope

The purpose of this report is to describe the effects of wastewater effluent discharge and facility upgrades on environmental and biological conditions in Indian Creek, downstream from the Middle Basin and Tomahawk WWTFs. Data collected by the USGS from the Indian Creek Basin during June 2004 through June 2013, including data from before and after the Middle Basin WWTF upgrade and the addition of CEPT at the Tomahawk WWTF, were used to evaluate environmental and biological conditions. Streamflow, discrete and continuously measured stream-water chemistry, streambed-sediment chemistry, and habitat data were used to evaluate differences in environmental conditions upstream and downstream from the wastewater effluent discharges, describe mean annual concentrations and loads of total and dissolved nitrogen and phosphorus in Indian Creek, and determine the percent contribution of wastewater nutrients to total annual nutrient loads in Indian Creek. Periphyton, macroinvertebrate, and stream metabolism (primary productivity and respiration of biological communities) data were used to evaluate differences in biological conditions upstream and downstream from the wastewater effluent discharges. Evaluation of environmental and biological data allowed assessment of the physical, chemical, and resulting ecological effects of wastewater effluent discharges in an urban area.

Description of Study Area

The Indian Creek Basin is 194 square kilometers (km^2) and includes parts of Johnson County, Kans., and Jackson County, Missouri. Approximately 86 percent of the Indian Creek Basin is located in Johnson County, Kans. Indian Creek flows east from its headwaters in central Johnson County, Kansas, to the Blue River (fig. 1). Overall, 93 percent of land use in the Indian Creek Basin is classified as urban and 47 percent is classified as impervious surface.

Two WWTFs, Middle Basin and Tomahawk Creek, discharge into Indian Creek within Johnson County, Kans. (fig. 1). The Middle Basin WWTF was originally constructed in the 1950s as a facultative lagoon plant and has undergone numerous upgrades to increase capacity and improve technology. The most recent upgrades during 2007–10 increased treatment capacity and implemented biological nutrient removal (Johnson County Wastewater, written commun., 2013). Upgrades increased permitted design capacity from 18.6 cubic feet per second (ft^3/s) to 22.4 ft^3/s (12 to 14.5 million gallons per day) and complete mix activated sludge was replaced with a biological nutrient removal activated sludge system (NPDES permit number KS0119601). Expansion and upgrades were officially completed in summer 2010. The Tomahawk Creek WWTF, originally constructed in 1955, is a trickling filter plant and has a permitted design capacity of 15.5 ft^3/s (10 million gallons per day; NPDES permit number

KS0055484). During 2011 and 2012, the Middle Basin and Tomahawk Creek WWTFs contributed about 25 and 15 percent, respectively, of the total wastewater effluent discharged by Johnson County Wastewater (Johnson County Wastewater, 2012 and 2013).

The Middle Basin and Tomahawk Creek WWTFs are located upstream from the continuous water-quality monitoring site on Indian Creek at State Line Road (fig. 1, table 1) that has been operated since 2004. Study sites located upstream and downstream from both WWTFs were needed to assess environmental and biological conditions before and after the upgrades to the Middle Basin facility and to compare wastewater and urban influences on environmental and biological conditions; therefore, five sites along a 15.4-km reach of Indian Creek and one site on Tomahawk Creek, the largest tributary to Indian Creek, were sampled (fig. 1, table 1). For simplicity, the Indian Creek and Tomahawk Creek sites are collectively referred to as the Indian Creek study sites throughout the report. The 119th and Tomahawk sites are located upstream from WWTF effluent discharges. The College, Marty, and Mission Farms sites are located 1.0, 5.1, and 9.5 km, respectively, downstream from the Middle Basin WWTF effluent discharge. The State Line site is located 13 km downstream from the Middle Basin WWTF effluent discharge and 2.3-km downstream from the Tomahawk Creek WWTF effluent discharge (fig. 1, table 1). The Tomahawk Creek subbasin is the least developed area of the drainage basin; 83 percent of land use is classified as urban and 47 percent is classified as impervious surface. Land use at all other Indian Creek study sites is greater than 90 percent urban and generally similar among sites (fig. 1, table 1).

The KDHE has listed several Johnson County, Kans., streams as impaired waterways under section 303(d) of the 1972 Clean Water Act. Five contaminants are listed as impairing designated uses of Indian Creek (Kansas Department of Health and Environment, 2012). Total phosphorus and diazinon, an organophosphate insecticide, are listed as impairments for aquatic life. Nitrate and chloride are listed as impairments for water supply. Fecal coliform bacteria is listed as an impairment for recreation.

Previous Investigations

Numerous sites in the Indian Creek Basin have been included in studies of water quality in Johnson County streams or large-scale assessments of water quality in the Kansas City metropolitan area (Lee and others, 2005; Wilkison and others, 2002, 2006, 2009; Poulton and others, 2007; Rasmussen and others, 2008, 2009b, 2012; Rasmussen and Gatotho, 2014). Continuous streamflow data have been collected at the Marty site since 1963 and at the State Line site since 2003. Continuous water-quality data have been collected at the State Line site since 2004. Current and previously collected streamflow and discrete and continuous water-quality data are available online at *http://waterdata.usgs.gov/nwis*.

Studies in Johnson County indicate that streamflow at sites located downstream from wastewater effluent discharges is largely composed of wastewater effluent during base-flow conditions. During below-normal streamflows, wastewater effluent may represent more than 99 percent of total streamflow (Wilkison and others, 2002; Lee and others, 2005). During below-normal and normal streamflows, nutrient concentrations are commonly an order of magnitude higher at sites located immediately downstream from WWTFs than at sites unaffected by wastewater effluent discharge. Concentrations of dissolved solids, pharmaceuticals, and organic wastewater-indicator compounds also are higher downstream from WWTFs. Because of the diluting effect of wastewater effluent, sediment and bacteria concentrations typically are lower downstream from WWTFs (Lee and others, 2005; Wilkison and others, 2006, 2009; Rasmussen and others, 2008; Graham and others, 2010).

Discrete and continuous water-quality data collected during 2002–06 were used to develop regression models for computing continuous measurements of suspended sediment, dissolved solids, major ions, total nitrogen, total phosphorus, and indicator bacteria in the five largest drainage basins in Johnson County including Indian Creek (Rasmussen and others, 2008). Constituent concentrations and loads were computed for the State Line site during 2004–11. During that time, water temperature of Indian Creek was higher than the other sites about 50 percent of the time, particularly during winter months. Dissolved oxygen concentrations were less than the KDHE minimum criterion of 5 mg/L more frequently at the Indian Creek site than the other sites, about 15 percent of the time. Each winter during the study period, chloride concentrations in Indian Creek exceeded the U.S. Environmental Protection Agency (EPA) recommended criterion of 230 mg/L for at least 10 consecutive days. Turbidity and suspended-sediment concentrations generally were lowest at the Indian Creek site because of wastewater contributions, but large sediment loading events occurred during stormwater runoff. Annual percent contribution of total nitrogen in Indian Creek from WWTFs ranged from 35 percent in 2010 to 93 percent in 2006. Annual percent contribution of total phosphorus in Indian Creek from WWTFs was at least 39 percent annually. Annual mean bacteria load and yield in Indian Creek was more than three times any other site. Less than 1 percent of the total downstream Indian Creek indicator bacteria load originated from WWTFs, except during 2006 when about 6 percent of the Indian Creek load originated from wastewater (Rasmussen and Gatotho, 2014).

During previous studies, results from habitat assessments indicated suboptimal overall conditions at the upstream Indian Creek sites, which was similar to conditions at other sites in the Johnson County. The downstream State Line site had among the poorest stream habitat conditions in Johnson County. Lower habitat scores at the State Line site relative to other sites in the Indian Creek Basin were associated with

Table 1. Location and description of Indian Creek Basin study sites in Johnson County, Kansas, including drainage area, land cover, and distance from the Middle Basin and Tomahawk Creek Wastewater Treatment Facility effluent discharges.

[km^2, square kilometers; km, kilometers; C, creek; KS, Kansas; Blvd, boulevard; Co, county; Pkwy, parkway; nr, near; --, not applicable; Rd, road]

Site identifier (fig. 1)	Site description			Distance from Middle Basin Wastewater Treatment Facility discharge (km)	Distance from Tomahawk Creek Wastewater Treatment Facility discharge (km)	Approximate upstream land use (percent)	
	Site name	U.S. Geological Survey station number	Drainage area (km^2)			Urban[1]	Impervious surface[2]
119th	Indian C at 119th Street, Overland Park, KS	385446094430700	36.9	2.4 above	13 above	91	52
College	Indian C at College Blvd, Johnson Co, KS	385520094420000	40.9	1.0 below	10 above	94	52
Marty	Indian C at Overland Park, KS	06893300	68.9	5.1 below	5.8 above	95	54
Mission Farms	Indian C at Indian C Pkwy, KS	385608094380300	94.8	9.5 below	1.4 above	96	53
Tomahawk	Tomahawk C nr Overland Park, KS	06893350	61.9	--	2.7 above	83	47
State Line	Indian C at State Line Rd, Leawood, KS	06893390	166	13 below	2.3 below	90	49

[1] Urban land use was derived from the 2006 30-meter resolution National Land Cover Dataset (NLCD; Fry and others, 2011).

[2] Impervious surface was derived from 2.5-meter resolution Mid-America Regional Council (MARC) 2012 land cover data (NRI 2.0) (Mid-America Regional Council, 2013).

increased channel disturbance and alteration, diminished and altered riparian areas, including loss of riparian vegetation, and diminished in-stream habitat for aquatic organisms (Rasmussen and others, 2009b, 2012). Not only was the downstream site affected by the large percentage of upstream urban land use and discharge from two WWTFs, it also may have been more susceptible to localized effects of several major roadways.

Algal periphyton biomass and community composition were assessed in three synoptic studies of Johnson County streams in March 2007, July 2007, and April 2010. Three Indian Creek sites, two of which are included in the current study (College and State Line), and the Tomahawk Creek site (fig. 1, table 1) were sampled as part of the 2007 and 2010 synoptic studies (Rasmussen and others, 2009b, 2012). In general, diatoms dominated (greater than 95 percent of abundance and biovolume) the periphytic algal community at these sites, though cyanobacteria and green algae also were occasionally present. Chlorophyll, a surrogate for algal biomass, at the State Line and Tomahawk sites occasionally exceeded 100 milligrams per square meter (mg/m^2), but did not exceed the numeric endpoint of 150 mg/m^2 that KDHE uses as a total maximum daily load (TMDL) endpoint (Kansas Department of Health and Environment, 2010).

Macroinvertebrate bioassessments of Johnson County streams included the same Indian and Tomahawk Creek sites as algal periphyton. Data collected in 2003, 2004, 2007, and 2010 indicated that the Indian and Tomahawk Creek sites were consistently nonsupporting of aquatic life according to KDHE criteria that use a combination of macroinvertebrate metrics to evaluate status (Rasmussen at others, 2012). Environmental variables that were negatively correlated with biological quality of streams included specific conductance of water, polycyclic aromatic hydrocarbon concentrations in streambed sediment, nutrient concentrations in water, percentage of impervious surface, wastewater discharges, and density of stormwater outfalls adjacent to streams (Rasmussen and others, 2009b, 2012).

During 2008 through 2010, the USGS, in cooperation with Johnson County Wastewater, conducted a study to assess the effects of the Blue River Main WWTF effluent discharge and treatment facility upgrades on the environmental and biological conditions of the upper Blue River using data collected during January 2003 through March 2009. Upgrades to the Blue River Main WWTF improved wastewater effluent quality, but wastewater effluent discharge still had negative effects on water quality and biological conditions at downstream sites. Wastewater effluent discharge into the upper Blue River likely contributed to changes in ecosystem structure (streamflow, water chemistry, algal biomass, algal periphyton, and macroinvertebrate community composition) and function (primary production) along the upstream-downstream gradient. Because the Blue River Main WWTF is located in a rapidly urbanizing area, urbanization effects also may play a role in the decline in environmental and biological conditions along the upstream-downstream gradient. Despite these differences in environmental and biological conditions, functional stream health was not impaired downstream from the WWTF during most times of the year, indicating the declines in environmental and biological conditions along the upstream-downstream gradient were not substantial enough to cause persistent changes in ecosystem function (Graham and others, 2010).

Methods

Environmental and biological conditions were assessed at six sites in the Indian Creek Basin; five sites were located on Indian Creek and one was located on Tomahawk Creek, the largest tributary to Indian Creek. Study sites were located upstream (119th, Tomahawk) from the WWTFs, downstream from the Middle Basin WWTF but upstream from the Tomahawk Creek WWTF (College, Marty, and Mission Farms), and downstream from the Middle Basin and Tomahawk Creek WWTFs (State Line; fig. 1). Data collected by the USGS during June 2004 through June 2013 were used to evaluate the environmental and biological conditions upstream and downstream from the wastewater effluent discharges to Indian Creek.

Data Collection

Middle Basin and Tomahawk Creek Wastewater Treatment Facility Effluent Data

The Middle Basin and Tomahawk Creek WWTFs keep a daily record of wastewater effluent discharge volume. In addition, wastewater effluent is monitored for several water-quality variables, including nutrients, once per week. All wastewater effluent samples are analyzed by the Johnson County Wastewater Water-Quality Laboratory, Olathe, Kans. Daily wastewater effluent volume and weekly water-quality data were obtained from Johnson County Wastewater for the period January 2004 through December 2013. These data were used to describe annual mean wastewater effluent discharge volume, TN and TP concentrations in wastewater effluent, and TN and TP loads contributed by the WWTFs. The period 2004 through 2013 was selected for analysis because it allowed an evaluation of changes in wastewater effluent discharge volume, nutrient concentrations, and nutrient loads after capacity and biological nutrient removal upgrades were completed at the Middle Basin WWTF and CEPT was added to the treatment process at the Tomahawk WWTF; in addition, continuous water-quality monitoring at the State Line site began in 2004.

Previously Collected Data

Streamflow data from the Marty site (fig. 1), continuously measured since 1963, were used to compare streamflow conditions during the June 2004 through June 2013 study period to historical streamflow conditions in Indian Creek. A streamflow gage has been operating at the State Line (fig. 1) site since April 2003; a continuous water-quality monitor has been operating at the State Line site since February 2004. Discrete water-quality data have been routinely collected from the State Line site since April 2003. These data facilitated comparison of water-quality conditions in Indian Creek before and after upgrades to the Middle Basin WWTF and the addition of CEPT at the Tomahawk WWTF. For parity, Indian Creek data collected before 2003 were not used in this report. Previously collected samples were analyzed for a variety of water-quality constituents; analyses were most commonly conducted by the USGS National Water Quality Laboratory (NWQL), Lakewood, Colorado, and the Johnson County Environmental Laboratory (now called the Johnson County Wastewater Water-Quality Laboratory) (Lee and others, 2005; Rasmussen and others, 2008, 2009b, 2012; Rasmussen and Gatotho, 2014). Samples were collected by several methods, including equal-width-increment (EWI) methods, grab samples, and autosampler-collected samples (Stone and Graham, 2014). Streamflow and water-chemistry data were downloaded from the USGS National Water Information System Web site at *http://waterdata.usgs.gov/nwis*.

Discrete Water-Quality Samples

Stream-water samples were collected from all six sites over a range of streamflow conditions during June 2011 through June 2013 (Stone and Graham, 2014). In addition, water samples were collected concurrent with biological samples during August 20–21, 2012 and April 2, 2013. Water samples were collected following USGS EWI methods, unless precluded by extreme low-flow conditions (U.S. Geological Survey, 2006). Single vertical or grab samples were collected from the centroid of flow during extreme low flow (U.S. Geological Survey, 2006). Additional details on discrete water-quality sample collection are provided in Stone and Graham (2014). All water samples were analyzed for suspended sediment, dissolved solids, major ions, nutrients (nitrogen and phosphorus species), organic carbon, biochemical and chemical oxygen demand (BOD and COD, respectively), and indicator bacteria. Samples collected on April 2, 2013, also were analyzed for organic wastewater-effluent compounds.

Suspended-sediment concentration was analyzed at the USGS Iowa Sediment Laboratory, Iowa City, Iowa, according to methods described in Guy (1969). Dissolved solids, major ions, nutrients, BOD, COD, and indicator bacteria were analyzed by the Johnson County Wastewater Water-Quality Laboratory according to Standard Methods (American Public Health Association and others, 2005). Total and dissolved organic carbon (TOC and DOC, respectively) were analyzed by the NWQL according to Standard Methods (American Public Health Association and others, 2005) and methods presented in Brenton and Arnett (1993). Select replicate samples and samples collected during evenings and weekends were sent to the NWQL and analyzed according to methods presented in Fishman and Friedman (1989).

Organic wastewater-indicator compounds were analyzed at the NWQL using methods described by Zaugg and others (2006). These methods are sensitive to sub-microgram per liter (µg/L) levels. Reported values may be denoted as estimated (E) for some constituents when values are reported outside of instrument calibration range, performance of the analyte does not meet acceptable method-specific criteria, or there were matrix interferences. Values reported with the E qualifier are considered firm detections, although the precision of the value is frequently less than for values without this qualifier (Childress and others, 1999).

Continuous Water-Quality Monitoring

Continuous streamflow and water-quality data were collected from all six sites (fig. 1). Streamflow gages have been operating at the Marty site since March 1963 and the State Line site since April 2003. Streamflow gages were installed at the 119th, College, and Mission Farms sites in June 2011 and the Tomahawk site in July 2011. Streamflow was measured using standard USGS methods (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). A continuous water-quality monitor has been operating at the State Line site since February 2004; monitors were installed at the other five sites in May 2011. The continuously monitored sites were equipped with YSI 6600EDS water-quality monitors that measured specific conductance, pH, water temperature, turbidity (YSI 6136 optical turbidity sensor), and dissolved oxygen (YSI optical dissolved oxygen sensor). In March 2012, nitrate monitors (HACH® Nitratax plus sc) also were installed at all sites. The nitrate sensor does not differentiate between nitrate and nitrite; therefore, all reported concentrations include nitrate plus nitrite (Pellerin and others, 2013). For simplicity, nitrate is used throughout the report to refer to the sensor and associated data. To facilitate comparison of sensor- and laboratory-measured nitrate concentrations, grab samples were collected near the nitrate monitors on a weekly basis during May 4 through September 19, 2012, and analyzed for nitrate at the Johnson County Wastewater Water-Quality Laboratory.

Monitors were installed near the centroid of the stream cross-section to best represent conditions across the width of the stream and were maintained in accordance with standard USGS procedures (Wagner and others, 2006; Rasmussen and others, 2008; Pellerin and others, 2013). Continuous water-quality data were recorded at 15-minute intervals. Continuous streamflow and water-quality data are available on the USGS Web site at *http://waterdata.usgs.gov/ks/nwis*. Results are presented in this report for the State Line site for the period June 1, 2004 through June 30, 2013 and all other sites for the period July 1, 2011, through June 30, 2013; nitrate data are reported for the period April 1, 2012, through June 30, 2013.

Streambed-Sediment Samples

Streambed-sediment samples were collected concurrent with biological sampling at all six sites during April 4–5, 2013, after a period of at least 1 week without any substantial streamflow events. Streambed-sediment samples were collected from the upper 2 centimeters (cm) of deposition using Teflon® scooping utensils. Only the most recently deposited fine material was removed from 6 to 10 separate depositional zones along the streambed at each site. Samples were collected in a large glass container, homogenized, passed through a 63-µm sieve, split into aliquots for different laboratories, and either shipped chilled (Shelton and Capel, 1994; Radtke, 2005) for nitrogen and wastewater compound analyses or allowed to air dry for approximately 2 weeks before shipping for analysis. Analysis was done only on the fraction of the sediment sample with particles less than 63 µm in diameter (silt and clay size) to minimize sediment-size effects on chemical concentrations. Streambed-sediment samples were analyzed for nutrients (nitrogen and phosphorus), trace elements, total organic carbon, total carbon, and organic wastewater-indicator compounds.

Test America Laboratories, Denver, Colo., analyzed sediment nitrogen (nitrate plus nitrite and total Kjeldahl nitrogen) according to methods described in O’Dell (1993a and 1993b) and U.S. Environmental Protection Agency (1983). Sediment trace elements and total phosphorus were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) 4-acid digestion by the USGS Crustal Geophysics and Geochemistry Science Center, Denver, Colo., following methods by Taggart (2002). Sediment carbon, sulfur, and selenium were analyzed by the USGS Central Mineral and Environmental Resources Science Center, Denver, Colo., following methods detailed in Brown and Curry (2002a and 2002b), Brown and others (2002), and Hageman and others (2002).

Organic wastewater-indicator compounds were analyzed at the NWQL using methods described by Burkhardt and others (2006). These methods are sensitive to sub-microgram per kilogram (µg/kg) levels. Reported values may be denoted as E for some constituents when values are reported outside of instrument calibration range, performance of the analyte does not meet acceptable method-specific criteria, or there were matrix interferences. Values reported with the E qualifier are considered firm detections, although the precision of the value is frequently less than for values without this qualifier (Childress and others, 1999).

Habitat Assessment

Light Intensity

Light intensity data were collected at all six sampling sites during October 1, 2011, through June 30, 2013, using HOBO Pendant® Temperature-Light Data Loggers. The HOBO light sensor measures relative light levels for light wavelength response between approximately 150 and

1,200 nanometers (nm), a much broader spectrum of light wavelengths than are visible to the human eye (approximately 390 to 700 nm; Wetzel, 2001). Five data loggers were deployed at each site: one on the streamgage house, one adjacent to the YSI 6600EDS water-quality monitor, and three in the stream near the water-quality monitor at approximately the left bank, centroid of flow, and right bank. Light data were recorded every 5 minutes. The data loggers were cleaned every 1 to 2 weeks depending on stream conditions, and data were downloaded approximately monthly. Data from the three in-stream sensors were averaged to summarize light conditions at each site.

Physical-Habitat Characteristics

Physical-habitat characteristics were evaluated at all six sampling sites during July 2012 using methods described in Rasmussen and others (2009b). A total of 17 habitat variables in three categories (channel conditions and characteristics, bank and riparian conditions, and aquatic habitat availability) were evaluated. Data collection was completed using a combination of field measurements and surveys, and available aerial photography and topographic maps.

Each habitat variable was assigned a score on a scale of 1 to 12 (Rasmussen and others, 2009b); all habitat data were integrated into one total site score by summing each of the scores from individual variables. All scores were normalized to a scale of 0 to 100 by dividing each score by the total possible score and then multiplying by 100 to simplify comparisons and graphic presentations. Four rating categories (based on those described by Rasmussen and others, 2009b) of relative quality were used to evaluate habitat conditions at each site (score 80 to 100 is optimal, 55 to 79 is suboptimal, 30 to 54 is marginal, and less than 30 is poor). Normalized scores of individual habitat variables and normalized total habitat scores were used to describe among-site differences in habitat conditions.

Periphyton

Periphyton Communities

Periphyton community samples were collected from all six sites during August 21–22, 2012 (summer) and April 3–5, 2013 (spring), after a period of at least 1 week without substantial streamflow events. Cobble substrate in riffles and runs was sampled for periphyton at each site because the streambed along the study reach was dominated by coarse-grained substrates (gravel and cobbles). This single habitat sampling approach for periphyton helps to minimize variability among sites because of habitat differences (Stevenson and Bahls, 1999; Moulton and others, 2002). Duplicate or triplicate samples were collected at each site to more accurately compare differences among sites while accounting for within-site variability.

Periphyton samples were collected using the methods described in Rasmussen and others (2012). Samples were a composite of 12 cobbles collected from 3 adjacent riffles. Periphyton was scraped from a known area on each cobble and composited into a single sample. Samples were analyzed for chlorophyll and taxonomic identification and enumeration of algae. Chlorophyll samples were processed as described in Hambrook-Berkman and Canova (2007). Samples for taxonomic identification and enumeration were preserved with a 9:1 Lugol's iodine:acetic acid solution.

Chlorophyll was analyzed at the USGS Kansas Water Science Center. Chlorophyll (uncorrected for degradation products) was analyzed fluorometrically using a modification of EPA Method 445.0 (Arar and Collins, 1997); instead of acetone extraction, samples were extracted in heated ethanol (Knowlton, 1984; Sartory and Grobbelar, 1986). Samples were analyzed in duplicate and the results reported as an average of the two. BSA Environmental Services, Inc., Beachwood, Ohio, analyzed periphyton samples for taxonomic identification, enumeration, and biovolume of diatoms and soft algae as described in Rasmussen and others (2012).

Periphyton Biomass

Periphyton biomass may change rapidly because of changing environmental conditions, such as scouring during high-flow events, and repeated sampling is necessary to evaluate among-site differences. Periphyton samples were collected approximately weekly during August 30, 2011, through September 25, 2012, at all six sites and analyzed for chlorophyll, an indicator of algal biomass. Periphyton samples for chlorophyll analysis were a composite of three cobbles collected from one riffle. Cobbles were placed in a plastic bucket with enough streamwater to ensure all cobbles were covered and transported to the laboratory for more convenient sample processing. All samples were processed within 4 hours of collection. Cobbles were processed as described in Rasmussen and others (2012) and chlorophyll was analyzed in the same manner as described for periphyton communities.

Macroinvertebrates

Macroinvertebrates were collected from all six sites during August 21–23, 2012 (summer) and April 2–4, 2013 (spring) after a period of at least 1 week without substantial streamflow events. Duplicate or triplicate samples were collected at each site to more accurately compare differences among sites while accounting for within-site variability. Macroinvertebrate samples were collected following semiquantitative KDHE protocols (Kansas Department of Health and Environment, 2000) as described in previous reports (Poulton and others, 2007; Rasmussen and others, 2009b; Graham and others, 2010; Rasmussen and others, 2012). Two independent 100-organism samples were collected from multiple habitat types and counted onsite by two scientists simultaneously for about 1 hour and later pooled into one 200-organism sample. Samples were preserved in 80-percent ethanol and shipped to the USGS NWQL for taxonomic identification and enumeration following methods described by Moulton and others (2000).

Data Analysis

Stream-Water Chemistry Data

Water-quality conditions at the State Line site before (June 1, 2004, through May 31, 2008), during (June 1, 2008, through May 31, 2010) and after (June 1, 2010, through June 30, 2013) the Middle Basin WWTF upgrade and at all six sites along the upstream-downstream gradient were compared with respect to below-normal, normal, and above-normal streamflows. Streamflow conditions were classified using the percentile classes defined on the USGS WaterWatch Web site (U.S. Geological Survey, 2014); below-normal streamflows are less than the 25th percentile (exceeded 75 percent of the time), normal streamflows are between the 25th and 75th percentiles (exceeded 25 to 75 percent of the time), and above-normal streamflows are greater than the 75th percentile (exceeded 25 percent of the time).

Ordinary least squares analysis (Helsel and Hirsch, 2002) was used to develop regression models between sensor- and laboratory-measured nitrate concentrations for all sites using all available data. In general, the nitrate sensor tended to overestimate nitrate concentrations by about 7 percent relative to laboratory-measured concentrations, but there were strong linear relations [all adjusted coefficient of determination (R^2) greater than or equal to 0.95] between sensor- and laboratory-measured nitrate at all sites (fig. 2, appendix 1). The regression relations for each individual site were used to adjust sensor-measured nitrate concentrations to more closely reflect laboratory-measured nitrate concentrations before data analysis and interpretation.

Duration curves were used to compare streamflow and water-quality conditions for continuously measured variables at the State Line site during the before-upgrade, transitional, and after-upgrade periods during June 2004 through June 2013 and among sites along the upstream-downstream gradient during July 2011 through June 2013. Duration curves are cumulative distribution functions and were constructed using 15-minute values to evaluate and compare frequency and magnitude characteristics (Rasmussen and Ziegler, 2003; Rasmussen and others, 2005). The curves indicate the percentage of time that specified conditions were equaled or exceeded, or the frequency of exceedance (Maidment, 1993). Although several similar formulas exist for calculating plotting position, the Weibull formula (Helsel and Hirsch, 2002) was used in this study. Streamflow, water-quality condition duration curves, and periods of exceedance for water-quality criteria for all six sites are available for the period of record on the USGS Web site at *http://nrtwq.usgs.gov/ks/*.

Annual mean nutrient concentrations and loads from the Middle Basin and Tomahawk Creek WWTFs were calculated from weekly water-quality and wastewater effluent discharge volume data provided by Johnson County Wastewater for 2004 through 2013. There were occasional peak wet-weather flow events at the WWTFs during the study period. These peak flow events were not included in load calculations from the WWTFs because data on nutrient concentrations were

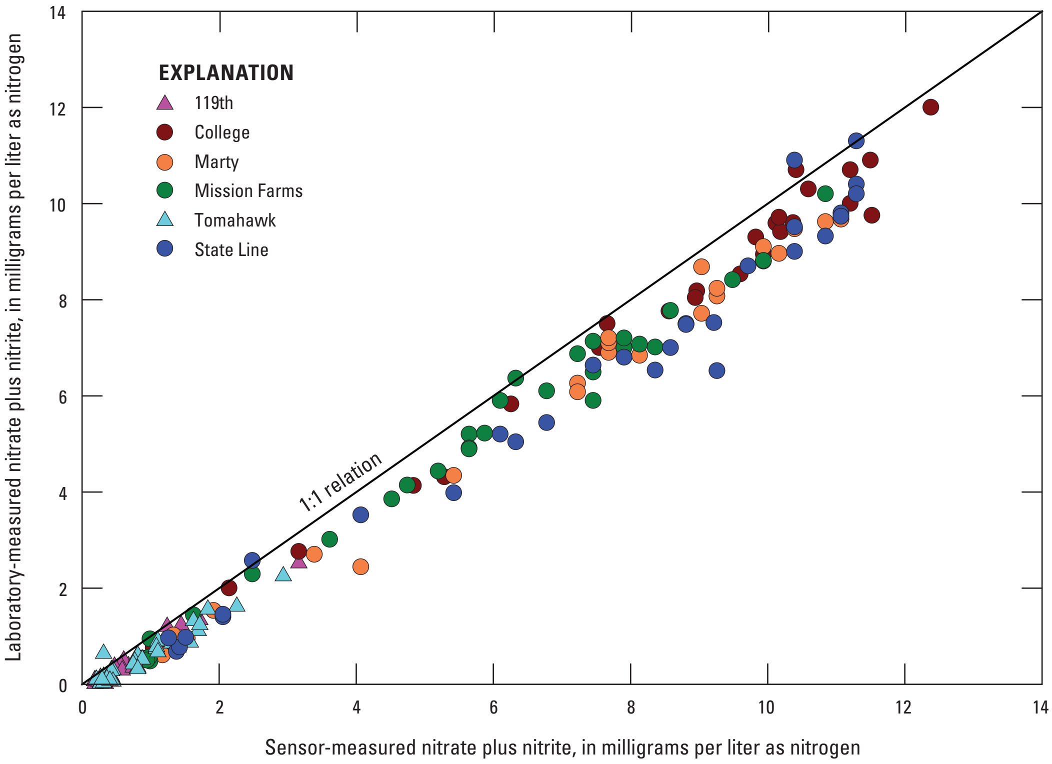


Figure 2. Comparison between sensor-measured and laboratory-measured nitrate plus nitrite concentrations at the Indian Creek study sites.

not available; therefore, total annual nutrient loads from the WWTFs likely are underestimates.

Relative differences in Indian Creek water-quality conditions among sites, streamflow conditions, and the before-upgrade, transitional, and after-upgrade periods at the Middle Basin WWTF were described using relative percentage difference (RPD). The RPD was calculated by dividing the difference between two values by the mean and multiplying that value by 100 (Zar, 1999). The RPD approach was used in these instances because of the emphasis on relative differences in conditions among time periods, sites, and streamflows. Decreases in wastewater effluent nutrient concentrations after changes in wastewater treatment practices and increases and decreases in nutrient concentrations along the upstream-downstream gradient in Indian Creek were described using percentage change. Percentage change was calculated by dividing the difference between two values by one of the values and multiplying that value by 100 (Zar, 1999). The percentage change approach was used in these instances to quantify how much nutrient concentrations in effluent decreased after wastewater treatment processes were improved and increased in Indian Creek downstream from wastewater effluent discharges.

Regression models were developed for all six Indian Creek study sites to establish relations between continuously measured water-quality parameters and discretely collected water-quality constituents in Stone and Graham (2014). Nutrient models differed among sites, and explanatory variables included turbidity, streamflow, and a seasonal variable. A combination of total, particulate, and dissolved nutrient models were used to calculate 15-minute concentrations of TN and TP for the period July 1, 2011, through June 30, 2013. Model development and selection criteria are discussed in detail in Stone and Graham (2014). Total nitrogen models were used to calculate TN concentrations for the 119th, Tomahawk, and State Line (after upgrade) sites, and TP models were used to calculate TP for 119th and Tomahawk sites. Total nutrient concentrations at all other sites were calculated by adding the computed values for particulate and dissolved forms rather than using the TN and TP models directly because the separate models generally explained more variability than the total nutrient models (appendix 2). Continuous loads were calculated using 15-minute concentration (in milligrams per liter), 15-minute streamflow (in cubic feet per second), and a unit conversion factor as described in Rasmussen and others (2009a). Monthly and total loads were calculated by summing 15-minute calculations. Nutrient loads derived from urban sources other than WWTFs at the downstream sites were calculated as the difference between total load and load derived from upstream WWTFs.

Data exceeding 20 percent of the maximum measured value in discrete samples were truncated to avoid calculating concentrations outside the range used to develop nutrient models. Nutrient concentrations were interpolated between the data points on either side of the truncated gap by linear regression to avoid missing data. Less than 0.05 percent of all data at each site were interpolated.

Turbidity was an explanatory variable in some nutrient models, and computed concentrations and loads of nutrients at some sites were affected by missing turbidity data. Streamflow-based models were developed and used to calculate nutrient concentrations when turbidity data were missing to minimize the effect on concentration and load estimates. Total nitrogen calculations at the College, Mission Farms, and State Line sites and total phosphorus calculations at all six sites occasionally used streamflow-based models in place of the best-available model because of missing turbidity data (appendix 2). No more than 5 percent of nutrient concentrations were calculated using streamflow-based models in place of turbidity-based models, depending on the site and the constituent.

Periphyton Data

A total of 277 periphyton community metrics were calculated using the Algal Data Analysis System v. 2.5.2 (ADAS) developed for the USGS National Water-Quality Assessment (NAWQA) Program (Cuffney, 2003). During analysis with ADAS, rare taxa were not deleted and lowest taxonomic levels were used. Abundance was selected for these calculations rather than biovolume because abundance is used in the calculation of most published bioassessment metrics for periphyton and interpretation of biovolume results can be ambiguous (Stevenson and Bahls, 1999). The ADAS program uses a common logarithm (log10) base to calculate the Shannon Diversity Index; however, previous studies in Johnson County used a natural logarithm base (ln) for Shannon Diversity Index calculation. The ADAS calculated Shannon Diversity Index values were converted to a natural logarithm base by multiplying by 2.3026 to allow direct comparison among studies (Brower and others, 1990). A subset of 24 metrics in five categories (oxygen tolerance, saprobity, trophic condition, nitrogen-uptake metabolism, and other indices) was selected for additional analyses to determine among-site differences. All metrics, with the exception of the Shannon Diversity Index, used only diatom data. These metrics were chosen to minimize redundancy and represent water-quality variables of particular interest. Some metrics, such as TN, TP, specific conductance, and chloride tolerances, were excluded because less than 50 percent of all taxa present, and less than 30 percent of dominant taxa, had autecological classifications in ADAS with respect to these variables. Utility of these metrics is limited because of the small amount of autecological data available relative to other metrics calculated by ADAS. Statistical differences in periphyton chlorophyll, abundance, biovolume, and community metrics among sites were tested using analysis of variance (ANOVA), least-squares means, and simultaneous confidence intervals (Sokal and Rohlf, 1995) as described in Graham and others (2010). The August 2012 and April 2013 sampling periods were analyzed independently. Significance for these analyses was set at a probability value (p-value) of less than 0.05.

Weekly collected periphyton chlorophyll concentrations were related to average water-quality conditions during the 7 days before sample collection using available continuous streamflow and water-quality data. Nonparametric Spearman rank-correlation analysis was used to test for monotonic relations between chlorophyll concentrations and environmental variables. Spearman rank-correlation coefficients (rho values) were considered significant when *p*-values were less than 0.01.

Macroinvertebrate Data

A total of 194 macroinvertebrate community metrics were calculated using the Invertebrate Data Analysis System v. 5.0.28 (IDAS) developed for NAWQA (Cuffney, 2003). During analysis with IDAS, rare taxa were not deleted, lowest taxonomic levels were used, and taxonomic ambiguities were resolved by retaining ambiguous taxa. Shannon Diversity Index values were converted as described for periphyton. Five metrics not included in the IDAS program (Macroinvertebrate Biotic Index, Kansas Biotic Index, Percentage of Intolerant Organisms, Clinger Richness, and Percentage of Clingers) also were calculated as described in Barbour and others (1999) and Poulton and others (2007). A subset of 34 metrics was selected for additional analyses to determine among-site differences. Selected metrics included the 4 KDHE aquatic life support status metrics (Kansas Department of Health and Environment, 2008), 7 metrics that were used for multimetric site scoring in Poulton and others (2007) and Rasmussen and others (2009b), and an additional 23 metrics selected from the EPA Rapid Bioassessment Protocols (RBP; Barbour and others, 1999). These metrics represent core metrics used in many State evaluation programs, those known to be sensitive and reliable for measuring degradation of stream assemblages, and those that allow determination of stream impairment status and comparisons with data from previous Johnson County studies. The four KDHE aquatic life support metrics (Macroinvertebrate Biotic Index, Davenport and Kelly, 1983; Kansas Biotic Index, Huggins and Moffet, 1988; Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa richness; and relative abundance of EPT taxa) were used to calculate multimetric aquatic life support scores for each site (Kansas Department of Health and Environment, 2008; Graham and others, 2010). Statistical differences in macroinvertebrate community composition among sites were determined as described for periphyton.

Stream Metabolism Data

Stream metabolism was determined using the whole stream metabolism program developed for the USGS NAWQA Nutrient Enrichment Effects Team (NEET; Bales and Nardi, 2007). The calculations and assumptions in the stream metabolism program are described in detail in Bales and Nardi (2007) and are based on standard approaches (Odum, 1956; Marzolf and others, 1994; Mulholland and others, 2001). Stream metabolism was calculated as described in Graham and others (2010) using the one-monitor method, modified to simulate a two-monitor method by entering the continuous data from each site into the program twice, with the second entry offset by 15 minutes (Bales and Nardi, 2007; Graham and others, 2010).

Daily estimates of gross primary production (GPP), community respiration (CR), net ecosystem production (NEP), and the production to respiration ratio (P/R) were calculated for the period July 1, 2011, through June 30, 2013, for each site. Because stream metabolism variables should only be calculated during stable flow conditions, 24-hour periods with flow that varied by more than 25 ft^3/s were excluded from the analysis. Mean daily discharge and 15-minute dissolved oxygen, specific conductance, and water temperature data were used in stream metabolism calculations. Estimates of several physical variables required by the program, including velocity, wetted width, depth, reach length, channel slope, and a reaeration coefficient, were determined as described in Graham and others (2010). Conditions for each of these variables during the study period are presented in appendix 3.

Among-site differences in stream metabolism variables were determined for the entire study period (July 2011 through June 2013) and seasonally. Seasons were defined as spring (April through June), summer (July through September), fall (October through December), and winter (January through March) and were combined across all years. Spearman rank-correlation analysis was used to determine monotonic relations between GPP, CR, and daily mean values of available continuous streamflow and water-quality data as described for periphyton data.

Quality Assurance and Quality Control

Stream-Water Chemistry Data

Quality-assurance and quality-control data for discrete and continuously measured water chemistry data are described in detail in Stone and Graham (2014). Discrete quality-assurance and quality-control samples were collected within a range of streamflow conditions during July 2011 through June 2013. Replicate samples were analyzed for suspended sediment, dissolved solids, major ions, nutrients, organic carbon, BOD, COD, and indicator bacteria; between 18 and 43 replicate samples were collected depending on the constituent (median=20). Two concurrent replicate samples were analyzed for organic wastewater-indicator compounds. RPD was used to evaluate differences in analyte concentrations detected in replicate water samples. The RPD was calculated by dividing the difference between replicate pairs by the mean and multiplying that value by 100, creating a value that represents the percent difference between replicate samples (Zar, 1999). Median RPDs between replicate pairs were within acceptable limits for inorganic, organic, nutrient, and bacterial constituents. For organic wastewater-indicator compounds, the median RPD between replicate pairs was less than 20 percent for all constituents except N, N-Diethyl-m-toluamide (DEET, median=66 percent).

Comparison with cross-section measurements provided verification that bias in continuous data because of monitor location within the stream cross-section was minimal. Continuous data during the study period generally required corrections of less than 10 percent, which classifies the data-quality rating as good according to established guidelines (Wagner and others, 2006). During July 2011 through June 2013, 0 percent of the streamflow records; 5 percent or less of the specific conductance, pH, water temperature, dissolved oxygen, and turbidity records; and 10 percent or less of the nitrate records were missing or deleted at each site because of equipment malfunction or excessive sensor fouling.

Streambed-Sediment Chemistry Data

Two concurrent replicate streambed-sediment samples from the College and Tomahawk sites were analyzed for nutrients, trace elements, carbon, and organic wastewater-indicator compounds. The RPD values for phosphorus, carbon, and most trace elements generally were less than or equal to 25 percent. At the College site, organic carbon, bismuth, molybdenum, and silver had RPDs of 26, 35, 45, and 38 percent, respectively. The RPD values for ammonia plus organic nitrogen and nitrate were high (between 40 and 78 percent) at both sites. The RPDs for nitrate likely were high because most values were above the laboratory reporting level but still left censored; high RPDs for ammonia plus organic nitrogen may have been due to spatial heterogeneity in the streambed, or variability in sample collection or laboratory analyses. Most organic wastewater-indicator compound data were below either the laboratory reporting level or reported as estimated concentrations. Where concentrations were measured or estimated, the RPD ranged from 0 to 37 percent for both sites (median=5.1). Poor replication and large RPD values are likely because of the low detection levels for these compounds and matrix interference conditions.

Periphyton Data

Concurrent replicate samples for periphyton community and chlorophyll analyses were collected in duplicate or triplicate during August 2012 and April 2013. Triplicate samples were collected at the College and Tomahawk sites; duplicate samples were collected at all other sites. The coefficient of variation (CV) was used to evaluate differences in periphyton community metrics and chlorophyll concentrations because more than two samples can be included in the calculations. The CV was calculated by dividing the standard deviation by the mean and multiplying that value by 100, creating a value that represents the percent variation between replicate samples (Zar, 1999). Chlorophyll and algal abundance had smaller CVs (medians=20 and 25 percent, respectively; both n=12) than biovolume (median=38 percent; n=12). The CVs for the 24 individual periphyton community metrics ranged from 0 to 173 percent (median=28 percent; n=288); 63 percent of metric comparisons had CVs less than 40 percent. Metric comparisons with CVs greater than 75 percent (20 percent of metric comparisons) were caused by rare taxa (comprising less than 10 percent of the overall periphyton community) present in some of the replicate samples but not others. Metrics affected by rare taxa included autotrophs of low and high tolerance, very low and nearly 100 percent oxygen saturation, and oligosaprobic and polysaprobic taxa. Large CV values in metrics not affected by rare taxa were likely caused by natural variation of the periphyton community at each site (Stevenson, 1997). Large variance in some metrics because of the natural spatial variation in periphyton communities precludes statistical detection of small differences among sites (Morin and Cattaneo, 1992).

Macroinvertebrate Data

Concurrent replicate samples for macroinvertebrate community analyses were collected in duplicate or triplicate during August 2012 and April 2013. Triplicate samples were collected at the College and Tomahawk sites; duplicate samples were collected at all other sites. The CV was used to evaluate differences in macroinvertebrate community metrics as described for periphyton. The CVs for the 34 individual macroinvertebrate community metrics ranged from 0 to 173 percent (median=15 percent; n=408); however, 71 percent of metric comparisons had CVs less than 40 percent. Metric comparisons with CVs greater than 75 percent (5 percent of metric comparisons) were caused by rare taxa (comprising less than 10 percent of the overall community) present in some of the replicate samples but not others. Metrics affected by rare taxa included clinger richness, percent clingers, Trichoptera richness, percent Trichoptera, percent Ephemeroptera, percent Ephemeroptera and Plecoptera, percent Oligochaeta, percent Hydropsychidae Trichoptera, and percent Tanytarsini midges Additional sources of variability likely were differences in habitat among the three riffle-pool sampling locations at each site. Large variance in some metrics because of natural spatial variation in macroinvertebrate communities precludes statistical detection of small differences among sites (Miller and others, 2008).

Environmental Conditions in Indian Creek

Evaluated environmental conditions included streamflow, stream-water chemistry, streambed sediment chemistry, and habitat. Conditions were evaluated at two sites located upstream from WWTF effluent discharges (119th and Tomahawk), three sites located downstream from the Middle Basin WWTF (College, Marty, and Mission Farms), and one site located downstream from the Middle Basin and Tomahawk Creek WWTFs (State Line) (fig. 1, table 1). Data collected from the State Line site during June 2004 through June 2013 were used to evaluate environmental conditions during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin WWTF and the addition of CEPT at the Tomahawk Creek WWTF. Data collected from all six sites during June 2011 through June 2013 were used to evaluate environmental conditions upstream and downstream from the Middle Basin and Tomahawk Creek WWTFs.

Streamflow

The structure and function in stream ecosystems are largely affected by streamflow. Alterations to the natural streamflow regime may affect water quality, physical habitat, biological communities, and ecosystem function (Poff and others, 1997; Poff and Zimmerman, 2010; Carlisle and others, 2014). Wastewater effluent discharge may substantially alter natural streamflow regimes, especially during periods when streamflow is naturally low.

Duration curves, which graphically represent the relation between the magnitude and frequency of streamflow during a period of time, were computed for all six Indian Creek study sites from July 2011 through June 2013 (fig. 3). The drainage area of the upstream 119th site (36.9 km^2) was about 40 percent smaller than the drainage area of the upstream Tomahawk site (61.9 km2) (fig. 1, table 1). Consistent with a smaller drainage area, normal streamflows at the 119th site were about 3 times lower than at the Tomahawk site. By comparison, normal streamflows at the 119th and Tomahawk sites were about 10 and 4 times lower, respectively, than at sites located downstream from the Middle Basin and Tomahawk Creek WWTFs regardless of differences in drainage area. Upstream sites transported between 52 and 43 percent (119th and Tomahawk, respectively) of their total streamflow during less than 1 percent of the study period, compared to an average of 32 percent of total streamflows at the downstream sites where streamflow is augmented by wastewater effluent discharge. Streamflows were generally similar at the College, Marty, and Mission Farms sites during below-normal and normal streamflow conditions (fig. 3); below-normal streamflows (exceeded more than 75 percent of the time on fig. 3) were less than 13 to 14 ft^3/s and normal streamflows were less than 22 to 29 ft^3/s (exceeded 25 to 75 percent of the time on fig. 3). Differences among these sites were larger during above-normal streamflows, likely due to several ephemeral tributaries (fig. 1) downstream from the College site that do not contribute flow during below-normal and normal streamflows. Wastewater contributed between 24 and 100 percent to streamflows during below-normal and normal streamflow conditions at the downstream Indian Creek study sites during July 2011 through June 2013. Wastewater contributions to streamflow were highest at the College site and decreased in the downstream direction. Over the range of streamflow conditions, wastewater contributed, on average, about 84 percent of the flow at the College

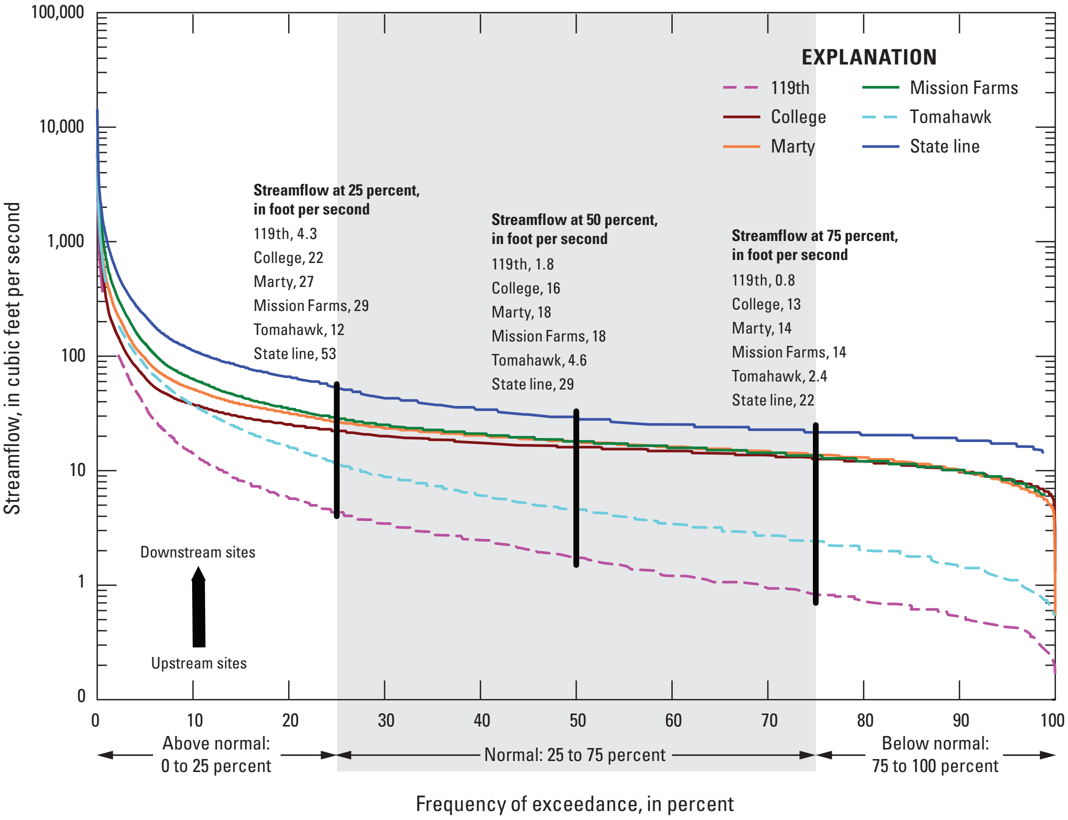


Figure 3. Streamflow duration curves at the Indian Creek study sites during July 2011 through June 2013.

site, 76 percent at the Marty site, 73 percent at the Mission Farms site, and 52 percent at the State Line site.

Streamflows at the Marty site (fig. 1) were lowest during 2012, with annual mean streamflow about 1.1 times smaller than the period-of-record (March 1963 through December 2013) mean, and highest during 2010, with annual mean streamflow about 1.7 times greater than the period-of-record mean (table 2). Mean streamflow at the Marty site during 2010 was the highest on record. The State Line site had the lowest annual mean streamflow during 2012 and the highest during 2008 and 2010 during the period of record (table 2). Mean streamflow at the State Line site (99.1 ft^3/s) was about 2 times higher than at the Marty site (48.0 ft^3/s) during the study period (January 2004 through December 2013; table 2).

During 2004 through 2013, wastewater effluent contribution to total annual streamflow volume at the Marty site below the Middle Basin WWTF ranged from 26 percent during wet years to 46 percent during dry years (table 2). Wastewater effluent contribution to total annual streamflow volume at the State Line site below the Middle Basin and Tomahawk Creek WWTFs ranged from 17 to 36 percent. Overall, wastewater effluent contributed about 34 percent to total streamflow volume at the Marty site and 23 percent at the State Line site.

The contribution of wastewater effluent to streamflow at the Marty and State Line sites ranged from negligible (less than 1 percent) during large runoff events to nearly 100 percent during the lowest streamflows (fig. 4). On average, wastewater effluent contributed nearly 100 percent to total streamflow during below-normal streamflows (25 percent of the time) during 2004 through 2013 at the Marty and State Line sites. More than 90 percent of total streamflow was contributed by wastewater effluent about 38 percent and 19 percent of the time at the Marty and State Line sites, respectively.

Wastewater effluent contributions to streamflow did not change substantially before (January 2004 through May 2008) and after (June 2010 through 2013) capacity upgrades at the Middle Basin WWTF. At the Marty site, wastewater effluent contributions during normal streamflows ranged between 40 to nearly 100 percent during both periods; mean values decreased slightly from 84 percent before upgrades to 81 percent after (fig. 4*A*). At the State Line site, wastewater effluent contributions during normal streamflows ranged between 28 to nearly 100 percent during both periods; mean values increased from 70 percent before upgrades to 78 percent after (fig. 4*B*). The increase in wastewater contribution at the State Line site likely was caused by increased wastewater effluent discharge from the Tomahawk Creek WWTF rather than capacity upgrades at the Middle Basin WWTF (table 2). Upgrades increased the permitted design capacity of the Middle Basin WWTF by about 20 percent (from 18.6 to 22.4 ft^3/s); however, on average, effluent discharge post-upgrade was 16.9 ft^3/s, an increase of about 11 percent relative to the pre-upgrade period (15.2 ft^3/s). Continued increases in wastewater effluent discharge approaching permitted design capacity (22.4 ft^3/s) will change the contribution of wastewater effluent to streamflow in Indian Creek.

Stream-Water Chemistry

Discrete and continuous water-quality data collected at the State Line site during June 2004 through June 2013 were used to evaluate stream-water chemistry during the before-upgrade (June 2004 through May 2008), transitional (June 2008 through May 2010), and after-upgrade (June 2010 through June 2013) periods at the Middle Basin WWTF. Stream-water chemistry upstream and downstream from the Middle Basin and Tomahawk Creek WWTFs was evaluated using discrete and continuous water-quality data from all six sites; discrete data were collected during June 2011 through June 2013 and continuous data were collected during July 2011 through June 2013. Discrete samples were analyzed for suspended solids and sediment, dissolved solids, major ions, organic carbon, BOD and COD, and indicator bacteria. Samples collected concurrent with periphyton and macroinvertebrate samples during April 2013 also were analyzed for organic wastewater-effluent compounds. Continuous water-quality data included specific conductance, pH, water temperature, turbidity, dissolved oxygen, and nitrate (April 2012 through June 2013).

Specific Conductance, pH, Water Temperature, and Dissolved Oxygen

Specific conductance, pH, water temperature, and dissolved oxygen are described using the continuous data collected at the State Line site during June 2004 through June 2013 and at all six sites during July 2011 through June 2013. Specific conductance is an indirect measure of dissolved solids in water (Hem, 1992). Some dissolved solids, such as chloride and some nutrients, may have elevated concentrations in wastewater effluent; therefore, wastewater effluent generally has larger specific conductance values than receiving stream water (Cheremisinoff, 1995). Median specific conductance values at the State Line site varied by less than 10 percent among the before-upgrade, transitional, and after-upgrade periods at the Middle Basin WWTF, even during below-normal streamflow conditions when wastewater represents the largest percentage of total flow (fig. 5*A*, table 3). Specific conductance was generally larger at sites located downstream from the WWTFs than at the upstream sites (fig. 6*A*). The difference between upstream and downstream sites occurred across the range of streamflow conditions, with median values at the downstream sites [College, Marty, Mission Farms, and State Line; 863–1,090 microsiemens per centimeter at 25 degrees Celsius (µS/cm)] about 10 to 20 percent larger than median values at the upstream sites (119th and Tomahawk; 782–948 µS/cm) (table 4); however, maximum specific conductance values at the upstream sites were equal to or larger than maximum values at the downstream sites (table 4). Road salt may substantially affect specific conductance in streams during winter months (Rasmussen and others, 2008). The largest specific conductance values at all Indian Creek study sites

Table 2. Streamflow statistics for the Marty and State Line sites on Indian Creek, flow statistics for the Middle Basin and Tomahawk Creek Wastewater Treatment Facilities, and the percent contribution of wastewater effluent to annual streamflow at the Marty and State Line sites during January 2004 through December 2013.

[Streamflow and flow statistics are based on mean daily values for each site; Indian Creek streamflow data are available on the U.S. Geological Survey National Water Information Web site (*http://waterdata.usgs.gov/nwis*); ft^3/s, cubic feet per second; min, minimum; max, maximum; --, not applicable]

Time period	Indian Creek							
	Marty streamflow (ft^3/s)				State Line streamflow (ft^3/s)			
	Median	Mean	Min	Max	Median	Mean	Min	Max
2004	17.3	44.5	1.3	4,900	37.4	104	13.5	11,597
2005	17.5	50.4	4.4	5,210	31.0	99.0	12.7	10,646
2006	15.2	34.2	3.1	5,198	25.3	71.6	10.4	10,797
2007	18.1	53.0	6.0	4,748	34.1	107	13.5	7,410
2008	20.8	60.8	1.9	6,234	41.0	129	11.2	17,914
2009	21.5	55.2	5.9	4,097	39.2	107	8.5	6,230
2010	23.6	64.3	5.4	8,972	44.8	129	11.9	18,710
2011	19.6	38.4	3.7	2,289	34.1	79.0	8.5	3,526
2012	16.2	33.3	0.6	4,883	25.3	66.0	10.4	10,841
2013	19.6	45.8	3.8	5,704	37.4	99.1	12.7	14,122
2004 through 2013	18.5	48.0	0.6	8,972	34.1	99.1	8.5	18,710
Period of record[1,2]	15.0	37.5	0.0	12,800	34.1	100	8.5	18,710

Time period	Wastewater Treatment Facilities									
	Middle Basin effluent flow (ft^3/s)				Percent contribution of wastewater at Marty	Tomahawk Creek effluent flow (ft^3/s)				Percent contribution of wastewater at State Line[3]
	Median	Mean	Min	Max	Contribution of wastewater effluent to annual streamflow	Median	Mean	Min	Max	Contribution of wastewater effluent to annual streamflow
2004	15.4	15.2	10.4	20.0	34	6.9	7.2	0	13.6	22
2005	15.0	15.0	12.7	19.7	30	6.7	5.2	0	9.6	20
2006	15.0	14.7	9.4	17.6	43	6.1	5.3	0	8.0	28
2007	15.8	15.9	12.5	20.1	30	6.3	6.2	0	11.4	21
2008	15.5	15.6	8.2	27.9	26	6.5	5.8	0	21.5	17
2009	16.4	17.3	13.6	25.8	31	7.1	7.4	4.3	16.9	23
2010	17.2	18.7	10.8	37.6	29	8.2	8.3	4.7	19.2	21
2011	14.5	15.8	11.2	37.5	41	8.7	7.8	0	13.2	30
2012	14.1	15.5	11.3	39.4	46	8.8	8.6	0	13.8	36
2013	15.4	17.7	10.7	34.6	39	8.8	8.8	0	13.3	27
2004 through 2013	15.3	16.1	8.2	39.4	34	7.5	7.1	0	21.5	23
Period of record[1,2]	--	--	--	--	--	--	--	--	--	--

[1] Period of record for Marty based on daily mean with the exception of the max value, which is based on peak flow data.

[2] Period of record for Marty March 7, 1963, through December 2013, period of record for State Line April 22, 2003, through December 2013.

[3] Includes effluent from the Middle Basin and Tomahawk Creek Wastewater Treatment Facilities.

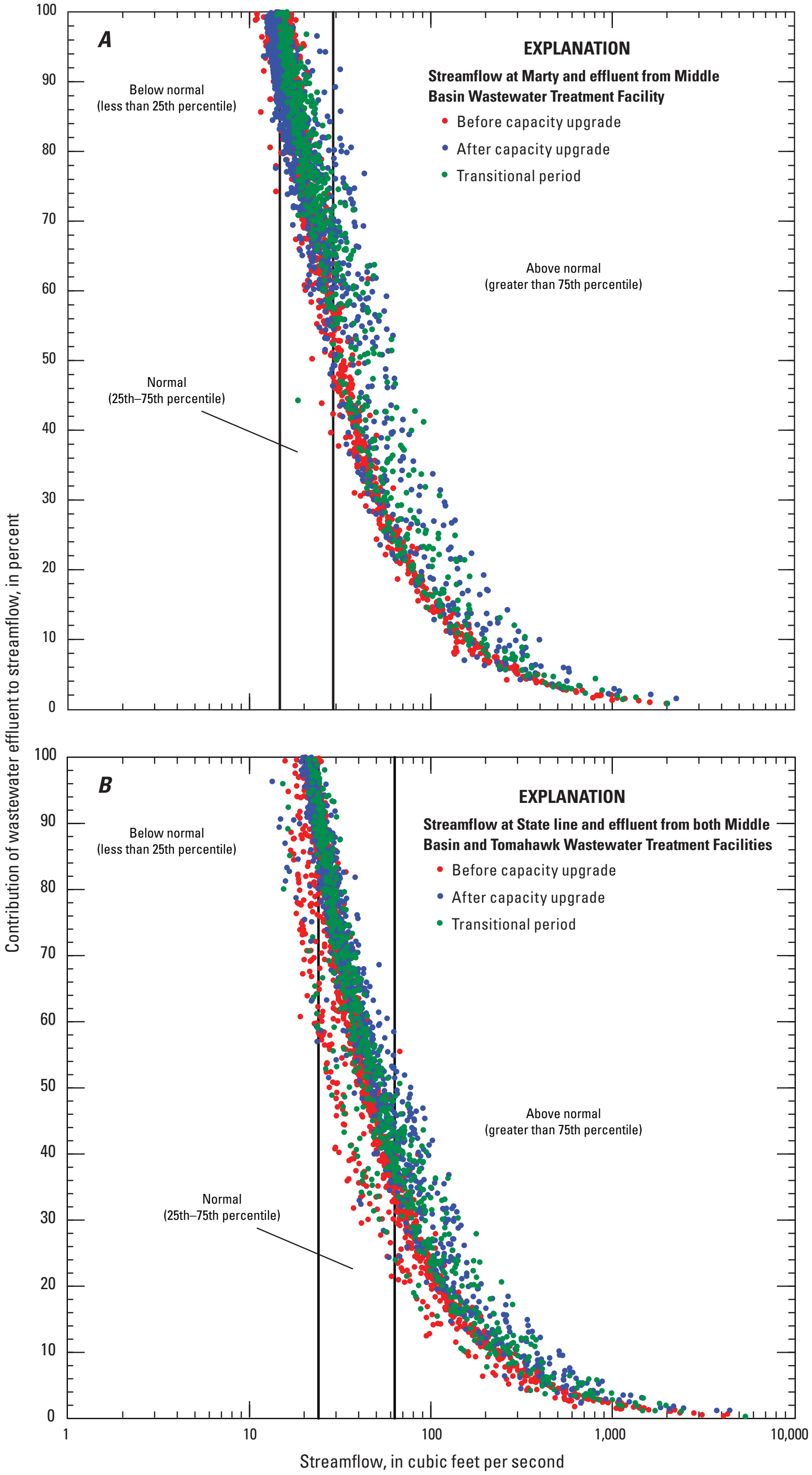


Figure 4. The percent contribution of wastewater effluent to streamflow during below-normal, normal, and above-normal streamflows at the Marty and State Line study sites on Indian Creek during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin Wastewater Treatment Facility. *A*, Marty and *B*, State Line.

Table 3. Summary statistics for water-quality constituents measured continuously at the State Line study site during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin Wastewater Treatment Facility during below-normal, normal, and above-normal streamflow conditions, June 2004 through June 2013.

[Continuous real-time water-quality data are available on the U.S. Geological Survey National Real-Time Water-Quality Web site (*http://nrtwq.usgs.gov/ks*); *n*, number of measurements; min, minimum; max, maximum; med, median; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; FNU, formazin nephelometric units]

Water-quality property	Before upgrade					Transitional					After upgrade				
	n	Min	Max	Mean	Med	*n*	Min	Max	Mean	Med	*n*	Min	Max	Mean	Med
Below-normal streamflow conditions[1]															
Specific conductance (µS/cm)	36,792	587	2,750	1,012	975	9,275	571	3,040	1,161	979	34,748	576	3,680	1,100	1,060
pH	37,030	6.9	9.1	7.6	7.6	9,275	7.2	9.2	7.8	7.8	34,748	7.0	9.6	7.7	7.6
Water temperature (°C)	37,035	0.20	33	18	18	9,275	0.20	33	16	19	34,748	0.30	35	17	17
Dissolved oxygen (mg/L)	34,773	0.90	20	7.8	7.6	9,275	0.50	20	8.9	10	34,748	0.50	26	8.2	8.2
Turbidity (FNU)	34,721	0.10	40	4.1	3.2	9,180	0.10	68	4.6	4.0	34,012	0.10	120	3.4	2.6
Normal streamflow conditions[2]															
Specific conductance (µS/cm)	71,396	322	5,970	1,152	949	38,070	355	5,840	1,204	974	48,771	401	4,630	1,099	999
pH	68,504	6.9	9.0	7.7	7.7	38,070	7.1	8.9	7.8	7.7	48,924	7.0	9.7	7.7	7.6
Water temperature (°C)	71,839	0.00	33	15	15	38,070	0.10	32	15	15	48,771	0.10	32	16	17
Dissolved oxygen (mg/L)	64,171	1.5	21	8.5	8.3	37,943	1.5	18	8.7	8.5	48,770	0.90	27	8.3	8.1
Turbidity (FNU)	68,413	0.20	569	8.5	5.7	35,691	0.10	260	6.1	4.3	48,732	0.40	92	4.8	3.3
Above-normal streamflow conditions[3]															
Specific conductance (µS/cm)	29,760	136	5,280	899	739	22,491	144	5,870	974	808	24,368	145	5,640	926	763
pH	28,672	6.9	8.5	7.7	7.7	22,491	7.2	8.8	7.8	7.7	24,424	7.1	9.1	7.7	7.7
Water temperature (°C)	30,507	0.70	30	15	16	22,491	0.90	30	15	15	24,368	1.1	32	16	17
Dissolved oxygen (mg/L)	27,718	2.4	15	8.4	7.9	21,808	0.70	18	8.7	8.5	24,368	2.1	20	8.9	8.4
Turbidity (FNU)	29,974	1.0	1,760	88	33	21,993	0.10	1,490	61	20	24,159	0.80	1,440	55	18

[1] Below-normal streamflow conditions were defined as streamflows less than the 25th percentile for the period June 1, 2004, through June 30, 2013. Below-normal streamflows were less than 24.0 cubic feet per second.

[2] Normal streamflow conditions were defined as streamflows between the 25th and 75th percentiles for the period June 1, 2004, through June 30, 2013. Normal streamflows were between 24.0 and 64.5 cubic feet per second.

[3] Above-normal streamflow conditions were defined as streamflows greater than the 75th percentile for the period June 1, 2004, through June 30, 2013. Above-normal streamflows were greater than 64.5 cubic feet per second.

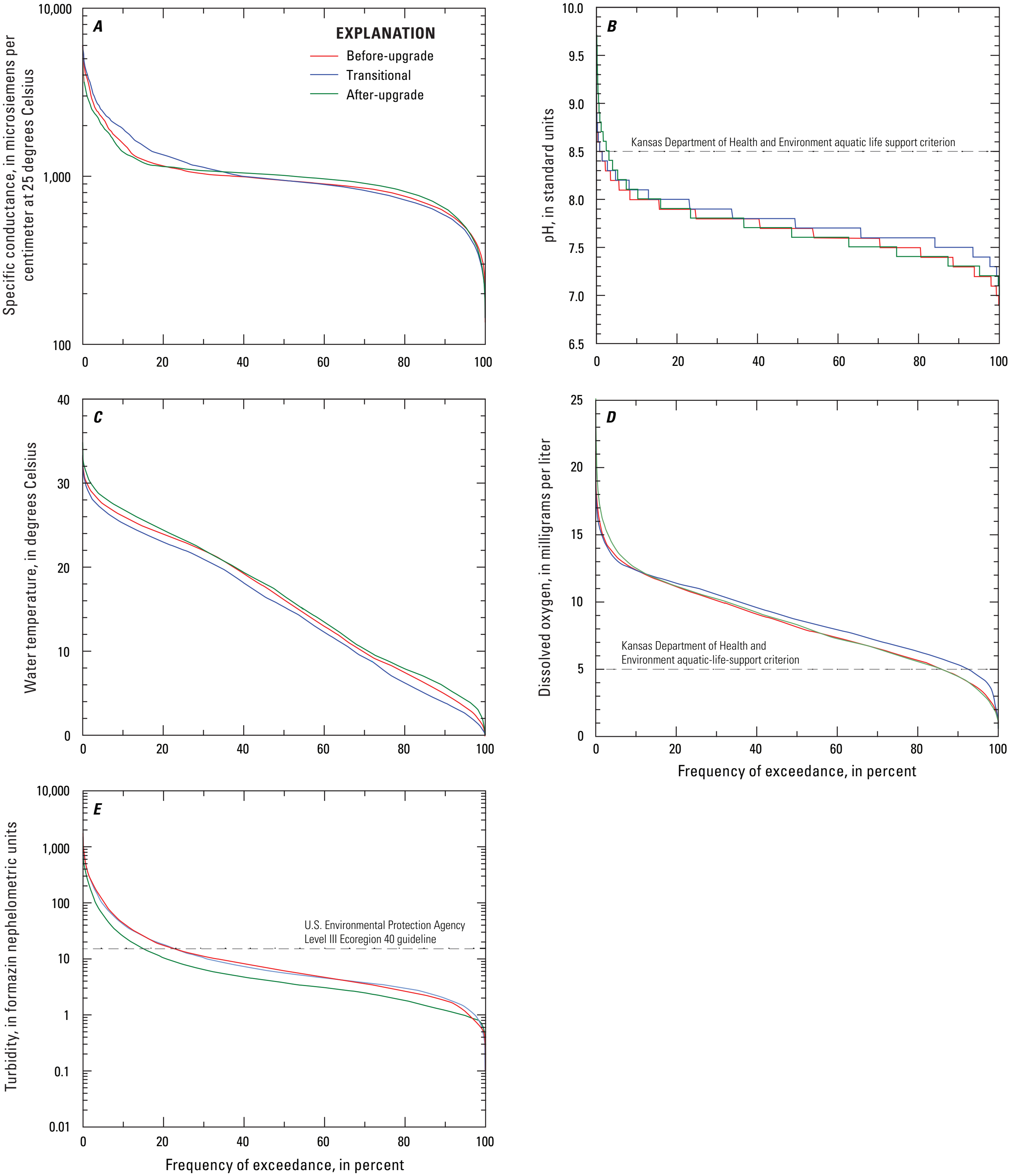


Figure 5. Duration curves for continuously measured water-quality constituents at the State Line site during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin Wastewater Treatment Facility. *A*, specific conductance; *B*, pH; *C*, water temperature; *D*, dissolved oxygen; and *E*, turbidity.

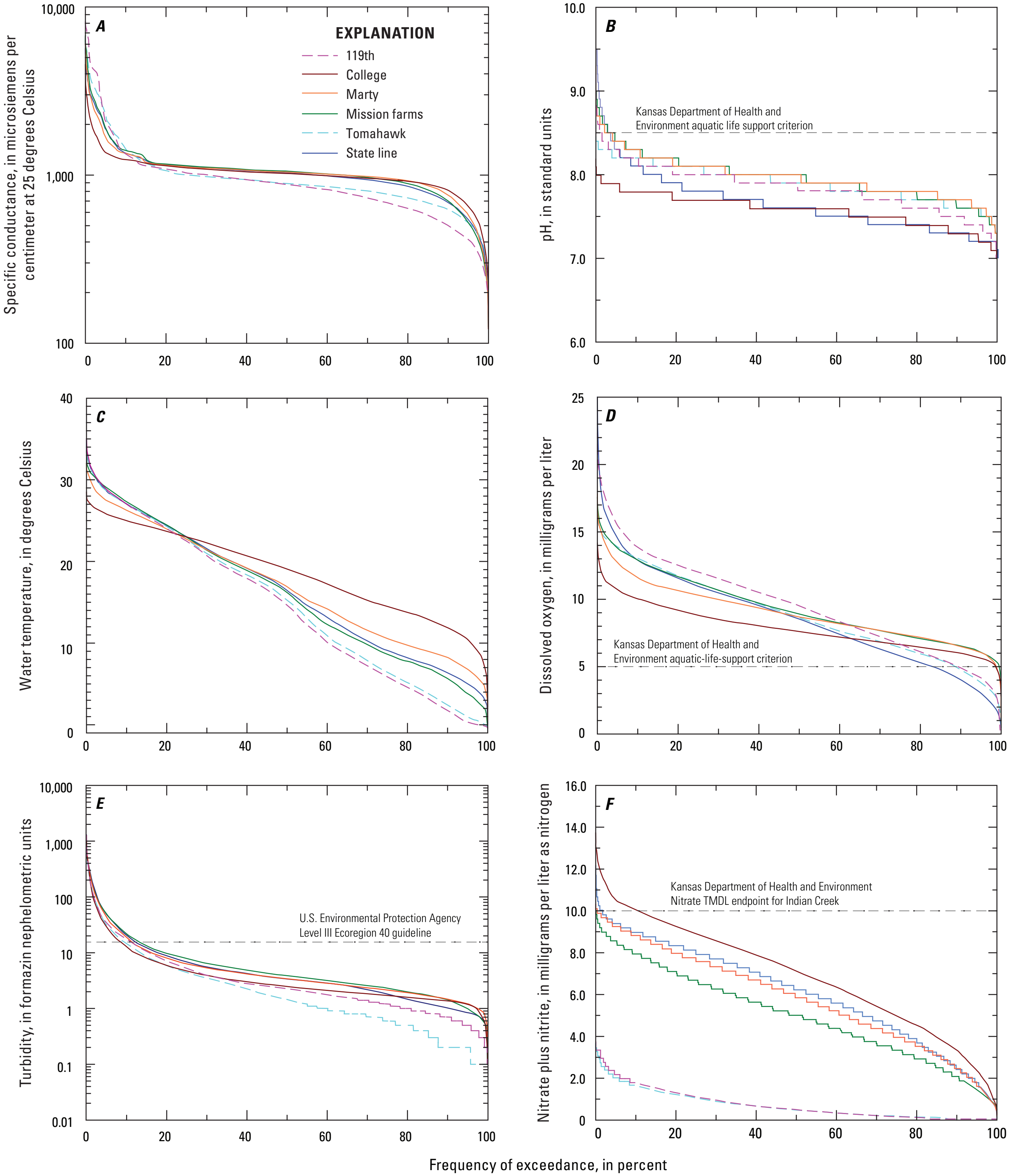


Figure 6. Duration curves for continuously measured water-quality constituents at all Indian Creek study sites, July 2011 through June 2013. *A*, specific conductance; *B*, pH; *C*, water temperature; *D*, dissolved oxygen; *E*, turbidity; and *F*, nitrate plus nitrite. [TMDL, total maximum daily load]

Table 4. Summary statistics for water-quality constituents measured continuously at all Indian Creek study sites during below-normal, normal, and above-normal streamflow conditions, July 2011 through June 2013.

[Continuous real-time water-quality data are available on the U.S. Geological Survey National Real-Time Water-Quality Web site (*http://nrtwq.usgs.gov/ks*); *n*, number of measurements; min, minimum; max, maximum; med, median; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; FNU, formazin nephelometric units; <, less than]

Water-quality property	119th					College				
	n	Min	Max	Mean	Med	*n*	Min	Max	Mean	Med
Below-normal streamflow conditions[1]										
Specific conductance (µS/cm)	17,832	374	4,390	968	839	20,485	668	2,750	1,066	1,060
pH	16,341	7.0	8.9	7.9	7.9	20,195	7.0	8.1	7.6	7.6
Water temperature (°C)	17,832	-0.20	34.9	18.5	19.9	20,485	6.90	27.8	21.1	22.4
Dissolved oxygen (mg/L)	17,832	1.6	22	8.2	7.3	20,485	2.8	13.4	6.8	6.7
Turbidity (FNU)	17,832	0.10	90	2	1.3	19,796	0.10	41.0	2.29	1.8
Nitrate (mg/L)[2]	11,952	<0.1	2.2	0.20	0.15	12,719	2.3	13.7	8.8	9.0
Normal streamflow conditions[3]										
Specific conductance (µS/cm)	34,752	261	8,110	1,081	922	32,116	530	3,060	1,069	1,020
pH	35,111	6.9	9.2	7.8	7.8	32,339	7.0	8.2	7.6	7.6
Water temperature (°C)	35,171	-0.40	35.0	13.1	11.8	32,342	3.20	28.5	18.8	19.2
Dissolved oxygen (mg/L)	35,171	0.20	22	10	10	32,340	3.4	14.0	7.9	7.7
Turbidity (FNU)	35,171	0.10	85	4	2.3	32,005	0.10	86.0	3.01	2.30
Nitrate (mg/L)[2]	20,351	<0.1	3.7	0.68	0.54	20,242	0.8	13.7	7.4	7.4
Above-normal streamflow conditions[4]										
Specific conductance (µS/cm)	16,898	103	7,490	994	782	16,978	134	4,530	955	900
pH	17,169	7.0	8.9	7.8	7.9	17,163	7.0	8.2	7.5	7.6
Water temperature (°C)	17,173	-0.30	30.0	12.6	11.8	17,163	2.20	28.5	15.4	14.6
Dissolved oxygen (mg/L)	17,173	0.80	19	10	10	16,804	4.5	14.2	8.9	9.0
Turbidity (FNU)	17,173	0.40	1,260	34	9.5	16,297	1.00	1,050	33	9
Nitrate (mg/L)[2]	11,473	<0.1	3.3	1.4	1.3	11,739	0.3	10.3	4.0	3.9

Table 4. Summary statistics for water-quality constituents measured continuously at all Indian Creek study sites during below-normal, normal, and above-normal streamflow conditions, July 2011 through June 2013.—Continued

[Continuous real-time water-quality data are available on the U.S. Geological Survey National Real-Time Water-Quality Web site (*http://nrtwq.usgs.gov/ks*); *n*, number of measurements; min, minimum; max, maximum; med, median; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; FNU, formazin nephelometric units; <, less than]

Water-quality property	Marty					Mission Farms				
	n	Min	Max	Mean	Med	*n*	Min	Max	Mean	Med
Below-normal streamflow conditions[1]										
Specific conductance (µS/cm)	20,765	576	4,900	1,106	1,060	22,006	545	4,660	1,130	1,090
pH	20,843	7.4	8.9	8.0	8.0	22,158	7.3	8.9	8.0	8.0
Water temperature (°C)	20,843	0.50	31.9	18.1	18.6	22,003	-0.10	32.7	16.9	17.2
Dissolved oxygen (mg/L)	20,843	2.6	18	8.5	8.2	22,158	4.0	16	9.2	8.7
Turbidity (FNU)	20,843	0.30	27	2.7	2.3	22,140	0.10	55	3.4	2.7
Nitrate (mg/L)[2]	11,740	2.0	10.3	7.4	7.6	13,956	1.4	10.0	6.5	6.7
Normal streamflow conditions[3]										
Specific conductance (µS/cm)	31,814	428	4,900	1,104	1,040	29,949	393	5,460	1,130	1,050
pH	32,262	7.3	9.2	8.0	8.0	30,256	7.2	9.1	8.0	8.0
Water temperature (°C)	32,262	0.60	31.9	17.2	17.8	30,363	-0.30	32.3	16.3	17.2
Dissolved oxygen (mg/L)	32,262	1.0	18	9.1	8.9	30,411	4.0	17	9.4	8.9
Turbidity (FNU)	32,088	0.30	170	4.2	3.2	29,922	0.10	110	4.7	3.4
Nitrate (mg/L)[2]	16,711	1.1	10.1	6.3	6.3	17,116	0.5	10.0	5.2	5.2
Above-normal streamflow conditions[4]										
Specific conductance (µS/cm)	16,878	122	6,010	1,051	922	16,772	126	6,740	1,052	892
pH	17,071	7.2	9.3	7.8	7.8	16,959	7.2	9.1	7.8	7.8
Water temperature (°C)	17,071	2.90	29.0	14.6	13.8	16,959	1.8	33.8	14.4	13.0
Dissolved oxygen (mg/L)	17,071	3.2	16	9.3	9.1	16,959	4.2	18	9.4	9.2
Turbidity (FNU)	16,699	1.60	1,220	44	12	16,818	1.0	860	45	14
Nitrate (mg/L)[2]	11,006	0.2	9.5	3.2	3.3	11,490	0.49	8.6	2.8	2.7

Table 4. Summary statistics for water-quality constituents measured continuously at all Indian Creek study sites during below-normal, normal, and above-normal streamflow conditions, July 2011 through June 2013.—Continued

[Continuous real-time water-quality data are available on the U.S. Geological Survey National Real-Time Water-Quality Web site (*http://nrtwq.usgs.gov/ks*); *n*, number of measurements; min, minimum; max, maximum; med, median; µS/cm, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; mg/L, milligrams per liter; FNU, formazin nephelometric units; <, less than]

Water-quality property	Tomahawk					State Line				
	n	Min	Max	Mean	Med	*n*	Min	Max	Mean	Med
					Below-normal streamflow conditions[1]					
Specific conductance (µS/cm)	18,395	588	3,570	1,065	948	18,411	585	3,670	1,069	1,070
pH	18,395	7.1	8.6	7.9	7.8	18,411	7.1	9.5	7.7	7.5
Water temperature (°C)	18,395	-0.10	34.4	17.5	19.1	18,411	2.50	34.8	19.8	20.4
Dissolved oxygen (mg/L)	18,279	1.6	17	8.2	7.6	18,411	0.50	26	7.9	7.5
Turbidity (FNU)	18,098	0.10	18	1.0	0.60	17,805	0.10	120	3.1	1.8
Nitrate (mg/L)[2]	11,276	<0.1	0.68	0.18	0.16	10,041	2.4	11.9	8.2	8.3
					Normal streamflow conditions[3]					
Specific conductance (µS/cm)	34,451	397	6,050	1,058	899	34,267	404	4,630	1,120	1,030
pH	34,451	7.3	8.5	7.9	8.0	34,267	7.0	9.0	7.6	7.6
Water temperature (°C)	34,451	-0.10	33.3	13.6	12.9	34,267	0.10	32.2	15.6	15.3
Dissolved oxygen (mg/L)	34,333	0.80	16	8.9	8.9	34,267	0.70	27	8.3	8.2
Turbidity (FNU)	34,438	0.10	220	2.9	1.2	34,050	0.40	69	4.1	3.1
Nitrate (mg/L)[2]	19,434	<0.1	2.2	0.52	0.49	21,449	2.0	12.1	6.7	6.6
					Above-normal streamflow conditions[4]					
Specific conductance (µS/cm)	16,609	132	5,940	972	782	17,498	145	5,640	1,023	863
pH	16,609	7.4	8.5	7.9	7.9	17,498	7.1	9.1	7.7	7.6
Water temperature (°C)	16,609	-0.20	29.5	13.6	13.3	17,498	1.60	31.7	14.4	13.7
Dissolved oxygen (mg/L)	16,609	3.3	16	9.1	9.1	17,498	2.0	20	10	10
Turbidity (FNU)	16,394	0.20	900	32	9.4	17,128	1.3	1,290	44	13
Nitrate (mg/L)[2]	11,438	<0.1	3.6	1.3	1.2	12,286	0.09	10.7	3.2	3.0

[1] Below-normal streamflow conditions were defined as streamflows less than the 25th percentile for the period July 1, 2011, through June 30, 2013. Below-normal streamflows were less than 0.8, 13, 14, 14, 2.4, and 22 cubic feet per second for the 119th, College, Marty, Mission Farms, Tomahawk, and State Line sites, respectively.

[2] Nitrate was measured at all sites during April 2012 through June 2013.

[3] Normal streamflow conditions were defined as streamflows between the 25th and 75th percentiles using streamflow duration curves for the period July 1, 2011, through June 30, 2013. Normal streamflows were between 0.8 and 4.3, 13 and 22, 14 and 27, 14 and 29, 2.4 and 12, and 22 and 53 cubic feet per second for the 119th, College, Marty, Mission Farms, Tomahawk, and State Line sites, respectively.

[4] Above-normal streamflow conditions were defined as streamflows greater than the 75th percentile using streamflow duration curves for the period July 1, 2011, through June 30, 2013. Above-normal streamflows were greater than 4.3, 22, 27, 29, 12, and 53 cubic feet per second for the 119th, College, Marty, Mission Farms, Tomahawk, and State Line sites, respectively.

occurred during February 2012 and December 2012 through March 2013, indicating that road salt likely affected specific conductance at all sites.

pH is a measure of the effective hydrogen ion concentration and is often used to evaluate chemical and biological reactions in water (Hem, 1992). Kansas aquatic life support criteria require that pH in streams not measure less than 6.5 or more than 8.5 standard units (Kansas Department of Health and Environment, 2005). Median pH values at the State Line site varied by 0.2 standard units or less among the before-upgrade, transitional, and after-upgrade periods at the Middle Basin WWTF (fig. 5*B*, table 3). Measured pH was never lower than 6.5 (minimum 6.9), but exceeded the maximum aquatic life support criterion of 8.5 standard units about 1 percent of the time during the before-upgrade and transitional periods and about 2 percent of the time during the after-upgrade period (fig. 5*B*). Exceedances typically were in March through August during below-normal and normal streamflows. Exceedances generally were for a few hours or days rather than for extended periods of time, and likely were caused by increased algal photosynthesis.

In general, pH at the sites located immediately downstream from the WWTFs (College and State Line) was lower than at the other sites (fig. 6*B*); median values were 0.3 to 0.4 standard units lower at the College and State Line (7.5–7.6) sites than the other sites (7.8–8.0) across the range of streamflow conditions (table 4). Wastewater effluent may have influenced pH at the College and State Line sites. During July 2011 through June 2013, the median pH of effluent from the Middle Basin (*n*=312, median=7.2, range=6.4–7.8) and Tomahawk Creek (*n*=288, median=7.2, range=6.3–7.9) WWTFs was 0.3 to 0.8 standard units lower than measured at the Indian Creek study sites. Measured pH was never lower than 6.5 (minimum 6.9) during the study period, but exceeded the maximum aquatic life support criterion of 8.5 standard units at all sites except College. The criterion was only exceeded once at the Tomahawk site. With the exception of the College and Tomahawk sites, the frequency at which pH exceeded 8.5 increased along the upstream-downstream gradient. pH exceeded 8.5 less than 1 percent of the time at the 119th site, about 2 percent of the time at the Marty site, and about 3 percent of the time at the Mission Farms and State Line sites. Exceedances typically were during below-normal and normal streamflows, but the timing of exceedances varied among sites. At the 119th site, most exceedances were in April and August–September. Most exceedances at the Marty site were during January–February and August. Exceedances at the Mission Farms site were almost exclusively during January through April. By comparison, exceedances at the State Line site were during March through August. Among-site differences in occurrence of pH exceedances may have been caused by differences in biological activity. Wastewater influences on pH at the downstream sites also may have influenced the occurrence of exceedances. Exceedances generally were for a few hours or days rather than for extended periods of time.

Water temperature affects the solubility of chemicals in water and biological activity. Kansas water-quality criteria require that discharges to streams not change water temperature more than 3 degrees Celsius (°C) or raise the water temperature above 32 °C (Kansas Department of Health and Environment, 2005). Differences in water temperature at the State Line site during the before-upgrade, transitional, and after-upgrade periods were small (fig. 5*C*, table 3); overall median water temperature at the State Line site varied by 1.3 °C during the before-upgrade (16 °C), transitional (15 °C), and after-upgrade (17 °C) periods. Differences in water temperature were observed along the upstream-downstream gradient in Indian Creek across the range of streamflow conditions, and were most pronounced at the College site located immediately downstream from the Middle Basin WWTF (fig. 6*C*, table 4). Water temperature at the wastewater-influenced sites commonly was warmer in the winter and cooler in the summer than at the upstream sites. For example, on average, water temperature at the College site was 10 °C warmer than at the 119th site during November–February and 2 °C cooler during June–August. Differences were less pronounced as distance from the Middle Basin WWTF increased; however, at the Mission Farms site located 9.5-km downstream, water temperature was, on average, 3 °C warmer than at the 119th site during November–February and 0.4 °C cooler during June–August. The influence of the Tomahawk Creek effluent on water temperatures at the State Line site was not as evident, likely because of the influence of Middle Basin effluent and cooler effluent temperatures (2.0 °C on average) from the Tomahawk Creek WWTF relative to the Middle Basin WWTF; however, water temperatures typically were warmer at the State Line site (0.5 °C on average) than at the Mission Farms site (fig. 6*C*). Wastewater discharges from the Middle Basin and Tomahawk Creek WWTFs did not raise water temperatures at the downstream sites above the KDHE criterion of 32 °C. The KDHE criterion that wastewater discharges to streams not change water temperature by more than 3 °C was frequently exceeded downstream from the Middle Basin WWTF. Water temperature at the College site was more than 3 °C higher than at the 119th site about 52 percent of the time during July 2011 through June 2014. By comparison, water temperature at the State Line site was more than 3 °C higher than at the Mission Farms site less than 1 percent of the time. About 75 percent of exceedances at the College and State Line sites were during October–February.

Dissolved oxygen is an important factor for the survival of aquatic organisms, and concentrations in surface water are related primarily to photosynthesis, respiration, atmospheric reaeration, and water temperature (Lewis, 2006). Kansas aquatic life support criteria require that dissolved oxygen concentrations are not less than 5.0 mg/L (Kansas Department of Health and Environment, 2005). Dissolved oxygen concentrations at the State Line site generally were similar across the range of streamflow conditions during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin WWTF (fig. 5*D*, table 3). Dissolved oxygen concentrations were less than the minimum aquatic- life-support criterion about 14 percent of the time during the before- and after-upgrade periods and about 8 percent of the time during the transitional period. Dissolved oxygen concentrations generally were highest at the 119th site, upstream from the Middle Basin WWTF, and lowest at the College site, immediately downstream from the Middle Basin WWTF (fig. 6*D*, table 4). Dissolved oxygen concentrations were less than the minimum aquatic life support criterion about 17 percent of the time at the State Line site, 10 percent of the time at the two upstream sites, and less than 1 percent of the time at all other sites, including College (fig. 6*D*). Dissolved oxygen concentrations less than 5 mg/L typically were at night in May through October during below-normal and normal streamflows, reflecting increased water temperatures and the influence of biological activity during seasonal low flows. Lower dissolved oxygen concentrations overall at the College site are likely a result of warmer water temperatures (fig. 6*C*) during winter because of the Middle Basin effluent; however, the low frequency of concentrations less than 5 mg/L at the College, Marty, and Mission Farms sites may reflect greater streamflows during summer months and reaeration by the WWTF. Dissolved oxygen concentrations may have been below the Kansas aquatic life support criterion most frequently at the State Line site because of biological activity resulting in large diurnal fluctuations. Dissolved oxygen concentration varied by as much as 24 mg/L diurnally at the State Line site, compared to maximum diurnal differences of between 8 and 15 mg/L at all other sites.

Turbidity, Suspended Solids, and Suspended Sediment

Suspended solids and sediment in stream water typically are from erosion and subsequent transport of surface and channel bank soils. Increased suspended sediment in streams decreases light penetration and photosynthesis, smothers benthic habitats, and interferes with feeding activities (Wetzel, 2001). In addition, suspended particulates promote sorption of nutrients, organic compounds, and other potential contaminants. Turbidity, caused by suspended and dissolved matter such as clay, silt, fine organic matter, microscopic organisms, organic acids, and dyes (Wetzel, 2001), often is used as a surrogate for suspended solids and sediment.

Turbidities at the State Line site during June 2004 through June 2013 generally were similar during below-normal and normal streamflows [mean and median values within 4 formazin nephelometric units (FNU)]; however, mean turbidities during above-normal streamflows were 46 percent larger during the before-upgrade period and 10 percent larger during the transitional period than during the after-upgrade period (fig. 5*E*, table 3). The EPA guidelines for turbidity (based on reference conditions) list 15.5 FNUs for level III ecoregion 40 (central irregular plains) streams, which includes Indian Creek (U.S. Environmental Protection Agency, 2000a). Guidelines are nonenforceable criteria developed for the protection of water quality, aquatic life, and human health. Turbidities exceeded 15.5 FNUs about 22 percent of the time during the before-upgrade and transitional periods and about 15 percent of the time during the after-upgrade period. Most of the exceedances were during above-normal streamflows.

Along the upstream-downstream gradient, turbidities were lower at the upstream sites than the downstream sites about 50 percent of the time (fig. 6*E*, table 4); however, overall among-site differences during below-normal and normal streamflows generally were small (less than 3 FNU). During above-normal streamflows, mean and median turbidities were about 28 percent and 33 percent higher, respectively, at the three most downstream sites (Marty, Mission Farms, and State Line) than at the other sites upstream (119th, College, and Tomahawk). Turbidities exceeded 15.5 FNUs between 8 and 13 percent of the time during July 2011 through June 2013; exceedances were lowest at the College site and highest at the Mission Farms site.

Suspended solids are effectively removed by most wastewater treatment processes, and in Johnson County, turbidity, total suspended solids, and sediment concentrations typically are lower downstream from wastewater effluent discharges than upstream during below-normal streamflows (Lee and others, 2005; Wilkison and others, 2006; Rasmussen and others, 2008, 2009b, 2012, 2014; Graham and others, 2010). Higher turbidities during above-normal streamflows during the before-upgrade and transitional periods at the State Line site and at the downstream sites during July 2011 through June 2013 likely are due to larger drainage basin areas or activities, such as construction, that increased sediment runoff, rather than wastewater influences. Construction efforts are recognized causes of increased sediment loads (Lee and Ziegler, 2010).

Patterns in total suspended solids (TSS) and suspended-sediment concentration (SSC) at the State Line site during 2004 through 2013 match patterns in turbidity (fig. 5*E*, tables 3 and 5). During below-normal and normal streamflows, TSS and SSC between the before- and after-upgrade periods generally were similar (median values within 5.5 mg/L). As observed with turbidity, during above-normal streamflows, median TSS and SSC were higher (7 and 22 percent, respectively) during the before-upgrade period than the after-upgrade period. Patterns in TSS and SSC did not necessarily match among-site patterns in turbidity (fig. 6*E*, tables 4 and 6). Among-site differences in median TSS and SSC values during below-normal and normal streamflows generally were small (less than 7 mg/L); however, maximum values at the 119th, Marty, and Mission Farms sites were between 46 and 130 percent higher than at the College, Tomahawk, and State Line sites. During above-normal streamflows, median TSS and SSC were 56 to 148 percent higher at the sites located on Indian Creek than at the Tomahawk site. Among the sites located on Indian Creek, TSS and SSC were lowest at the 119th and Mission Farms sites (TSS medians 134 and 136 mg/L, respectively; SSC medians 173 and 182 mg/L, respectively) and highest at the College and Marty sites (TSS medians 497 and 504 mg/L, respectively; SSC medians 567 and 478 mg/L,

Table 5. Summary of results from discrete water-quality samples collected at the State Line study site during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin Wastewater Treatment Facility, June 2004 through June 2013.

[*n*, number of samples; ft^3/s, cubic feet per second; --, not applicable; %, percent; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; NTRU, nephelometric turbidity ratio unit; <, less than; col/100 mL, colonies per 100 milliliters of sample]

Water-quality property or chemical (unit of measure)	Before upgrade			Transitional			After upgrade		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median
				Below-normal and normal streamflow conditions					
Physical properties, suspended solids, and sediment									
Streamflow (ft^3/s)	10	14–60	33	1	64	--	8	19–60	28
Wastewater effluent (% streamflow)	10	2.4–100	56	1	12	--	8	43–100	78
Dissolved oxygen, field (mg/L)	9	9.3–14	10	1	8.0	--	8	4.7–15	10
pH, field (standard units)	10	7.2–8.2	7.9	1	7.8	--	8	7.3–8.4	7.8
Specific conductance, field (µS/cm)	10	298–5,760	1,120	1	926	--	8	831–3,860	1,250
Water temperature, field (degrees Celsius)	10	2.80–26.7	8.90	1	16.9	--	8	4.70–28.2	16.1
Turbidity, laboratory (NTRU)	7	<2–360	4.0	1	22	--	7	1.6–7.4	5.6
Total suspended solids (mg/L)	7	<10–828	5.00	1	24.0	--	7	all <10	7.50
Suspended sediment (mg/L)	8	2.0–836	6.50	1	26.0	--	7	3.0–50.0	12.0
Dissolved solids and major ions									
Dissolved solids (mg/L)	9	206–3,030	620	1	543	--	7	575–2,190	780
Calcium (mg/L)	10	26.2–138	80.2	1	67.6	--	7	56.8–109	72.2
Magnesium (mg/L)	10	3.93–23.2	15.9	1	10.0	--	7	13.3–19.7	19.0
Potassium (mg/L)	10	3.00–13.7	8.64	1	4.8	--	7	7.00–15.9	14.7
Sodium (mg/L)	10	21.5–933	99.0	1	86.0	--	7	84.2–623	174
Chloride (mg/L)	10	32.0–1,680	161	1	155	--	7	137–1,020	225
Sulfate (mg/L)	10	20.0–128	108	1	62.0	--	7	94.0–155	139
Nutrients and carbon									
Ammonia plus organic, total, as nitrogen (mg/L)	10	0.89–3.60	1.70	1	1.80	--	7	1.20–4.10	1.70
Nitrite plus nitrate as nitrogen, dissolved (mg/L)	10	0.70–9.72	5.34	1	2.05	--	8	3.56–10.2	6.92
Ammonia, as nitrogen (mg/L)	10	<0.04–1.20	0.63	1	0.19	--	7	0.08–2.56	0.50
Total nitrogen (mg/L)[1]	10	4.30–11.4	7.24	1	3.85	--	7	5.16–14.0	9.00
Orthophosphorus, as phosphorus (mg/L)	9	0.11–2.64	1.18	1	0.28	--	6	0.39–1.60	0.98
Dissolved phosphorus (mg/L)	10	0.17–2.80	1.34	1	0.33	--	7	0.39–1.65	0.84
Total phosphorus (mg/L)	10	0.66–2.80	1.38	1	0.42	--	7	0.43–1.75	0.90
Particulate phosphorus (mg/L)[2]	10	<0.05–0.85	0.06	1	0.09	--	7	<0.05–0.12	0.06
Dissolved organic carbon (mg/L)	1	7.12	--	1	6.43	--	7	3.53–8.32	7.58
Total organic carbon (mg/L)	1	19.8	--	1	7.60	--	7	6.70–11.2	9.30
Biochemical and bacteria									
Biochemical oxygen demand (mg/L)	1	11	--	1	7.0	--	6	4.0–8.0	4.0
Chemical oxygen demand (mg/L)	1	126	--	1	20	--	7	24–56	33
Enterococci (col/100 mL)	6	<10–9,700	28	1	200	--	6	10–360	330
Escherichia coli (col/100 mL)	6	20–20,000	590	1	1,100	--	6	<10–260	800
Fecal coliform (col/100 mL)	7	30–23,000	30	1	104	--	7	<10–330	86

Table 5. Summary of results from discrete water-quality samples collected at the State Line study site during the before-upgrade, transitional, and after-upgrade periods at the Middle Basin Wastewater Treatment Facility, June 2004 through June 2013.—Continued

[*n*, number of samples; ft^3/s, cubic feet per second; --, not applicable; %, percent; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; NTRU, nephelometric turbidity ratio unit; <, less than; col/100 mL, colonies per 100 milliliters of sample]

Water-quality property or chemical (unit of measure)	Before upgrade			Transitional			After upgrade		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median
Above-normal streamflow conditions									
Physical properties, suspended solids, and sediment									
Streamflow (ft^3/s)	18	71–9,660	1,460	5	468–9,220	2,180	13	151–2,190	1,140
Wastewater effluent (% streamflow)	18	0.39–39	2.8	5	0.30–16	3.1	13	3.5–39	7.7
Dissolved oxygen, field (mg/L)	18	6.4–13	8.8	5	7.2–8.4	7.6	13	6.5–11	8.2
pH, field (standard units)	18	7.5–8.2	7.7	5	7.6–8.0	7.8	13	6.8–8.0	7.8
Specific conductance, field (µS/cm)	18	211–3,330	336	5	185–728	239	13	224–1,260	523
Water temperature, field (degrees Celsius)	18	3.80–24.3	17.6	5	15.9–22.6	19.2	13	8.40–25.1	15.0
Turbidity, laboratory (NTRU)	17	18–750	270	5	140–490	330	13	30–400	200
Total suspended solids (mg/L)	17	26.0–1,900	538	5	132–1,280	668	13	55–1,370	502
Suspended sediment (mg/L)	17	21.0–1,880	672	5	147–1,730	749	13	63.0–1,480	537
Dissolved solids and major ions									
Dissolved solids (mg/L)	18	102–1,780	206	5	136–604	187	13	112–724	294
Calcium (mg/L)	18	15.3–128	28.5	5	19.3–74.6	20.0	13	19.3–63.0	39.9
Magnesium (mg/L)	18	2.00–18.9	4.17	5	2.70–12.0	3.30	13	2.50–10.9	6.00
Potassium (mg/L)	18	2.30–6.69	3.50	5	2.60–4.10	3.60	13	2.70–7.74	4.20
Sodium (mg/L)	18	8.20–524	26.7	5	9.90–54.0	16.1	13	13.8–200	51.2
Chloride (mg/L)	18	9.00–857	32.9	5	12.0–89.0	25.0	13	17.0–304	63.6
Sulfate (mg/L)	18	11.5–93.7	26.0	5	16.0–63.0	18.0	13	17.0–62.0	40.0
Nutrients and carbon									
Ammonia plus organic, total, as nitrogen (mg/L)	18	1.20–8.00	2.40	5	1.30–4.30	1.90	13	1.30–4.20	2.80
Nitrite plus nitrate as nitrogen, dissolved (mg/L)	18	0.43–4.44	1.06	5	0.51–1.70	0.82	13	0.70–2.77	1.43
Ammonia, as nitrogen (mg/L)	18	0.07–1.00	0.20	5	0.11–0.20	0.17	13	<0.04–0.33	0.20
Total nitrogen (mg/L)[1]	18	2.30–10.8	3.28	5	1.87–4.81	3.50	13	2.63–5.66	4.10
Orthophosphorus, as phosphorus (mg/L)	17	0.09–0.77	0.16	5	0.06–0.21	0.10	12	<0.05–0.48	0.26
Dissolved phosphorus (mg/L)	18	0.11–0.86	0.18	5	0.11–0.25	0.15	13	<0.05–0.57	0.33
Total phosphorus (mg/L)	18	0.32–2.67	0.76	5	0.36–1.48	0.64	13	0.17–1.45	0.68
Particulate phosphorus (mg/L)[2]	18	<0.05–2.13	0.60	5	0.19–1.33	0.53	13	0.08–1.10	0.52
Dissolved organic carbon (mg/L)	2	4.25–6.67	5.46	5	2.72–8.51	5.64	12	4.86–15.8	6.11
Total organic carbon (mg/L)	2	12.8–30.4	21.6	5	11.9–25.2	18.6	12	9.3–32.5	19.8
Biochemical and bacteria									
Biochemical oxygen demand (mg/L)	2	9.0–10	9.5	5	4.0–11	7.0	12	4.0–17	10
Chemical oxygen demand (mg/L)	1	146	--	5	45–216	94	12	29–137	84
Enterococci (col/100 mL)	14	120–35,000	19,500	5	140–92,000	48,000	12	40–25,000	10,700
Escherichia coli (col/100 mL)	14	8,500–37,000	10,800	5	13,000–36,000	29,000	12	29,000–33,000	8,000
Fecal coliform (col/100 mL)	16	1,200–140,000	23,000	5	2,800–60,000	36,000	13	570–55,000	14,000

[1] Calculated as the sum of nitrite plus nitrate, dissolved, and ammonia plus organic, total.

[2] Calculated as the difference between total phosphorus and dissolved phosphorus.

respectively). Elevated concentrations at the College and Marty sites during above-normal streamflows may be due to bridge construction upstream from the College site (but downstream from the 119th site) during the study period.

Dissolved Solids and Major Ions

Major constituents of dissolved solids generally are calcium, magnesium, sodium, potassium, bicarbonate, carbonate, sulfate, and chloride ions. The amount of dissolved solids in stream water primarily is determined by the amount of groundwater contributing to streamflow, the amount of urbanization, and effluent discharges from wastewater and industrial sites (Hem, 1992). Water use often results in the addition of dissolved solids to the wastewater effluent stream; for example, when chloride is added through chlorination of drinking water and sodium and chloride are added through water softeners.

Overall, dissolved solids concentrations at the State Line site were higher during the after-upgrade period than the before-upgrade period. Median concentrations were 23 percent higher during below-normal and normal streamflows (before-upgrade median=620 mg/L; after-upgrade median=780 mg/L) and 35 percent higher during above-normal streamflows (before-upgrade median=206 mg/L; after-upgrade median=294 mg/L) (table 5). The increase in dissolved solids concentrations between the before- and after-upgrade periods largely was due to increased concentrations of sodium and chloride, and likely was caused by differences in road salt application and runoff, rather than changes in wastewater treatment processes.

There were no consistent patterns in concentrations of dissolved solids and major ions along the upstream-downstream gradient during June 2011 through June 2013; however, there was a clear increase in concentrations between the upstream 119th site and the College site, located immediately downstream from the Middle Basin WWTF (fig. 1, table 6). Median dissolved solids concentrations increased by about 27 to 34 percent between the 119th (below-normal and normal streamflow median=521 mg/L; above-normal streamflow median=224 mg/L) and College (below-normal and normal streamflow median=664 mg/L; above-normal streamflow median=301 mg/L) sites depending on streamflow conditions. The increase in concentration downstream from the Middle Basin WWTF largely was due to increased concentrations of potassium, sodium, chloride, and sulfate (table 6). Increasing streamflow dilutes dissolved solids concentrations because of low concentrations in rainfall and runoff. In general, concentrations of dissolved solids were between 70 and 85 percent lower at all sites during above-normal streamflows than below-normal and normal streamflows (table 6).

Of the chemicals that make up dissolved solids, chloride is the only one with an established criterion for protection of aquatic life (U.S. Environmental Protection Agency, 1988). The EPA acute exposure criterion is 860 mg/L and the chronic exposure criterion is 230 mg/L. Based on discrete samples (tables 5 and 6), acute and chronic exposure criteria were occasionally exceeded at all sites. Continuous estimates of chloride concentration were calculated from regression models that used specific conductance as an explanatory variable (appendix 4; Stone and Graham, 2014). Based on these estimates, the chronic exposure criterion was exceeded about 15 percent of the time during the before- and after-upgrade periods at the State Line site and about 24 percent of the time during the transitional period. The acute exposure criterion was exceeded between 1 and 3 percent of the time at the State Line site during June 2004 through June 2013. Along the upstream-downstream gradient during July 2011 through June 2013, the chronic exposure criterion was exceeded between 12 and 14 percent of the time and the acute exposure criterion was exceeded between 1 and 3 percent of the time at all sites. Exceedances of the chronic and acute exposure criteria likely are the result of runoff during winter road-salt application periods. All exceedances were between late November and early April, the period of peak road-salt application. Between December 2012 and April 2013, computed chloride concentrations exceeded the chronic exposure criterion for between 96 and 110 days; the chronic criterion was exceeded for at least 47 consecutive days at all sites. The acute criterion was exceeded between 5 and 18 consecutive days during this time period, with the largest number of consecutive days at the two upstream sites.

Nutrients

Data from discrete stream-water and wastewater effluent samples were used to describe nutrient concentrations at the State Line site during the before-upgrade (June 2004 through May 2008), transitional (June 2008 through May 2010), and after-upgrade (June 2010 through June 2013) periods at the Middle Basin WWTF. Discretely sampled and continuously measured data were used to describe nutrient concentrations upstream and downstream from the Middle Basin and Tomahawk Creek WWTFs. Continuous TN and TP data, developed from regression models that utilized discrete data, were used to compute total nutrient loads during 2005 through 2012 at the State Line site and during July 2011 through June 2013 at all Indian Creek study sites.

Nutrients in Wastewater Effluent

The transition to biological nutrient removal (BNR) at the Middle Basin WWTF was made between June 2008 and May 2010. Biological nutrient removal enhances the removal of both nitrogen and phosphorus. Starting in 2009, CEPT using ferric chloride was used for improved process settling, with the added effect of enhanced phosphorus removal, at the Tomahawk Creek WWTF. There are currently (2014) no nitrogen removal treatment processes at the Tomahawk Creek WWTF.

Annual mean TN concentration in the Middle Basin WWTF effluent decreased by about 46 percent, on

Table 6. Summary of results from discrete water-quality samples collected at all Indian Creek study sites, June 2011 through June 2013.

[*n*, number of samples; ft3/s, cubic feet per second; --, not applicable; %, percent; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; NTRU, nephelometric turbidity ratio unit; <, less than; col/100 mL, colonies per 100 milliliters of sample]

Water-quality property or chemical (unit of measure)	119th			College			Marty		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median
			Below-normal and normal streamflow conditions						
Physical properties, suspended solids, and sediment									
Streamflow (ft^3/s)	5	0.43–1.1	0.76	5	10–17	14	5	4.4–20	14
Wastewater effluent (% streamflow)	--	--	--	5	80–100	100	5	74–100	100
Dissolved oxygen, field (mg/L)	6	6.2–14	9.5	5	6.4–10	7.4	5	7.9–15	9.3
pH, field (standard units)	6	7.4–8.3	7.8	5	6.7–7.9	7.5	5	6.8–8.4	8.1
Specific conductance, field (µS/cm)	6	699–1,190	806	5	930–1,440	1,090	5	905–1,310	1,100
Water temperature, field (degrees Celsius)	6	0.00–26.3	21.0	5	11.9–23.9	22.2	5	6.10–26.9	21.8
Turbidity, laboratory (NTRU)	6	1.3–80	3.1	5	1.1–4.8	2.0	5	2.5–8.1	3.9
Total suspended solids (mg/L)	6	<15.0–75.0	<15.0	5	<15.0–7.50	<15.0	5	<15.0–26.0	<15.0
Suspended sediment (mg/L)	6	2.00–100	9.00	5	3.00–26.0	9.00	5	4.00–94.0	13.0
Dissolved solids and major ions									
Dissolved solids (mg/L)	6	448–653	521	5	611–831	664	5	585–770	643
Calcium (mg/L)	6	68.4–119	80.5	5	55.4–65.9	62.8	5	59.3–68.8	63.2
Magnesium (mg/L)	6	11.4–20.8	13.7	5	12.9–19.1	15.8	5	11.4–19.7	17.0
Potassium (mg/L)	6	2.90–4.50	3.80	5	15.4–18.4	16.9	5	13.3–19.1	17.3
Sodium (mg/L)	6	59.2–101	65.4	5	95.9–186	128	5	91.2–164	127
Chloride (mg/L)	6	79.0–187	110	5	121–264	139	5	125–217	150
Sulfate (mg/L)	6	54.0–102	80.0	5	100–144	135	5	92.0–142	134
Nutrients and carbon									
Ammonia plus organic, total, as nitrogen (mg/L)	6	<0.50–0.80	0.70	5	1.00–1.40	1.30	5	1.00–1.20	1.20
Nitrite plus nitrate as nitrogen, dissolved (mg/L)	6	<0.02–0.40	0.12	5	5.87–11.1	9.96	5	7.05–9.70	7.40
Ammonia, as nitrogen (mg/L)	6	<0.04–0.06	<0.04	5	<0.04–0.13	0.07	5	<0.04–0.07	<0.04
Total nitrogen (mg/L)[1]	6	0.26–1.20	0.75	5	7.17–12.4	11.1	5	8.25–10.7	8.60
Orthophosphorus, as phosphorus (mg/L)	6	all <0.05	<0.05	5	<0.05–4.97	2.08	5	<0.05–5.08	1.56
Dissolved phosphorus (mg/L)	6	all <0.05	<0.05	5	0.10–4.97	2.08	5	0.10–5.08	1.59
Total phosphorus (mg/L)	6	<0.05–0.06	<0.05	5	0.12–4.97	2.12	5	0.11–5.08	2.13
Particulate phosphorus (mg/L)[2]	6	all <0.05	<0.05	5	<0.05–0.07	<0.05	5	<0.05–0.58	<0.05
Dissolved organic carbon (mg/L)	6	3.18–7.84	3.94	5	3.94–7.03	6.32	5	4.88–6.52	5.80
Total organic carbon (mg/L)	6	3.30–7.30	5.50	5	7.10–8.80	7.40	5	6.60–8.40	6.90
Biochemical and bacteria									
Biochemical oxygen demand (mg/L)	6	all <2.0	<2.0	4	all <2.0	<2.0	4	<2.0–2.0	<2.0
Chemical oxygen demand (mg/L)	6	5–29	16	5	17–31	24	5	15–33	24
Enterococci (col/100 mL)	6	<10–300	68	4	160–240	185	4	20–200	38
Escherichia coli (col/100 mL)	6	<10–200	130	4	140–360	260	4	41–360	220
Fecal coliform (col/100 mL)	6	10–890	155	5	80–260	210	5	52–560	309

Table 6. Summary of results from discrete water-quality samples collected at all Indian Creek study sites, June 2011 through June 2013.—Continued

[*n*, number of samples; ft3/s, cubic feet per second; --, not applicable; %, percent; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; NTRU, nephelometric turbidity ratio unit; <, less than; col/100 mL, colonies per 100 milliliters of sample]

Water-quality property or chemical (unit of measure)	119th			College			Marty		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median
Above-normal streamflow conditions									
Physical properties, suspended solids, and sediment									
Streamflow (ft^3/s)	14	4.6–1,510	141	12	25–2,230	298	13	33–954	419
Wastewater effluent (% streamflow)	--	--	--	12	0.75–99	5.9	13	2.1–70	4.7
Dissolved oxygen, field (mg/L)	14	7.1–18	10	12	7.5–11	9.6	13	7.2–15	9.8
pH, field (standard units)	14	6.5–8.5	7.9	12	7.2–8.1	7.7	13	6.9–8.5	7.9
Specific conductance, field (µS/cm)	14	109–4,020	410	12	138–2,490	497	13	162–3,420	418
Water temperature, field (degrees Celsius)	14	1.60–23.7	9.50	12	7.20–22.7	12.6	13	6.90–23.8	12.3
Turbidity, laboratory (NTRU)	14	2.9–480	60	12	3.5–800	190	13	3.0–560	97
Total suspended solids (mg/L)	14	<15.0–1,440	134	12	<15.0–1,920	497	13	<15.0–1,640	504
Suspended sediment (mg/L)	14	5.00–1,790	173	12	6.00–2,580	567	13	6.00–1,950	478
Dissolved solids and major ions									
Dissolved solids (mg/L)	14	58.0–2,260	224	12	68.0–1,420	301	13	93.0–1,940	262
Calcium (mg/L)	14	11.7–120	28.5	12	14.1–94.6	36.4	13	16.4–108	32.6
Magnesium (mg/L)	14	1.30–18.4	3.90	12	1.70–18.1	7.00	13	2.10–19.8	5.20
Potassium (mg/L)	14	1.60–4.00	2.90	12	2.00–10.2	3.40	13	2.50–9.40	4.00
Sodium (mg/L)	14	6.50–676	39.1	12	8.80–398	46.8	13	12.4–570	37.3
Chloride (mg/L)	14	8.00–1,100	54.0	12	10.0–643	59.5	13	15.0–931	50.0
Sulfate (mg/L)	14	<5.00–94.0	26.0	12	12.0–118	38.0	13	15.0–117	38.0
Nutrients and carbon									
Ammonia plus organic, total, as nitrogen (mg/L)	14	0.40–3.20	1.50	12	1.10–5.50	2.40	13	1.00–5.10	2.40
Nitrite plus nitrate as nitrogen, dissolved (mg/L)	14	0.04–1.85	0.76	12	0.53–4.41	1.46	13	0.63–4.50	1.39
Ammonia, as nitrogen (mg/L)	14	<0.02–0.30	0.11	12	0.02–0.24	0.12	13	0.02–1.03	0.20
Total nitrogen (mg/L)[1]	14	0.44–4.15	2.20	12	2.88–6.03	4.22	13	2.20–6.74	3.79
Orthophosphorus, as phosphorus (mg/L)	14	<0.05–0.15	<0.05	12	<0.05–1.23	0.13	13	0.05–1.24	0.19
Dissolved phosphorus (mg/L)	14	<0.05–0.21	0.06	12	<0.05–1.31	0.18	13	0.05–1.27	0.20
Total phosphorus (mg/L)	14	<0.05–1.00	0.30	12	0.06–1.81	0.98	13	0.05–2.22	0.73
Particulate phosphorus (mg/L)[2]	14	<0.05–0.95	0.18	12	<0.05–1.71	0.63	13	<0.05–1.69	0.53
Dissolved organic carbon (mg/L)	14	3.13–9.01	4.85	12	4.24–7.72	4.97	13	4.02–9.82	5.62
Total organic carbon (mg/L)	14	4.40–27.9	10.6	12	6.80–48.6	19.1	13	6.10–44.1	19.6
Biochemical and bacteria									
Biochemical oxygen demand (mg/L)	12	<2.0–9.0	6.0	12	4.0–15	8.0	12	<2.0–19	7.0
Chemical oxygen demand (mg/L)	14	20–110	41	12	26–192	53	13	26–178	63
Enterococci (col/100 mL)	12	10–110,000	7,400	12	100–69,000	8,400	12	10–82,000	6,000
Escherichia coli (col/100 mL)	12	41–69,000	5,800	12	320–310,000	5,200	12	410–31,000	5,400
Fecal coliform (col/100 mL)	14	30–52,000	3,000	12	130–100,000	3,000	13	240–60,000	5,800

Table 6. Summary of results from discrete water-quality samples collected at all Indian Creek study sites, June 2011 through June 2013.—Continued

[*n*, number of samples; ft^3/s, cubic feet per second; %, percent; --, not applicable; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; NTRU, nephelometric turbidity ratio unit; <, less than; col/100 mL, colonies per 100 milliliters of sample]

Water-quality property or chemical (unit of measure)	Mission Farms			Tomahawk			State Line		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median
Below-normal and normal streamflow conditions									
Physical properties, suspended solids, and sediment									
Streamflow (ft^3/s)	7	9.5–26	14	6	0.64–12	2.7	5	19–34	22
Wastewater effluent (% streamflow)	7	72–100	99	--	--	--	5	44–67	64
Dissolved oxygen, field (mg/L)	7	6.2–13	9.1	6	4.6–14	8.0	5	5.8–12	9.7
pH, field (standard units)	7	7.8–8.7	8.1	6	7.0–8.1	7.6	5	7.3–8.3	7.8
Specific conductance, field (µS/cm)	7	919–4,120	1,140	6	827–1,940	1,120	5	894–1,460	1,130
Water temperature, field (degrees Celsius)	7	3.80–28.6	17.4	6	0.70–27.2	14.5	5	4.80–28.2	21.4
Turbidity, laboratory (NTRU)	7	3.5–11	5.5	6	1.4–7.6	2.8	5	1.6–6.1	3.2
Total suspended solids (mg/L)	7	<15.0–24.0	<15.0	6	<15.0–7.50	<15.0	5	<15.0–8.00	<15.0
Suspended sediment (mg/L)	7	5.00–66.0	14.0	6	4.00–17.0	7.00	5	3.00–50.0	12.0
Dissolved solids and major ions									
Dissolved solids (mg/L)	7	589–2,320	696	6	532–1,030	638	5	575–828	676
Calcium (mg/L)	7	56.7–113	70.9	6	70.3–110	89.3	5	56.8–73.4	67.5
Magnesium (mg/L)	7	12.6–19.4	15.5	6	15.6–21.7	18.7	5	13.3–19.4	16.0
Potassium (mg/L)	7	8.70–16.8	15.0	6	2.80–4.80	3.50	5	10.6–15.9	15.0
Sodium (mg/L)	7	89.7–718	137	6	69.2–262	104	5	84.2–191	142
Chloride (mg/L)	7	126–1,080	152	6	80.0–429	144	5	137–258	142
Sulfate (mg/L)	7	84.0–144	123	6	96.0–148	112	5	94.0–155	149
Nutrients and Carbon									
Ammonia plus organic, total, as nitrogen (mg/L)	7	0.90–1.20	1.00	6	<0.50–0.90	0.50	5	1.20–4.10	1.80
Nitrite plus nitrate as nitrogen, dissolved (mg/L)	7	2.40–8.46	6.40	6	0.02–1.16	0.10	5	6.91–10.2	7.80
Ammonia, as nitrogen (mg/L)	7	<0.04–0.08	0.04	6	<0.04–0.04	<0.04	5	0.08–2.56	0.55
Total nitrogen (mg/L)[1]	7	3.40–9.46	7.50	6	0.27–2.06	0.56	5	8.71–14.0	10.3
Orthophosphorus, as phosphorus (mg/L)	7	0.10–2.96	0.50	6	all <0.05	<0.05	5	0.51–1.60	1.24
Dissolved phosphorus (mg/L)	7	0.17–2.98	0.58	6	all <0.05	<0.05	5	0.52–1.65	1.33
Total phosphorus (mg/L)	7	0.17–2.99	0.64	6	<0.05–0.05	<0.05	5	0.56–1.75	1.36
Particulate phosphorus (mg/L)[2]	7	<0.05–0.08	<0.05	6	all <0.05	<0.05	5	<0.05–0.12	0.06
Dissolved organic carbon (mg/L)	7	4.30–7.28	6.20	6	3.09–8.64	4.12	5	3.53–8.32	7.83
Total organic carbon (mg/L)	7	6.00–8.60	6.90	6	3.50–7.80	5.45	5	8.10–11.2	10.0
Biochemical and bacteria									
Biochemical oxygen demand (mg/L)	5	<2.0–3.0	<2.0	5	<2.0–3.0	<2.0	4	4.0–8.0	4.5
Chemical oxygen demand (mg/L)	7	18–54	22	6	15–35	20	5	24–42	31
Enterococci (col/100 mL)	5	10–380	20	5	20–600	41	4	10–360	30
Escherichia coli (col/100 mL)	5	20–340	110	5	<10–220	74	4	20–260	104
Fecal coliform (col/100 mL)	7	10–810	70	6	<10–3,900	52	5	<10–330	130

Table 6. Summary of results from discrete water-quality samples collected at all Indian Creek study sites, June 2011 through June 2013.—Continued

[*n*, number of samples; ft^3/s, cubic feet per second; %, percent; --, not applicable; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; NTRU, nephelometric turbidity ratio unit; <, less than; col/100 mL, colonies per 100 milliliters of sample]

Water-quality property or chemical (unit of measure)	Mission Farms			Tomahawk			State Line		
	n	Range	Median	*n*	Range	Median	*n*	Range	Median
Above-normal streamflow conditions									
Physical properties, suspended solids, and sediment									
Streamflow (ft^3/s)	11	30–3,040	318	10	14–1,510	170	12	58–2,190	478
Wastewater effluent (% streamflow)	11	1.0–83	6.1	--	--	--	12	1.0–42	4.7
Dissolved oxygen, field (mg/L)	11	6.8–11	9.8	11	6.6–14	9.6	12	6.5–15	9.8
pH, field (standard units)	11	6.9–8.3	7.9	11	7.4–8.1	7.9	12	6.8–8.4	7.9
Specific conductance, field (µS/cm)	11	191–1,510	451	11	216–3,340	477	12	224–3,860	546
Water temperature, field (degrees Celsius)	11	7.70–24.7	11.3	11	2.50–25.0	11.6	12	4.70–25.1	11.2
Turbidity, laboratory (NTRU)	11	4.9–590	75	11	4.8–490	51	12	5.6–400	84
Total suspended solids (mg/L)	11	<15.0–1,600	136	11	<15.0–1,320	75.0	12	<15.0–1,370	199
Suspended sediment (mg/L)	11	6.00–1,820	182	11	5.00–1,440	83.5	12	8.00–1,480	209
Dissolved solids and major ions									
Dissolved solids (mg/L)	11	122–888	278	11	94.0–1,870	308	12	112–2,190	324
Calcium (mg/L)	11	20.6–105	32	11	19.6–120	45.1	12	19.3–109	40.9
Magnesium (mg/L)	11	2.30–19.7	5.00	11	2.90–21.2	6.90	12	2.50–19.7	7.00
Potassium (mg/L)	11	2.50–7.70	3.40	11	1.90–4.00	2.90	12	2.70–8.30	4.30
Sodium (mg/L)	11	14.3–190	32.3	11	11.8–521	39.4	12	13.8–623	51.7
Chloride (mg/L)	11	19.0–300	53.0	11	13.0–884	56.0	12	17.0–1,020	67.3
Sulfate (mg/L)	11	14.0–114	31.0	11	19.0–99.9	45.0	12	17.0–123	48.0
Nutrients and carbon									
Ammonia plus organic, total, as nitrogen (mg/L)	11	1.00–5.70	2.00	11	0.60–3.10	1.50	12	1.30–4.20	1.95
Nitrite plus nitrate as nitrogen, dissolved (mg/L)	11	0.49–3.13	1.12	11	0.32–1.37	0.70	12	0.70–4.14	1.45
Ammonia, as nitrogen (mg/L)	11	0.02–0.20	0.10	11	<0.02–0.20	0.12	12	0.02–0.50	0.21
Total nitrogen (mg/L)[1]	11	2.15–6.31	3.19	11	1.30–3.80	2.41	12	2.63–5.54	4.24
Orthophosphorus, as phosphorus (mg/L)	11	<0.05–0.52	0.11	11	<0.05–0.08	<0.05	10	<0.05–0.48	0.30
Dissolved phosphorus (mg/L)	11	<0.05–0.60	0.14	11	<0.05–0.14	<0.05	12	<0.05–0.57	0.34
Total phosphorus (mg/L)	11	0.18–1.87	0.63	11	<0.05–1.04	0.18	12	0.17–1.45	0.55
Particulate phosphorus (mg/L)[2]	11	0.05–1.77	0.43	11	<0.05–0.95	0.12	12	0.06–1.10	0.23
Dissolved organic carbon (mg/L)	11	4.50–8.71	6.11	11	3.12–8.17	6.82	12	4.46–15.8	6.03
Total organic carbon (mg/L)	11	6.90–43.0	13.7	11	4.40–29.6	9.50	12	6.70–32.5	12.0
Biochemical and bacteria									
Biochemical oxygen demand (mg/L)	10	<2.0–14	8.0	10	3.0–10	5.5	11	4.0–13	8.0
Chemical oxygen demand (mg/L)	11	31–167	60	11	30–115	37	12	29–137	58
Enterococci (col/100 mL)	10	41–95,000	11,000	10	10–110,000	7,800	11	10–25,000	13,000
Escherichia coli (col/100 mL)	10	31–63,000	5,600	10	20–33,000	6,600	11	<10–33,000	6,400
Fecal coliform (col/100 mL)	11	41–42,000	5,000	11	30–55,000	3,900	12	20–55,000	4,200

[1] Calculated as the sum of nitrite plus nitrate, dissolved, and ammonia plus organic, total.

[2] Calculated as the difference between total phosphorus and dissolved phosphorus.

average, between the before-upgrade (2004 through 2007; mean=15.4 mg/L; range=14.7–16.8 mg/L) and after-upgrade (2010 through 2013; mean=8.4 mg/L; range=6.2–9.2 mg/L) periods. Annual mean wastewater effluent TN concentrations were below the NPDES permit goal (less than or equal to 8.0 mg/L) in 2010; during 2011 through 2013, annual mean TN concentrations exceeded the goal concentration by 11 to 14 percent (fig. 7*A*). Annual mean TN concentration in the Tomahawk Creek WWTF effluent, where nitrogen is not removed by treatment processes, generally were similar during 2004 through 2013 and ranged from 15.0 to 18.2 mg/L (mean=16.3 mg/L) (fig. 7*B*).

Effluent TP concentrations at the Middle Basin WWTF decreased by about 59 percent, on average, between the before-upgrade (mean=3.2 mg/L; range=2.9–3.6 mg/L) and after-upgrade periods (mean=1.3 mg/L; range=1.3–1.6 mg/L). Annual mean wastewater effluent TP concentrations were below the NPDES permit goal (less than or equal to 1.5 mg/L) during 2010, 2012, and 2013; TP concentrations exceeded the goal concentration by about 38 percent in 2011 (fig. 7*A*). During 2011, there was no means of TP removal at the Middle Basin WWTF, in part because of mechanical failure with the fermenter that runs the BNR process (Johnson County Wastewater, written commun., 2014). Annual mean TP concentration in the Tomahawk Creek WWTF effluent decreased by about 65 percent, on average, between the before-CEPT (2004 through 2008; mean=4.0 mg/L; range=3.9–4.4 mg/L) and after-CEPT (2010 through 2013; mean=1.4 mg/L; range=1.3–1.6 mg/L) periods. The NPDES permit for the Tomahawk Creek WWTF does not include nutrient concentration goals; however, annual mean TP concentrations did not exceed 1.5 mg/L during 2011 through 2013 (fig. 7*B*).

Annual TN and TP loads from the WWTFs reflected patterns in discharge volume and nutrient concentration (fig. 7, table 2). In general, nutrient loads from the Middle Basin WWTF were larger than loads from the Tomahawk Creek

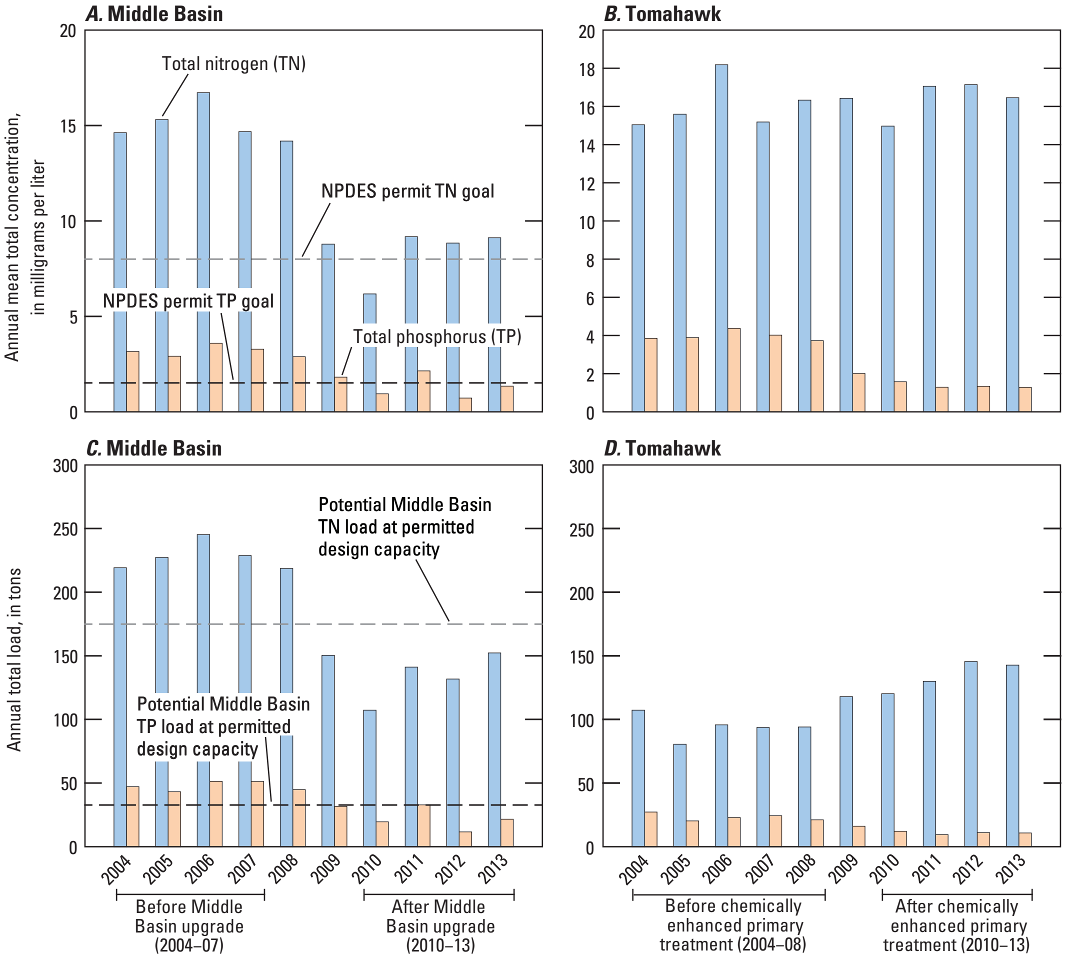


Figure 7. Annual mean wastewater effluent total nitrogen and phosphorus concentrations and loads at the Middle Basin and Tomahawk Creek Wastewater Treatment Facilities during 2004 through 2013. *A*, Middle Basin nutrient concentrations; *B*, Tomahawk Creek nutrient concentrations; *C*, Middle Basin nutrient loads; and *D*, Tomahawk Creek nutrient loads. [NPDES, National Pollutant Discharge Elimination System]

WWTF because of the higher volume of effluent processed; however, differences in load between the two facilities were less pronounced during the after-upgrade period because of the changes in treatment processes. Total nitrogen loads from the Middle Basin WWTF decreased by about 42 percent between the before- and after-upgrade periods (fig. 7*C*). In contrast, TN loads from the Tomahawk Creek WWTF increased by about 42 percent during the same time period (fig. 7*D*). Effluent discharge volume increased at both facilities by about 2 ft^3/s between the before- and after-upgrade periods (table 2). Substantial decreases in TN loads at the Middle Basin WWTF, despite increases in wastewater effluent discharge volume, reflect the addition of BNR at the facility. Total phosphorus loads from both WWTFs decreased by about 54 percent between the before- and after-upgrade periods (fig. 7*C*, *D*), indicating that BNR and CEPT were effective at reducing phosphorus in the effluent from these facilities.

During 2010 through 2013, annual wastewater effluent discharge from the upgraded Middle Basin WWTF was about 75 percent of the permitted design capacity (22.4 ft^3/s) (table 2). Potential maximum loads were calculated using the permitted design capacity of the upgraded WWTF and the NPDES permit TN and TP concentration goals (8.0 and 1.5 mg/L, respectively). These are theoretical maxima and assume the WWTF is continuously operated at permitted design capacity and that nutrient concentrations in effluent remain similar to permit goal concentrations. Potential maximum TN and TP loads are about 27 percent and 38 percent lower on average, respectively, than the annual loads before capacity upgrades; therefore, the addition of BNR to the Middle Basin WWTF will decrease overall nutrient loads from the facility relative to pre-capacity upgrade loads even if the facility is continuously operated at 22.4 ft^3/s.

Nutrient Concentrations Upstream and Downstream from Wastewater Treatment Facilities

Nutrients in wastewater effluent typically are inorganic (for example, nitrate and orthophosphorus) and dissolved. At stream sites influenced by wastewater effluent, concentrations of dissolved constituents typically decrease as streamflow increases because of dilution, and concentrations of suspended constituents increase with streamflow because of transport. At stream sites affected by nonpoint or urban sources, concentrations of all constituents tend to increase with increased streamflow (Welch and Lindell, 1992). Changes in nutrient concentrations with streamflow at the Indian Creek study sites reflect the effect of dominant sources. At the upstream sites (119th and Tomahawk), nutrient concentrations generally increased with increasing streamflow, indicating the relative contribution of urban sources to overall nutrient loads (fig. 8). In contrast, at the sites located downstream from WWTFs, dissolved nutrient concentrations decreased and suspended organic nutrient concentrations (total ammonia plus organic nitrogen and particulate phosphorus) increased with increasing streamflow. Total nutrient concentrations initially decreased with streamflow as the nutrient contribution from wastewater effluent was diluted, and then increased as the proportion of nutrients contributed by urban sources during runoff increased (fig. 8). These patterns were consistent at all WWTF influenced sites, regardless of distance downstream from wastewater effluent discharges.

In general, nitrogen concentrations increased and phosphorus concentrations decreased between the before- and after-upgrade periods at the State Line site (table 5). During below-normal streamflows, median TN during the after-upgrade period (9.0 mg/L) was about 22 percent higher than during the before-upgrade period (7.24 mg/L). In contrast, median TP concentration was about 43 percent lower during the after-upgrade period (0.90 mg/L) than the before-upgrade period (1.38 mg/L). Differences in nutrient concentrations at the State Line site likely reflect streamflow conditions when discrete samples were collected. Wastewater contributed about 22 percent more to streamflow during after-upgrade discrete sample collection than before-upgrade discrete sample collection (table 5), likely contributing to the higher nitrogen concentrations observed during the after-upgrade period. In addition, TN concentrations only decreased in effluent from the Middle Basin WWTF. Total phosphorus concentrations in effluent from the Middle Basin and Tomahawk Creek WWTFs substantially decreased between the before- and after-upgrade periods (fig. 7*A*, *B*); this decrease is reflected in lower TP concentrations at the State Line site during the after-upgrade period despite larger wastewater contributions to streamflow.

Total and dissolved nutrient concentrations downstream from the WWTFs were 10 to 100 times higher than at the upstream sites during below-normal and normal streamflows (fig. 8, table 6). At the downstream sites, nitrate comprised about 80 to 90 percent of the total nitrogen concentrations during below-normal and normal streamflows, compared to about 15 to 20 percent at the upstream sites (fig. 9). Differences in the relative contribution of orthophosphorus to total phosphorus were not as pronounced (median range=75–100 percent), likely due in part to the large number of phosphorus concentrations at or below the laboratory reporting level (0.05 mg/L) at the upstream sites (table 6). Nutrient concentrations also were higher downstream from the WWTFs than at the upstream sites during above-normal streamflows, but differences were less pronounced (as much as 7 times higher). In general, nitrate and orthophosphorus comprised less than half of the total nutrient concentrations at all sites during above-normal streamflows.

There was a clear pattern in total and dissolved nutrient concentrations along the upstream-downstream gradient in Indian Creek, particularly during below-normal and normal streamflow conditions (figs. 6*F* and 8, table 6). In general, nutrient concentrations were elevated immediately downstream from the Middle Basin WWTF discharge, then decreased with increasing downstream distance until reaching the Tomahawk Creek WWTF discharge into Indian Creek. Nutrient concentrations generally increased by an order of magnitude or more between the upstream 119th site

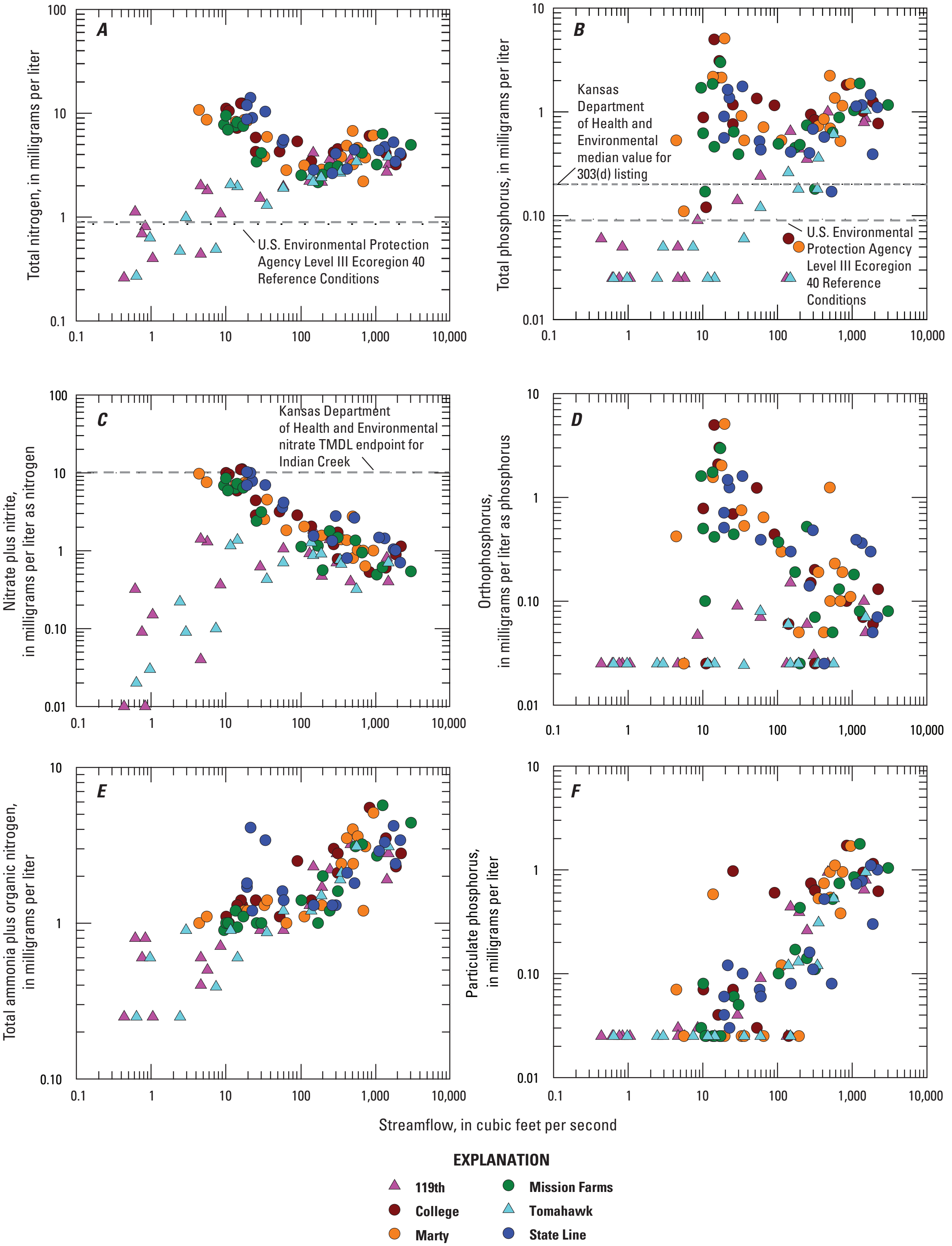


Figure 8. Relations between nutrient concentrations and streamflow at all Indian Creek study sites, June 2011 through June 2013. *A*, total nitrogen; *B*, total phosphorus; *C*, nitrate plus nitrite; *D*, orthophosphorus; *E*, total ammonia plus organic nitrogen; and *F*, particulate phosphorus. [TMDL, total maximum daily load]

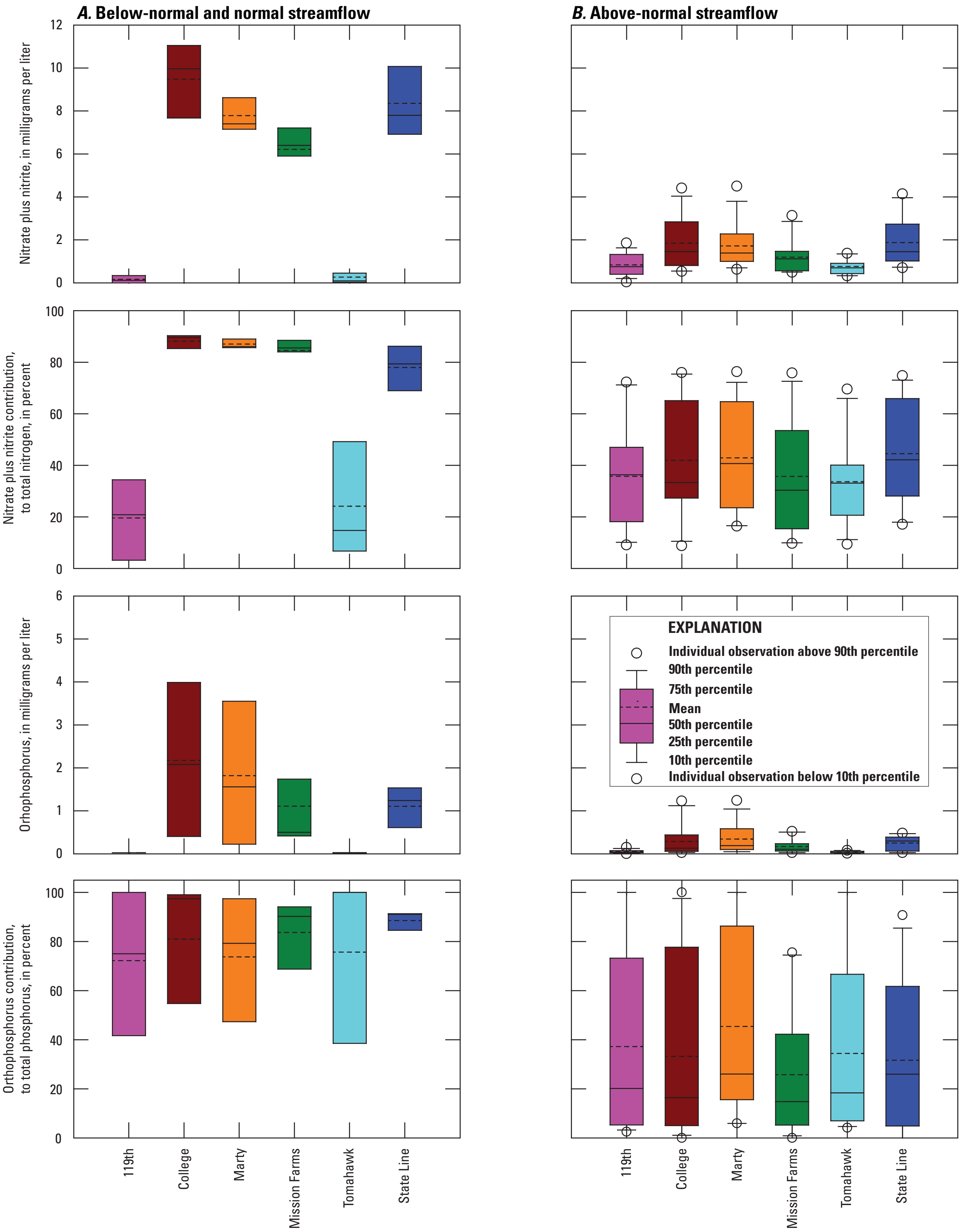


Figure 9. Nitrate plus nitrite and orthophosphorus concentrations and percent contribution to total nitrogen and phosphorus concentrations during below-normal, normal, and above-normal streamflows at all Indian Creek study sites, June 2011 through June 2013. *A*, below-normal and normal streamflow and *B*, above-normal streamflow.

and the College site located about 1.0-km downstream from the Middle Basin WWTF. Nutrient concentrations generally decreased by 8 to 25 percent between the College and Marty site and by 15 to 70 percent between the Marty and Mission Farms site. Total nitrogen and nitrate concentrations decreased by 30 to 40 percent between the Mission Farms site, located about 9.5-km downstream from the Middle Basin WWTF, and the College site; total phosphorus and orthophosphorus concentrations decreased by 70 to 80 percent. Nitrogen concentrations increased by about 20 to 40 percent and phosphorus concentrations by about 110 to 150 percent between the Mission Farms site and the State Line site located about 2.3-km downstream from the Tomahawk Creek WWTF.

In 2000, the EPA recommended ecoregion-based nutrient criteria for streams. Reference conditions for TN and TP in level III, ecoregion 40 streams are defined as 0.855 and 0.0925 mg/L, respectively (U.S. Environmental Protection Agency, 2000a). These criteria were intended as a preliminary attempt to describe the nutrient concentrations that would protect designated uses and mitigate the effects of nutrient enrichment and are not used for regulatory purposes. The KDHE uses a median TP concentration of 0.201 mg/L to determine if a stream site should be on the 303(d) list of impaired waters for phosphorus (Kansas Department of Health and Environment, 2014). Measured total nutrient concentrations always exceeded reference conditions and the KDHE value for 303(d) listing for phosphorus at the State Line site (fig. 8*A*, *B*, *C*, tables 5 and 6). Similarly, along the upstream-downstream gradient, reference conditions were always exceeded at sites located downstream from the WWTFs, with the exception of one date at the College and Marty sites. Median TP values at all downstream sites exceeded the KDHE value for 303(d) listing; however, TP concentrations were occasionally lower than 0.201 mg/L at the College, Marty, and Mission Farms sites (fig. 8*B*, table 6). By comparison, nutrient concentrations at the two sites located upstream from the WWTFs were typically lower than reference conditions during below-normal and normal streamflows and higher than reference conditions during above-normal streamflows (fig. 8*A*, *B*, table 6). Median TP values were below the KDHE value for 303(d) listing at the two sites located upstream from the WWTFs during below-normal and normal streamflows. During above-normal streamflows, the median TP value at the Tomahawk site (0.18 mg/L) was lower than 0.201 mg/L, but the median value at the 119th site (0.30 mg/L) was about 40 percent higher than the KDHE value for 303(d) listing (table 6).

Inorganic nitrogen compounds, such as nitrate and ammonia, may be toxic to aquatic organisms at high concentrations. In addition, high nitrate concentrations in drinking water can impair the oxygen-carrying capacity of hemoglobin in humans (Camargo and Álonso, 2006). The KDHE has established a nitrate TMDL for Indian Creek of 10 mg/L (Kansas Department of Health and Environment, 2007). Nitrate concentrations never exceeded 10 mg/L at the two upstream sites (fig. 6*F,* table 6). Based on discrete water-quality samples, nitrate concentrations at the downstream sites occasionally exceed nitrate concentrations of 10 mg/L. One of the samples (number of samples=55) of the samples collected at the State Line site during 2004 through 2013 exceeded 10 mg/L (concentration 10.2 mg/L) during the after-upgrade periods (table 5). Along the upstream-downstream gradient, exceedances only were at the College and State Line sites, both located immediately downstream from WWTFs. Twelve percent of the samples collected at the College site and 6 percent of the samples collected at the State Line site (number of samples=17) during June 2011 through June 2013 had nitrate concentrations above 10 mg/L (concentrations 10.2–11.1 mg/L) (table 6). By comparison, continuous nitrate data indicate that nitrate concentrations exceeded 10 mg/L at all sites located downstream from the WWTFs, with maximum concentrations about 2 mg/L higher than observed in discrete samples (13–14 mg/L) (fig. 6*F*). Nitrate concentrations exceeded 10 mg/L about 10 percent of the time at the College site, less than 1 percent of the time at the Marty and Mission Farms sites, and about 2 percent of the time at the State Line site. Exceedances typically were during below-normal and normal streamflows when wastewater effluent comprised most of the streamflow at these sites.

The EPA has established acute and chronic ammonia criteria for the protection of aquatic life (U.S. Environmental Protection Agency, 2013). The toxicity of ammonia is dependent on pH and water temperature; therefore, criteria vary with conditions of these water-quality parameters. At a pH of 7.0 and a water temperature of 20 °C, the acute criterion for total ammonia nitrogen (TAN) is 17 mg/L and the chronic criterion is 1.9 mg/L. Ammonia concentrations exceeded the chronic criterion in one discrete sample collected from the State Line site. The exceedance was during below-normal streamflows in summer at high water temperatures (°C =28.2, pH=8.3, ammonia=0.39 mg/L, chronic criterion=0.29 mg/L).

Computed Total Nitrogen and Total Phosphorus Concentrations and Loads

Regression models and summary statistics for computing nutrient concentrations for the Indian Creek study sites are provided in appendix 2. Model development and selection criteria are discussed in detail in Stone and Graham (2014). A comparison between measured and computed TN and TP values indicates model performance, in addition to the individual model statistics provided in appendix 2. The upper range concentrations of TN and TP likely are underestimated, especially at the wastewater-influenced sites (fig. 10). Computed TP concentrations were more variable relative to measured concentrations than TN, likely due to the larger uncertainty in the models used to calculate TP (nitrogen models, adjusted R^2=0.48–0.88; phosphorus models, adjusted R^2=0.27–0.97; appendix 2). The most extreme difference between measured and computed TP concentrations were on January 27, 2013, at the College, Marty, and Mission Farms sites (fig. 10*B*), despite normal streamflow conditions. Higher than typical TP concentrations in effluent from the Middle Basin WWTF likely resulted in higher in-stream concentrations during this time period. Computed TP values for this date are more typical of the values observed under normal flow conditions.

Computed nutrient concentrations during July 2011 through June 2013 were highest at the sites located downstream from the WWTFs (fig. 11). Median TN concentrations at the downstream sites (6.1–9.2 mg/L) were 6 to 9 times higher than at the upstream sites (0.98–1.0 mg/L) (fig. 11*A*). The TN concentrations at the College site, immediately downstream from the Middle Basin WWTF, exceeded all other sites approximately 20 percent of the time and concentrations at the State Line site exceeded all other sites approximately 80 percent of the time throughout the study period. Similar to the pattern observed in continuously measured nitrate data and discretely collected nitrogen samples (fig. 6*F*, table 6), total nitrogen concentrations typically were highest at the sites located immediately downstream from the WWTFs and decreased as distance from the WWTFs increased. Median TP concentrations at the downstream sites (0.78–1.1 mg/L) were 13 to 28 times higher than at the upstream sites (0.04 to 0.06 mg/L). Patterns in TP along the upstream-downstream gradient were not as clear as for TN. In contrast to discretely measured phosphorus concentrations, which followed a similar pattern to nitrogen (table 6), median computed TP concentrations generally increased in the downstream direction. Computed TP concentrations at the Mission Farms and State Line sites exceeded concentrations at all other sites nearly 100 percent of the time, with State Line exceeding Mission Farms approximately 50 percent of the time throughout the study period. Differences in nitrogen and phosphorus patterns along the upstream-downstream gradient may be due to uncertainties in computed TP concentrations or differences in dynamics of transport and uptake.

Nutrient loads at the State Line site were calculated for all years with a complete continuous record (2005 through 2012). Calculated TN and TP loads for the State Line site generally were similar to those estimated by Rasmussen and others (2014) using regression models developed for the site in 2008 (Rasmussen and others, 2008). Total nitrogen loads at the State Line site ranged from 354 tons in 2006 to 683 tons in 2010 (fig. 12*A*). The upstream WWTFs contributed between 33 (2010) and 97 (2006) percent to TN loads. In general, wastewater contributed a larger percentage to TN loads in years with lower streamflows and other urban sources contributed a larger percentage in years with higher streamflows. Annual mean streamflow in 2010 was one of the highest recorded during 2005 through 2012, and the 2010 TN load was the highest observed during the study period. During 2010, about 67 percent of the TN load was from other urban sources. In contrast, during 2006, annual mean streamflow was one of the lowest recorded, TN load was the lowest observed, and nearly 100 percent of the TN load was from WWTFs (fig. 12*A*, table 2). Despite substantial decreases in TN loads from the Middle Basin WWTF (fig. 7*C*), there were no clear patterns in annual TN loads with respect to changes in treatment processes at the WWTFs, likely due in part because of high among-year variability in streamflow; however, note that despite generally similar streamflows during 2006 (before upgrade) and 2011 and 2012 (after upgrade), the WWTFs contributed substantially less (58 to 65 percent) to TN loads in 2011 and 2012 than during 2006 (97 percent) (fig. 12*A*, table 2).

Total phosphorus loads at the State Line site ranged from 68 tons in 2012 to 127 tons in 2008 (fig. 12*B*). Correspondingly, 2012 had the lowest annual mean streamflow and 2008 had the highest streamflow during 2005 through 2012 (table 2). The upstream WWTFs contributed between 29 (2010) and about 100 (2006) percent to TP loads. As observed with TN, despite substantial decreases in TP loads from the Middle Basin and Tomahawk Creek WWTFs (fig. 7*C*, *D*), there were no clear patterns in annual TP loads with respect to changes in treatment processes, likely due in part because of high among-year variability in streamflow; however, like TN, despite generally similar streamflows and annual TP loads during 2006 (before upgrade) and 2011 and 2012 (after upgrade), the WWTFs contributed substantially less (35 to 57 percent) to TP loads in 2011 and 2012 than during 2006 (100 percent) (fig. 12*B*, table 2).

Nutrient loads for all sites were calculated for the periods July 2011 through June 2012 (Year 1) and July 2012 through June 2013 (Year 2). Overall, total nutrient loads were about 20 percent larger during Year 2 than Year 1 (fig. 13, table 7). This increase corresponded with an approximately 22 percent increase in streamflow between the 2 years. Total nutrient loads increased along the upstream-downstream gradient; the largest increases were between sites located immediately upstream and downstream from the WWTFs (between the 119th and College sites and the Mission Farms and State Line sites).

Total nitrogen loads were about 1.8 times higher at the Tomahawk site (58–78 tons) than the 119th site (33–43 tons) (fig. 13*A*, table 7), a difference that corresponds with the larger drainage area and higher streamflows at the Tomahawk site (fig. 3, table 1). Total nitrogen loads at the College site (191–203 tons), downstream from the Middle Basin WWTF, were between 3 and 6 times higher than at the upstream sites. Total nitrogen loads at the State Line site (448–539 tons), located downstream from both WWTFs, were between 7 and 13 times higher than at the upstream sites. Along the upstream-downstream gradient, TN loads increased by about 5 to 6 times between the 119th and College sites, about 1.2 times between the College and Mission Farms sites, and about 2 times between the Mission Farms and State Line sites (fig. 13*A*, table 7). The contribution of wastewater to TN loads decreased in the downstream direction, with the highest percentages at the College site (63–74 percent) and the lowest at the State Line site (50–62 percent) (fig. 13*A*). During Year 1, the largest TN loads originated from the WWTFs rather than from other urban sources during stormwater runoff. About 278 tons (62 percent) of the TN at the State Line site originated from the WWTFs. During Year 2, about one-half of the TN load at the State Line site (539 tons) originated from

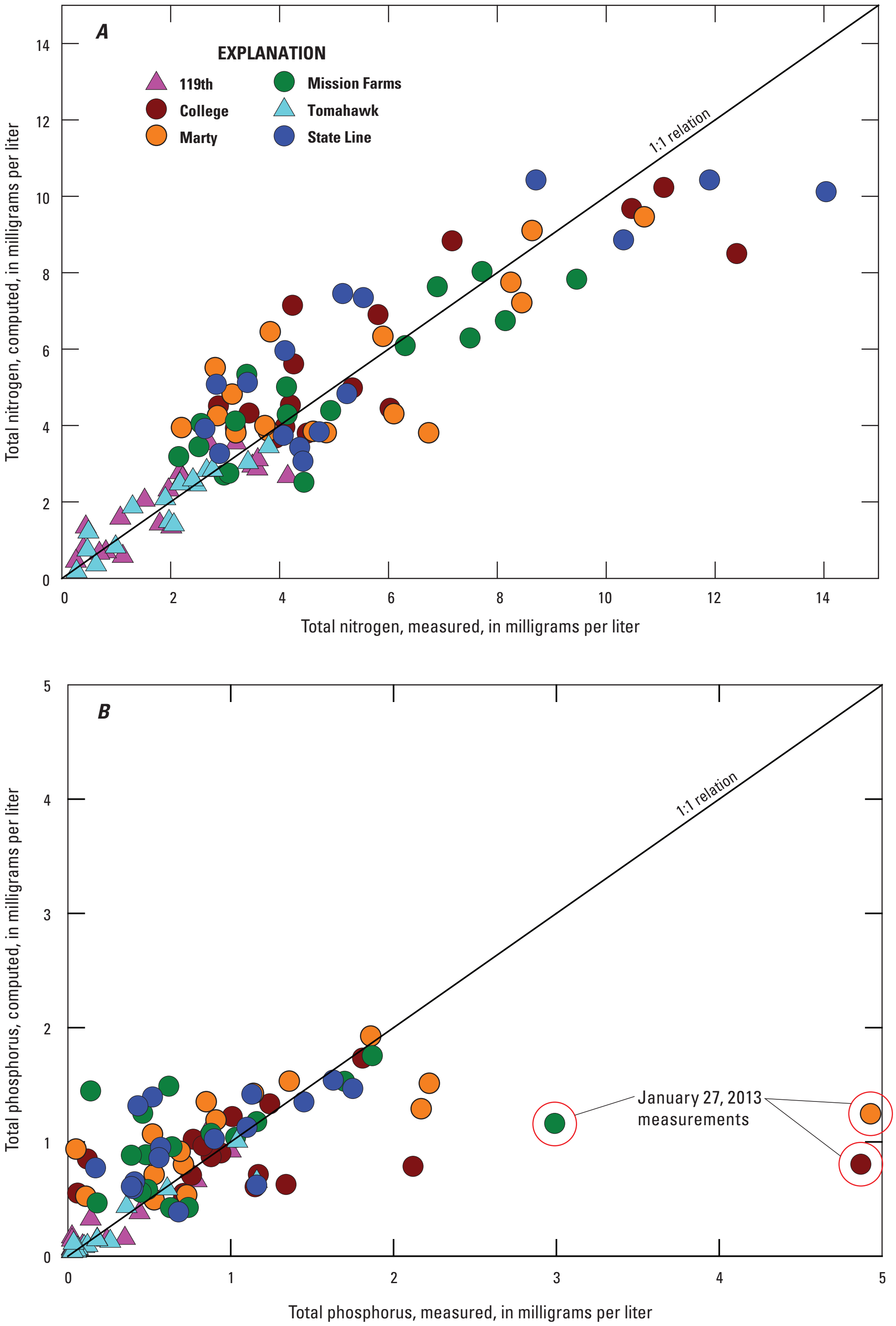


Figure 10. Comparison between measured and computed total nutrient concentrations at the Indian Creek study sites. *A*, total nitrogen and *B*, total phosphorus.

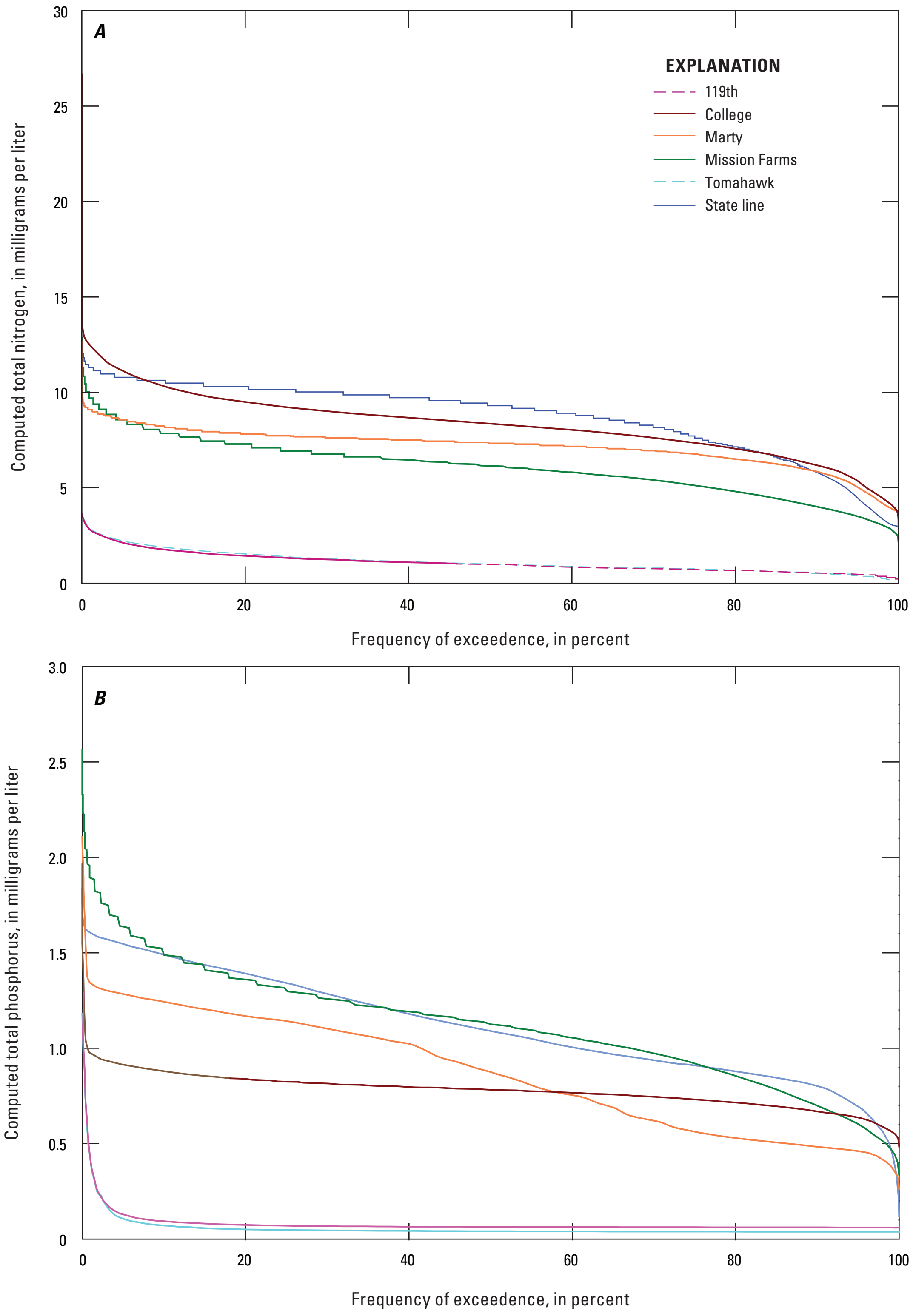


Figure 11. Duration curves for computed total nutrient concentrations at the Indian Creek study sites, July 2011 through June 2013. *A*, computed total nitrogen and *B*, computed total phosphorus.

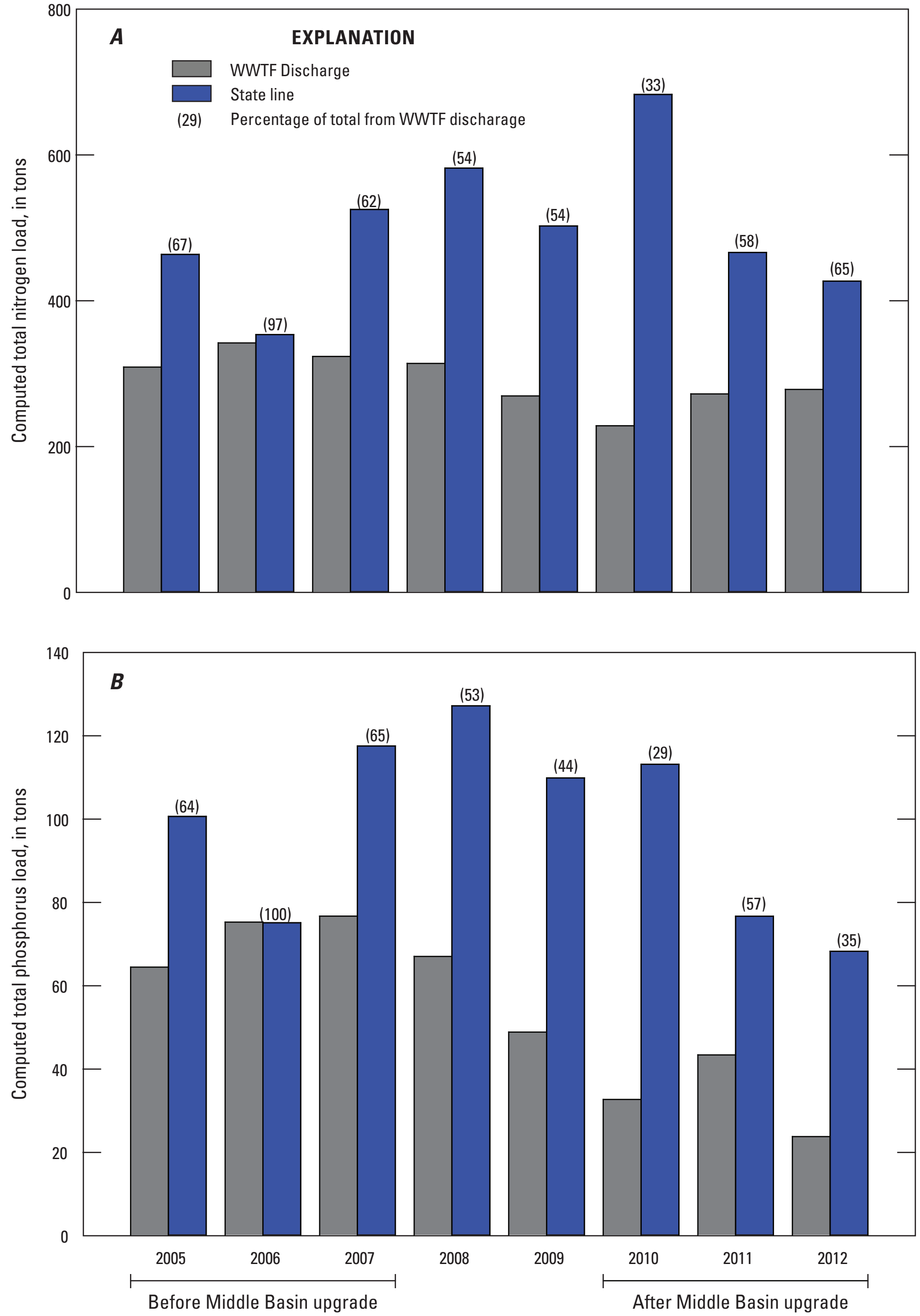


Figure 12. Computed total nutrient loads originating from wastewater treatment facility (WWTF) discharges compared to total loads at the State Line site during 2005 through 2012. *A*, computed total nitrogen and *B*, computed total phosphorus.

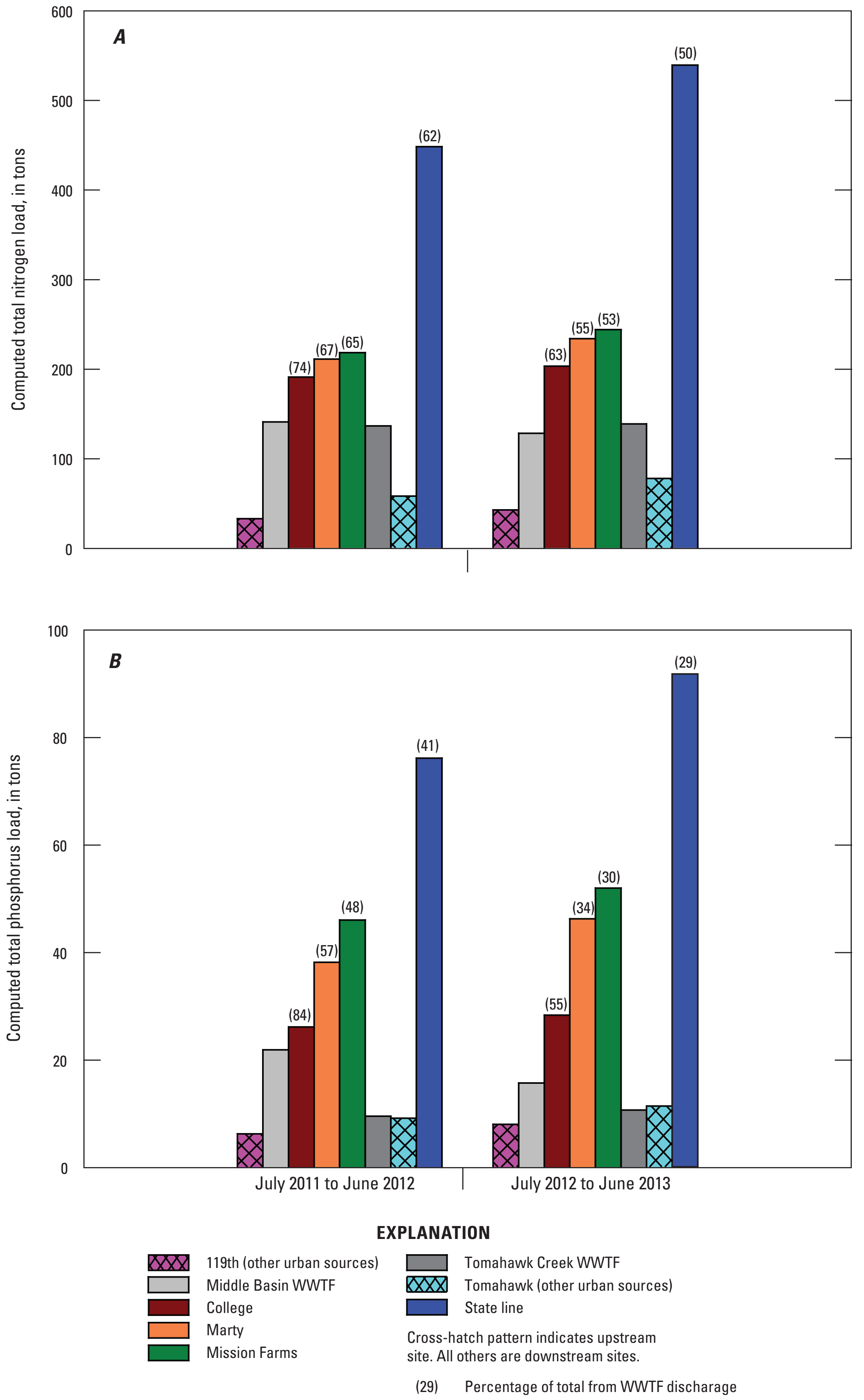


Figure 13. Computed total nutrient loads originating from wastewater treatment facility (WWTF) discharges compared to total loads at the Indian Creek study sites during July 2011 through June 2012 and July 2012 through June 2013. *A*, computed total nitrogen and *B*, computed total phosphorus.

Table 7. Computed loads for total nitrogen and phosphorus at the Indian Creek study sites, July 2011 through June 2013.

[WWTF, wastewater treatment facility]

	119th	Middle Basin WWTF	College	Marty	Mission Farms	Tomahawk Creek WWTF	Tomahawk	State Line
July 1, 2011–June 30, 2012								
Total nitrogen load, tons	33	141	191	211	218	137	58	448
Total phosphorus load, tons	6.3	22	26	38	46	9.6	9.2	76
July 1, 2012–June 30, 2013								
Total nitrogen load, tons	43	129	203	234	244	139	78	539
Total phosphorus load, tons	8.0	16	28	46	52	11	11	92

the WWTFs and about one-half originated from other urban sources. Based on the 2005 to 2012 loads for the State Line site, most of the TN loads in the Indian Creek Basin typically originate from the WWTFs, except during years with high streamflows (fig. 12*A*, table 2). The largest TN loads in Year 1 and Year 2 were in May and were associated with two large runoff events each year. May loads accounted for about 26 percent of the annual load at the upstream sites during Year 1 and about 40 percent during Year 2 (appendix 5). At the downstream sites, May loads accounted for about 17 percent of total loads in Year 1 and about 40 percent in Year 2. Monthly nitrogen loads originating from the WWTFs ranged from about 20 percent during months when streamflow was dominated by stormwater runoff (typically spring and early summer) to nearly 100 percent during drier months (typically late summer) (appendix 5).

Like TN, TP loads were about 1.5 times higher at the Tomahawk site (9 to 11 tons) than the 119th site (6–8 tons) (fig. 13*B*, table 7). Total phosphorus loads at the College site (26–28 tons) were between 2 and 5 times higher than at the upstream sites and loads at the State Line site (76–92 tons) were between 7 and 15 times higher. Along the upstream-downstream gradient, TP loads increased by about 4 to 5 times between the 119th and College sites, about 1.8 times between the College and Mission Farms sites, and about 1.8 times between the Mission Farms and State Line sites. The contribution of wastewater to TP loads decreased in the downstream direction, with the highest percentages at the College site (55–84 percent) and the lowest at the State Line site (29–41 percent) (fig. 13*B*). During Year 1, the largest TP loads at the College and Marty sites originated from the Middle Basin WWTFs, and about half the load at the Mission Farms site originated from the WWTF. By comparison, the largest TP load at the State Line site originated from other urban sources; about 31 tons (41 percent) of the phosphorus at the State Line site originated from the WWTFs. During Year 2, the College site was the only site where the largest TP load was derived from the WWTF; the largest loads at all other downstream sites originated from other urban sources. About 27 tons (29 percent) of the phosphorus at the State Line site originated from the WWTFs during Year 2 (fig. 13*B*, table 7). Based on the 2005 to 2012 loads for the State Line site, most of the phosphorus load may originate from either WWTFs or other urban sources depending on streamflow conditions (fig. 12*B*, table 2). In general, the largest TP loads in Year 1 and Year 2 were in May and were associated with two large runoff events each year. May loads accounted for about 36 percent of the annual load at the upstream sites during Year 1 and about 53 percent during Year 2 (appendix 6). At the downstream sites, May loads accounted for about 20 percent of total loads in Year 1 and about 40 percent in Year 2. Monthly phosphorus loads originating from the WWTFs ranged from about 4 percent during months when streamflow was dominated by stormwater runoff (typically spring and early summer) to nearly 100 percent during drier months (typically late summer) (appendix 6).

Biochemical Oxygen Demand

Biochemical oxygen demand (BOD) measures organic matter, which can support the growth of aquatic microorganisms and commonly is used to describe water-quality conditions (Cheremisinoff, 1995). Large concentrations of oxygen-demanding substances can substantially decrease oxygen concentrations in streams, thereby adversely affecting aquatic organisms. Pristine streams typically have a low BOD (less than 2.0 mg/L) and streams polluted by organic matter have increased BOD (greater than 13 mg/L; Van Dam and others, 1994; Porter, 2008). The BOD was not commonly measured during the before-upgrade and transitional periods at the State Line site, so data are not available to make meaningful comparisons with the after-upgrade period (table 5). Along the upstream-downstream gradient, BOD was less than 2 mg/L at all sites during below-normal and normal streamflows, with the exception of State Line (range=4.0–8 mg/L; median=4.5 mg/L) (table 6). The BOD was higher (medians=5.5–8 mg/L) at all sites during above-normal streamflows, and concentrations occasionally exceeded 13 mg/L at the College (maximum=15 mg/L), Marty (maximum=19 mg/L), and Mission Farms (maximum=14 mg/L) sites (table 6).

Indicator Bacteria

Fecal coliform, *Escherichia coli*, and enterococci are the three most common types of bacteria used as indicators of pathogens in surface water. Indicator bacteria are used to evaluate the sanitary quality of water and its use as a public water supply and for recreational activities (American Public Health Association and others, 2005). Reducing the number of fecal indicator and other potentially pathogenic bacteria and microorganisms in wastewater effluent requires disinfection. Many modern WWTFs include disinfection as part of the treatment process. The Middle Basin WWTF uses ultraviolet radiation (UV) for disinfection and the Tomahawk Creek WWTF uses chlorine. The UV disinfection is a physical, rather than chemical, process and there is no residual effect that can be harmful to humans or aquatic life (U.S. Environmental Protection Agency, 1999a). Chlorine disinfection is a chemical process that destroys bacteria and pathogens; however, the chlorine residual may be toxic to aquatic life and the total dissolved solids and chloride content of wastewater may be increased (U.S. Environmental Protection Agency, 1999b). Total dissolved solids and chloride concentrations at the State Line site, downstream from the Middle Basin and Tomahawk Creek WWTFs, were not appreciably higher than the Indian Creek study sites downstream from the Middle Basin WWTF (tables 5 and 6), indicating chlorine disinfection did not have a substantial effect on these water-quality constituents. As a result of the disinfection process, most of the fecal indicator bacteria and other pathogenic microorganisms in Johnson County streams usually come from nonpoint or urban sources and concentrations are orders of magnitude greater during runoff events than below-normal or normal streamflows (Rasmussen and others, 2009b, 2014; Wilkison and others, 2009; Graham and others, 2010). Urban sources are likely the primary source of fecal indicator bacteria at all Indian Creek study sites. Median concentrations of fecal indicator bacteria were 1 to 3 orders of magnitude higher during above-normal streamflows than below-normal and normal streamflows during the before-upgrade and after-upgrade periods at the State Line site (table 5), and along the upstream-downstream gradient in Indian Creek (table 6).

Organic Wastewater-Indicator Compounds

Organic wastewater-indicator compounds (OWCs) include a variety of synthetically and naturally derived compounds from sources such as industry, agriculture, and residential activities (Kolpin and others, 2002). These compounds represent a diverse array of chemicals, including pesticides, steroids, and solvents (Focazio and others, 2008; Wilkison and others, 2009). Organic wastewater-indicator compounds are present in trace concentrations (generally less than 1 µg/L), but may have negative effects on aquatic life and humans through chronic exposure or the additive effects of exposure to multiple compounds (Kolpin and others, 2002; Kolpin and others, 2004). Although regulatory standards do not exist for many OWCs (Focazio and others, 2008), they are compounds of concern because of their connection, albeit poorly understood, with abnormal physiology, impaired reproduction, increased cancer rates, and general toxicity (Daughton and Ternes, 1999; Kolpin and others, 2002). Many OWCs are incompletely removed during the wastewater treatment process, and wastewater effluent is one of the main pathways for OWCs to enter the environment (Daughton and Ternes, 1999; Kolpin and others, 2002; Focazio and others, 2008). Organic wastewater-indicator compounds may be transported for long distances downstream from a source because of sorption, incomplete dilution, and slow degradation processes (Kolpin and others, 2002; Focazio and others, 2008).

Discrete stream-water samples collected from all six sites in April 2013 during normal to slightly above-normal streamflow conditions were analyzed for a total of 60 OWCs. Of the compounds analyzed, 28 were detected at the Indian Creek sites, including pesticides, flavorings and fragrances, polyaromatic hydrocarbons (PAHs), detergents, stimulants, solvents, disinfectants, plastics, and fire retardants (appendix 7). Ten compounds were detected at all six sites, and were predominantly pesticides, PAHs, and fire retardants. Caffeine, a stimulant, was also detected at all sites; concentrations were small (less than or equal to 0.15 µg/L) except at the State Line site (1.1 µg/L). Eleven compounds (fragrances, pesticides, plastics, and disinfectants) were detected at only the four downstream sites; of these compounds, five had clear patterns with respect to the WWTFs. For example, triclosan, a disinfectant, was detected at the College site (0.1 µg/L), downstream from the Middle Basin WWTF. Triclosan concentrations decreased in the downstream direction with increased distance from the Middle Basin WWTF (Marty=0.06 µg/L, Mission Farms=0.02 µg/L) and then increased at the State Line site (0.19 µg/L), downstream from the Tomahawk Creek WWTF.

Streambed-Sediment Chemistry

Concentrations of some compounds are greater in sediment than in the overlying water column (Horowitz, 1991). Contaminated sediment can be toxic to benthic organisms, including periphyton and macroinvertebrates, and contaminants may bioaccumulate in fish and mammals (U.S. Environmental Protection Agency, 2000b). Streambed-sediment samples were collected for all Indian Creek sites during April 2013. All samples were analyzed for carbon, nutrients, trace elements, and organic wastewater-indicator compounds (appendixes 9 and 10). Because there are no set criteria for trace elements or OWCs in sediments, probable effect concentrations (PECs) have been developed for some compounds (MacDonald and others, 2000). The PEC represents the concentration of a contaminant in streambed sediment that is expected to adversely affect benthic biota.

Nutrient concentrations in sediment were higher downstream from the WWTFs. Total phosphorus concentration in the sediment was highest at the College site [1,800 milligrams per kilogram, (mg/kg)], decreased in the downstream direction to Mission Farms (830 mg/kg), then increased at the State Line site (1,000 mg/kg). Sediment TP concentration at the Mission Farms site was similar to concentrations at the upstream sites (119th=750 mg/kg; Tomahawk=700 mg/kg). Total phosphorus concentrations in sediment exceeded mean background levels for the conterminous United States (1,000 mg/kg) at the College, Marty, and State Line sites (Horowitz and Stephens, 2008). Patterns in nitrogen along the upstream-downstream gradient were not as clear as phosphorus, but ammonia plus organic nitrogen concentrations were three orders of magnitude larger downstream from the WWTFs than at the 119th site and 2–7 times larger than at the Tomahawk site (appendix 8). Background concentrations for nitrogen in sediment are not available for comparison. In general, sediment nutrient concentrations and patterns along the upstream-downstream gradient at the Indian Creek study sites match data previously collected in the drainage basin (Rasmussen and others, 2009b, 2012).

There were no clear patterns in concentrations of trace elements in sediment along the upstream-downstream gradient in Indian Creek. Some elements, such as copper, had the highest concentrations at the College and State Line sites, immediately downstream from the WWTFs, whereas others, such as arsenic, cobalt, and nickel had the highest concentrations at the 119th and Tomahawk sites, upstream from the WWTFs (appendix 8). None of the measured trace elements exceeded the PECs for aquatic life; however, several elements (for example, cadmium, lead, copper, and zinc) had sediment concentrations about 1.5 to 2 times higher than mean background levels for the conterminous United States at most sites (Horowitz and Stephens, 2008). Concentrations of trace elements above mean background levels in the Indian Creek Basin may be due to natural variability, local geology, or urbanization. Trace element concentrations were within the range of previously collected data in the drainage basin (Rasmussen and others, 2009b, 2012).

Streambed-sediment samples were analyzed for 57 OWCs, 31 of which were detected (appendix 9). Detected compounds included pesticides, PAHs, sterols or stanols, detergents, plastics, disinfectants, and flavorings or fragrances. Sediment concentrations of most compounds were within the range of previously collected data in the drainage basin (Rasmussen and others, 2009b, 2012). The most frequently detected compounds at all sites were PAHs, which generally are used in pavement sealants and indicate increased urbanization (Van Metre and others, 2008). Four PAHs [benzo(a)pyrene, fluoranthene, phenanthrene, and pyrene] were detected at concentrations above the PEC at the Marty, Mission Farms, and State Line sites, the three most downstream sites (fig. 1). In Johnson County, PAHs in streambed sediment were highly negatively correlated with habitat scores and benthic community diversity metrics and positively correlated with urbanization and stormwater (Rasmussen and others, 2012).

Eleven compounds (fragrances, plastics, disinfectants, detergents, and sterols/stanols) were detected only at the four downstream sites; of these compounds, five had clear patterns with respect to the WWTFs (appendix 9). For example, 3-beta-coprostanol, a sterol/stanol that is frequently used as a biomarker for increased human fecal matter in the environment, was detected at the College site (3,600 µg/kg), downstream from the Middle Basin WWTF. Concentrations of 3-beta-coprostanol decreased in the downstream direction with increased distance from the Middle Basin WWTF (Marty=2,500 µg/kg, Mission Farms=740 µg/kg) and then increased at the State Line site (2,000 µg/kg), downstream from the Tomahawk Creek WWTF.

Habitat

Habitat-quality evaluations integrate several factors that directly or indirectly affect the water-quality and biological condition of streams, and are a critical part of assessing ecological integrity (Barbour and others, 1996; Barbour and others, 1999). Degraded habitat conditions are one of the primary stressors affecting the diversity and abundance of aquatic organisms in streams (Karr and others, 1986). Light intensity was evaluated using data collected continuously during October 2011 through June 2013. Riparian and in-stream habitat characteristics were evaluated during July 2012.

Light Intensity

Light intensity at all sites followed typical seasonal patterns, with the highest intensity values in spring and summer and the lowest intensity values in fall and winter (fig. 14). Among-site differences in light intensity were most pronounced during spring and summer, when days are longer and streamside trees are fully leafed out. Patterns in light intensity along the upstream-downstream gradient varied seasonally, but in general intensity was lowest at the 119th site and highest at the State Line site. Overall, median light intensity at the State Line site [3,692 lumens per square meter; (lm/m^2)] was about 62 percent higher than median light intensity at the 119th site (1,948 lm/m^2); differences among other sites were less pronounced (medians 2,734–3,520 lm/m^2) and ranged from 5 to 30 percent higher than at the 119th site. The difference in light conditions between the 119th and State Line sites reflect differences in canopy cover between sites (appendix 10). The relative canopy cover score decreased by about 33 percent between the 119th and State Line sites, indicating there was much less overhanging vegetation at the terminal downstream site than at the upstream site. Overall among-site differences in light intensity likely reflect canopy cover and possibly placement of the light sensors in the stream.

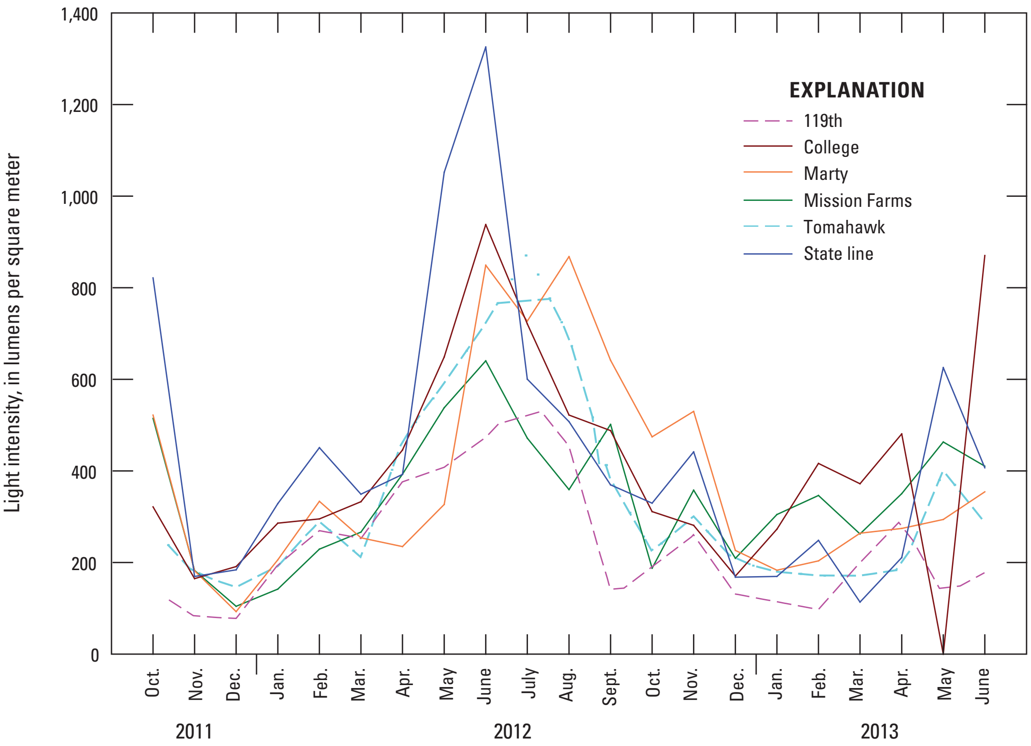


Figure 14. Monthly mean light intensity at the Indian Creek study sites during October 2011 through June 2013.

Physical-Habitat Characteristics

Total habitat scores at all sites indicated marginal and suboptimal conditions. The variability in total habitat scores among sites was fairly small, with the lowest score recorded at the State Line site, located furthest downstream (fig. 1, fig. 15*A*). Total habitat scores decreased in the downstream direction from College to State Line. But the site furthest upstream, 119th, did not follow that trend by scoring highest, partly because of low scores related to bank instability and lack of riparian protection, in spite of having the highest scores for canopy cover, buffer width, and unaltered stream banks (appendix 10). The sites with the best total scores (College, Marty, and Tomahawk, fig. 15*A*) also had high scores for riffle frequency, canopy cover, sediment deposition, and favorable riffle-substrate composition (appendix 10).

Although variability in total habitat scores among sites was fairly small, much larger differences among sites were recorded in individual habitat variables. Streambank alterations generally increased in the downstream direction, leading to lower percent altered bank scores. The percentage of altered banks was substantially lower at the 119th site (optimal conditions) than the State Line site (marginal conditions) (fig. 15*B*). Streambanks at the State Line site are altered because of bridge armor, retaining walls, and artificial riprap. Streams that have been altered generally have far fewer natural habitats for fish, macroinvertebrates, and plants than naturally meandering streams (Barbour and others, 1999). Riffle substrate fouling also varied among sites, with the poorest conditions at the downstream State Line site (fig. 15*C*). Riffle substrate fouling is a measure of periphyton growth and accumulation of fine materials covering substrate. Excessive amounts of accumulation can clog interstitial spaces in gravel and cobble substrates and lead to a decline in living space for macroinvertebrates and riffle-dwelling fishes. Substrate and cover diversity also varied among sites (fig. 15*D*). A large variety of in-stream habitats and cover types such as leaf packs, woody debris, root mats, overhanging and inundated vegetation, and undercut banks provide protection and feeding sites for macroinvertebrates and other aquatic organisms (Barbour and others, 1999). The State Line site scored in the lower marginal range for this variable, and all of the other sites scored in the suboptimal or optimal range (fig. 15*D*).

Habitat quality at all of the sites likely benefits from the presence of streamway parks that extend along the creeks and provide extra buffer areas and natural vegetation (Johnson County Parks and Recreation District, 2014). Most of the streamway parks are undeveloped except for paved pedestrian and biking trails. The park land provides stream buffer zones with vegetation including forest, shrubs, and grasses that help protect the streams from urban encroachment. The streamway parks contributed directly to improved habitat scores related to buffer width, buffer length, and canopy cover, and likely contributed indirectly to improvements in the other habitat variables.

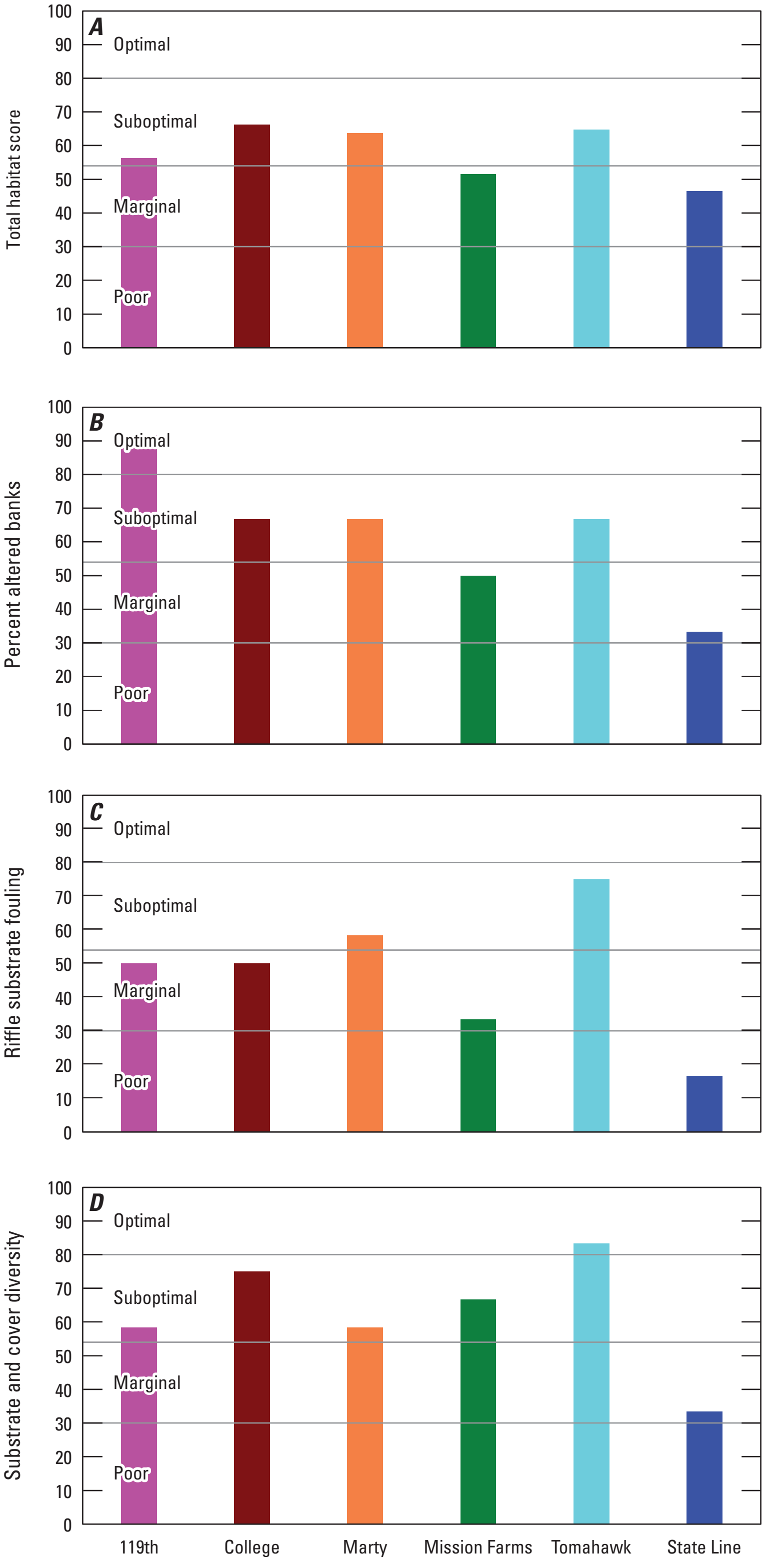


Figure 15. Normalized total habitat and selected individual habitat variable scores at the Indian Creek study sites during July 2012. *A*, total habitat score; *B*, percent altered banks; *C*, riffle substrate fouling; and *D*, substrate and cover diversity.

Biological Conditions of Indian Creek

Biological conditions evaluated were periphyton and macroinvertebrate communities and stream metabolism. Stream metabolism data were used to calculate a functional stream health metric. Periphyton and macroinvertebrate samples were collected during below-normal (August 2012) and normal to slightly above-normal (April 2013) streamflows. In addition, periphyton samples for chlorophyll (algal biomass) analysis were collected weekly from August 2011 through September 2012. Stream metabolism was calculated for the 2-year period July 2011 through June 2013 using continuously measured water-quality data.

Periphyton

The attached algae that grow on submerged surfaces in streams, such as rocks and woody debris, commonly are referred to as periphyton. Periphyton are at the base of the food web in stream ecosystems and serve as a primary link between abiotic (nonliving) factors, such as nutrients, and higher trophic levels (higher place in the food web), such as macroinvertebrates. Algae have short life cycles and respond rapidly to changes in environmental conditions; therefore, periphyton communities often are the first to respond to and recover from floods or contaminant pulses (Allan, 1995; Rosen, 1995; Lowe and Pan, 1996; Lowe and LaLiberte, 2007). Physical, chemical, and pollution tolerances and growth optima (autecological data) have been described for many periphytic algal species, which allows periphytic communities to be used as indicators of ecological conditions. Several States, including Florida (Florida Department of Environmental Protection, 2008), Kentucky (Kentucky Division of Water, 1993), Montana (Bahls, 1993), New Jersey (Ponader and Charles, 2005), and Oklahoma (Oklahoma Conservation Commission, 1993) use periphyton community composition in their bioassessment programs, but Kansas currently (2014) does not.

Periphyton Community Composition

At the 6 Indian Creek sites, 152 periphyton taxa were identified in August 2012 and April 2013 (appendix 11). Bacillariophyta (diatoms) represented 82 percent of the taxa identified. Chlorophyta (green algae) and Cyanophyta (cyanobacteria) represented 11 and 5 percent, respectively. About 60 percent of the taxa identified were rare (contributing less than 1 percent to total algal abundance, biovolume, or both) and 11 percent (16 of 152) of the taxa identified contributed 10 percent or more to total abundance and/or biovolume. Diverse communities dominated by few taxa are a common occurrence in Johnson County streams and streams throughout the nation (Graham and others, 2010; Rasmussen and others, 2012).

Diatoms represented between 81 and 95 percent of abundance at the six sites during August 2012 and between 92 and nearly 100 percent of abundance in April 2013 (table 8). Although diatoms always dominated (greater than 50 percent) algal abundance, they did not always dominate algal biovolume. Green algae dominated algal biovolume at the upstream 119th site (67 percent of total biovolume) and the downstream State Line site (82 percent) in August 2012. Green algae contributed between 3.4 and 34 percent to total biovolume at the other Indian Creek study sites in August. In April 2013, green algae were not dominant, but contributed as much as 35 percent to total biovolume. Cyanobacteria occurred only at the Tomahawk site during August 2012 (6.4 percent or less of abundance and biovolume), and were present in low amounts (less than 5 percent of abundance and biovolume) at the 119th, College, Marty, and Tomahawk sites in April 2013.

Green algae and cyanobacteria are most likely to dominate stream periphyton communities when water temperatures are warm and streamflows are at seasonal lows (Allan, 1995; Stevenson and Rollins, 2007). Filamentous green algae, such as *Cladophora*, *Stigeoclonium*, *Ulothrix*, and *Mougeotia*, become a nuisance in nutrient rich conditions because of excessive growth (Dodds and Gudder, 1992). Filamentous green algae occurred at all Indian Creek study sites during August 2012 (appendix 11), when conditions were ideal for their growth. Occurrence was less common in April 2013, but filamentous green algae were present at all sites except 119th. Because cyanobacteria have the ability to produce toxins and taste-and-odor compounds, they are generally considered a nuisance when present (Graham and others, 2008). Cyanobacteria were uncommon at the Indian Creek study sites (table 8, appendix 11); however, numerous cyanobacterial taxa were observed at the Tomahawk site in August 2012. Tomahawk Creek is the only Johnson County stream that has occasionally had cyanobacteria as a dominant component of the periphyton community (Rasmussen and others, 2009b, 2012).

The four most dominant taxa at each site represented between 48 and 87 percent of the abundance and biovolume at the six sites in August 2012 and April 2013 (appendix 12). The diatom *Achnanthidium minutissimum* was the most dominant taxa by abundance at all sites in August 2012, with the exception of the Mission Farms site, which was dominated by the diatom *Nitzschia inconspicua*. Based on biovolume, filamentous green algae were the dominant taxa at the 119th, College, Marty, and State Line sites in August 2012 (*Stigeoclonium* sp. at Marty and *Cladophora glomerata* at the other three sites; appendix 12). The dominant taxa were more variable among sites during April 2013 and included only diatoms. In general, *Surirella brebissonii* and *Gomphoneis olivacea* were among the four most dominant taxa at all sites during April 2013 (appendix 12). The dominant diatoms at the Indian Creek sites generally are indicative of somewhat degraded, eutrophic conditions with small to moderate amounts of organic enrichment. The dominant green algae are considered nuisance taxa (Porter, 2008). In Johnson County streams, *Sururella brebissonii* and *Gomphoneis olivacea* commonly are dominant in spring and *Stigeoclonium* sp. and *Cladophora glomerata* commonly

Table 8. Percent contributions of each algal periphyton division to total abundance and biovolume at the Indian Creek study sites during August 2012 and April 2013.

[Percentages based on the mean of three samples at Tomahawk and College and two samples at the other four sites; ±1 standard deviation in parentheses; ±, plus or minus; Bacillariophyta, diatoms; Chlorophyta, green algae; Cryptophyta, cryptophytes; Cyanophyta, blue-green algae or cyanobacteria; Other, Euglenophyta, Chrysophyta, and Pyrrophyta combined; <, less than]

Month	Site (fig. 1)	Percentage contributions to abundance[1]				
		Bacillariophyta	Chlorophyta	Cryptophyta	Cyanophyta	Other
August 2012	119th	90 (1.9)	5.8 (1.5)	4.2 (3.4)	0 (0)	0 (0)
	College	95 (0.84)	3.1 (0.83)	2.0 (1.2)	0 (0)	0 (0)
	Marty	93 (5.7)	2.7 (2.3)	3.8 (3.4)	0 (0)	0 (0)
	Mission Farms	84 (5.9)	11 (5.5)	4.2 (0.42)	0 (0)	0 (0)
	Tomahawk	90 (5.5)	2.1 (0.84)	1.9 (0.64)	6.4 (6.1)	0 (0)
	State Line	81 (0.30)	14 (1.9)	4.9 (1.5)	0 (0)	0.11 (0.11)
April 2013	119th	98 (3.2)	0 (0)	0 (0)	2.3 (3.2)	<0.01 (<0.01)
	College	95 (6.8)	0.52 (0.40)	0 (0)	4.5 (6.6)	<0.01 (<0.01)
	Marty	98 (1.6)	1.2 (1.7)	0 (0)	0.48 (0.69)	0 (0)
	Mission Farms	99 (0.29)	0.20 (0.29)	0 (0)	0 (0)	0 (0)
	Tomahawk	95 (5.8)	1.4 (1.1)	0 (0)	0.78 (1.1)	0 (0)
	State Line	92 (6.8)	6.6 (9.3)	0 (0)	0 (0)	0 (0)

Month	Site (fig. 1)	Percentage contributions to biovolume[1]				
		Bacillariophyta	Chlorophyta	Cryptophyta	Cyanophyta	Other
August 2012	119th	33 (35)	67 (35)	0.32 (0.15)	0 (0)	0 (0)
	College	65 (43)	34 (43)	0.44 (0.36)	0 (0)	0 (0)
	Marty	96 (3.0)	3.4 (2.1)	0.76 (0.91)	0 (0)	0 (0)
	Mission Farms	72 (15)	27 (15)	1.2 (0.24)	0 (0)	0 (0)
	Tomahawk	64 (14)	33 (16)	0.58 (0.26)	2.8 (2.7)	0 (0)
	State Line	16 (10)	82 (8.3)	0.43 (0.22)	0 (0)	1.2 (1.8)
April 2013	119th	100 (0.11)	0.11 (0.11)	0 (0)	0 (0)	<0.01 (<0.01)
	College	99 (1.0)	0.62 (0.52)	0 (0)	0.57 (0.54)	0.09 (0.09)
	Marty	65 (35)	35 (35)	0 (0)	<0.01 (<0.01)	0 (0)
	Mission Farms	100 (0.04)	0.04 (0.04)	0 (0)	0 (0)	0 (0)
	Tomahawk	80 (12)	20 (12)	0 (0)	0.10 (0.01)	0 (0)
	State Line	73 (23)	27 (23)	0 (0)	0 (0)	0 (0)

[1] Total percentages may not sum to 100 because of rounding.

are dominant in summer (Rasmussen and others, 2009b, 2014; Graham and others, 2010).

Periphyton Metrics

Autecological data define physical, chemical, and pollution tolerances and provide information about how organisms may respond to changing environmental conditions (Rosen, 1995; Van Dam and others, 1994). Metrics based on autecological information can provide insight into the environmental stresses experienced by organisms or be used to define organism response along an environmental gradient (Stevenson and Bahls, 1999). Among the algal periphyton, diatoms frequently are used as indicators of environmental change because they are known to be sensitive to many factors (for example, light, nutrients, oxygen, and organic carbon) (Porter, 2008). Among-site differences in periphyton community metrics were evaluated for 24 metrics in 5 categories (oxygen tolerance, saprobity, trophic condition, nitrogen-uptake metabolism, and other indices). Either a single metric or a combination of two or three metrics from each category except oxygen tolerance are discussed in this section. Oxygen tolerance metrics were omitted because results and interpretation are similar to saprobity. All 24 metric scores, the environmental conditions associated with each metric, and statistical comparisons among sites are presented in appendix 13.

Saprobity

Saprobes are organisms that live in and derive nourishment from decaying organic matter. The saprobien index, a measure of saprobity, was developed to evaluate diatom communities with respect to sensitivity to organic pollution and is based on organism tolerance to the presence of biodegradable organic matter and oxygen concentrations (Van Dam and others, 1994). The five saprobity categories calculated by ADAS are oligosaprobic, beta-mesosaprobic, alpha-mesosaprobic, alpha-mesosaprobic/polysaprobic, and polysaprobic. These categories represent a gradient of conditions ranging from pristine, with increased oxygen and decreased concentrations of biodegradable organic matter (oligosaprobic), to highly polluted, with decreased oxygen and increased concentrations of organic matter (polysaprobic; Van Dam and others, 1994; Porter, 2008). The percentage of diatoms in the oligosaprobic and beta-mesosaprobic categories were summed, treated as one category, and are discussed in this section. These two categories are indicative of unpolluted conditions, with BOD less than 4 mg/L and percent oxygen saturation greater than 70 (appendix 13).

During August 2012, the percentage of diatoms in the oligosaprobic and beta-mesosaprobic categories ranged from 46 to 78 percent. The percentage of diatoms in the oligosaprobic and beta-mesosaprobic categories was lower in April 2013 compared to August 2012 and ranged from 28 to 53 percent (fig. 16*A*). Among-site differences along the upstream-downstream gradient were not statistically significant (August 2012 ANOVA: F=2.76, *p*-value=0.10; April 2013 ANOVA: F=3.24, *p*-value=0.07); however, during August 2012 the two upstream sites had between 12 and 33 percent (119th=71 percent; Tomahawk=78 percent) more oligosaprobic and beta-mesosaprobic diatoms than the downstream sites (45 to 59 percent) (fig. 16*A*). In April 2013, the percentage of oligosaprobic and beta-mesosaprobic diatoms decreased in the downstream direction by 22 percent from the 119th (53 percent) site to the Marty (31 percent) site, increased by 13 percent between the Marty and Mission Farms site (44 percent), and then decreased to a minimum of 28 percent at the State Line site. These patterns along the upstream-downstream gradient, with larger percentages of diatoms indicative of less degraded conditions at the upstream sites and the site located the farthest downstream from the WWTFs, are indicative of wastewater influences on diatom community composition in Indian Creek.

Overall, the large percentage of oligosaprobic and beta-mesosaprobic diatoms during August 2012 generally reflected water-quality conditions when samples were collected. The BOD was low (less than or equal to 4 mg/L) and dissolved oxygen was moderate at all sites (greater than 6 mg/L) except Tomahawk (dissolved oxygen=4.6 mg/L) (appendix 14). The lower percentage of oligosaprobic and beta-mesosaprobic diatoms in April 2013 suggests that water-quality conditions were poorer at all sites during this time period; however, BOD was similar to August 2012 at all sites and dissolved oxygen was high (greater than 10 mg/L). The low abundance of these diatoms in Indian Creek during April 2013 is in direct contrast to spring diatom communities in the Blue River during 2008. Oligosaprobic and beta-mesosaprobic diatoms dominated (greater than 60 percent of total) the spring periphyton communities in the Blue River at all sites, regardless of wastewater influences (Graham and others, 2010). Wastewater contributed between 20 to 81 percent more to streamflow at Indian Creek than the Blue River during spring, and among-stream differences may have been due to wastewater influences; however, wastewater contributed more to streamflow at most Indian Creek sites in August 2012 (64 to 100 percent) than April 2013 (42 to 99 percent) (appendix 14). Other urban influences that affect environmental conditions may have affected Indian Creek diatom community composition in April 2013. For example, dissolved solids concentrations were between 20 and 46 percent higher at all sites during April 2013 than August 2012, primarily because of higher concentrations of sodium and chloride (appendix 14). Road salt can persist in the environment and cause elevated chloride concentrations for extended periods after applications (Kaushal and others, 2005). The chronic exposure criterion of 230 mg/L for chloride (U.S. Environmental Protection Agency, 1988) was exceeded at all sites during the collection of biological samples in April 2013, and was exceeded for extended periods of time in the 4 months before sample collection. Chronic exposure to elevated chloride concentrations may have decreased the abundance of diatoms indicative of unpolluted conditions in Indian Creek during April 2013 (Corsi and others, 2010).

Trophic Condition

Trophic condition indicates productivity of aquatic ecosystems with respect to concentrations of nitrogen and phosphorus and associated levels of primary productivity. Oligotrophic ecosystems have low levels of nutrients and productivity, mesotrophic systems have moderate levels of nutrients and productivity, and eutrophic systems have high levels of nutrients and productivity (Graham and others, 2008). The seven trophic condition categories that ADAS uses to classify diatoms are oligotrophic, oligo-mesotrophic, mesotrophic, meso-eutrophic, eutrophic, hypereutrophic, and ubiquitous. With the exception of ubiquitous, these categories represent a gradient in tolerance to trophic conditions. Ubiquitous diatoms have a wide range of nutrient tolerance and may be present under a range of trophic conditions. The eutrophic and hypereutrophic categories were summed, treated as one category, and are discussed in this section.

The percentage of diatoms in the eutrophic and hypereutrophic categories ranged from 39 to 76 percent in August 2012 and 57 to 80 percent in April 2013. The percentage of

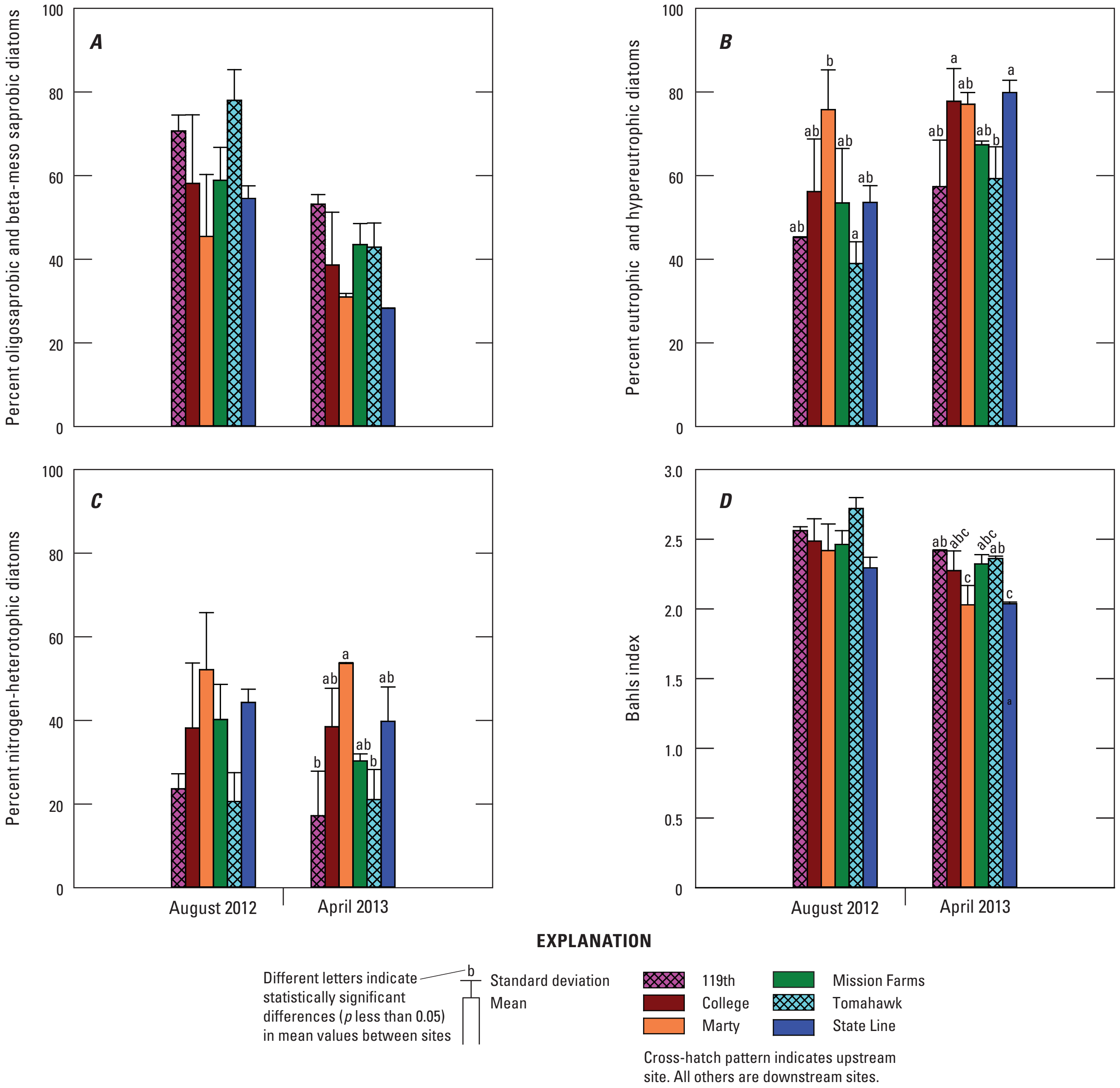


Figure 16. Selected periphyton metric scores at the Indian Creek study sites during August 2012 and April 2013. *A*, percent oligosaprobic and beta-mesosaprobic diatoms; *B*, percent eutrophic and hypereutrophic diatoms; *C*, percent nitrogen-heterotrophic diatoms; and *D*, Bahls Index values.

eutrophic and hypereutrophic diatoms was 12 to 26 percent higher in April 2013 than August 2012 at all sites except Marty. At the Marty site, the percentage of eutrophic and hypereutrophic diatoms was similar between August 2012 and April 2013 (fig. 16*B*). The higher abundance of eutrophic and hypereutrophic diatoms in Indian Creek during spring, rather than summer, is in direct contrast to the seasonal pattern observed in the Blue River during 2008 (Graham and others, 2010). The relative abundance of eutrophic diatoms increased by about 20 percent at all Blue River sites between spring and summer. The difference in the seasonal pattern between the two studies may be caused by the influence of other urban factors on diatom communities in Indian Creek as described for the saprobidity metrics.

Diatom community composition generally was indicative of eutrophic conditions at all sites, despite the large differences in total and inorganic nutrient concentrations between the upstream sites (119th and Tomahawk) and the sites located downstream from the WWTFs during below-normal and normal streamflows (fig. 8, table 6). Eutrophic and hypereutrophic diatoms dominated the periphyton community (greater than 50 percent of total) at all sites, except 119th and Tomahawk (45 and 39 percent, respectively) in August 2012. There were no clear patterns along the upstream-downstream gradient in August 2012 or April 2013; however, diatom communities at the wastewater-influenced sites had between 9 and 37 percent more eutrophic and hypereutrophic diatoms than the upstream sites (fig. 16*B*). During August 2012, the Marty site had the highest percentage of eutrophic and hypereutrophic diatoms (76 percent). In April 2013, the College, Marty, and State Line sites had the largest percentage of eutrophic and hypereutrophic diatoms (77 to 80 percent). Among-site differences were statistically significant (August 2012 ANOVA: F=4.42, *p*-value=0.03; April 2013 ANOVA: F=4.89, *p*-value=0.02). The pattern in eutrophic and hypereutrophic diatoms along the upstream-downstream gradient generally reflects the patterns observed in nutrient concentrations (fig. 8, table 6), with substantial increases immediately downstream from the WWTFs, followed by decreases as distance from WWTF effluent discharge increase. However, substantial decreases did not occur until the Mission Farms site, located 9.5-km downstream from the Middle Basin WWTF, indicating that environmental variables such as nutrient transport and uptake dynamics, streamflow, habitat conditions, and adjacent land use such as road density, rather than just nutrient concentrations, affect diatom community composition.

Nitrogen-Uptake Metabolism

Nitrogen-uptake metabolism refers to the source of nitrogen that diatoms require for growth. Nitrogen-autotrophic diatoms require inorganic nitrogen sources (such as nitrate or ammonia) for growth and nitrogen-heterotrophic diatoms require organic nitrogen sources (such as amino acids; Werner, 1977). Obligate nitrogen heterotrophs require organic sources of nitrogen, whereas facultative nitrogen heterotrophs may utilize inorganic and organic sources of nitrogen. The four categories of nitrogen-uptake metabolism calculated by ADAS are nitrogen autotrophs with a low tolerance for organic nitrogen, nitrogen autotrophs with a high tolerance for organic nitrogen, facultative heterotrophs, and obligate heterotrophs. In general, nitrogen autotrophs with a low tolerance for organic nitrogen develop optimally in oligotrophic waters and obligate nitrogen heterotrophs develop optimally in eutrophic waters (Werner, 1977). The percentage of diatoms in the facultative and obligate nitrogen-heterotroph categories were summed, treated as one category, and are discussed in this section.

The percentage of diatoms in the facultative and obligate nitrogen heterotroph categories ranged from 21 to 52 percent in August 2012 and 17 to 54 percent in April 2013 and matched patterns in eutrophic and hypereutrophic diatoms. In general, patterns along the upstream-downstream gradient were similar in August 2012 and April 2013. Facultative and obligate nitrogen heterotrophs represented a higher percentage of the diatom communities at the wastewater-influenced sites than the upstream sites (fig. 16*C*). There were 11 to 36 percent more of these diatoms at the wastewater-influenced sites (38 to 52 percent) than at the upstream sites (21 to 24 percent). Between the upstream 119th site and the Marty site, located 5.1-km downstream from the Middle Basin WWTF, the percentage of facultative and obligate nitrogen heterotrophic diatoms increased by 29 and 36 percent in August 2012 and April 2013, respectively. As discussed for the trophic metrics, numerous environmental variables, rather than just nutrient concentrations, likely influence diatom community composition in Indian Creek. Among-site differences were not statistically significant in August 2012 (ANOVA: F=3.20, *p*-value=0.07) but were in April 2013 [ANOVA: F=6.86, *p*-value less than (<) 0.01]. The pattern in facultative and obligate nitrogen heterotrophs along the upstream-downstream gradient reflects the substantial increase (orders of magnitude during below-normal and normal streamflow conditions) in nitrogen concentrations at sites located downstream from the WWTFs (fig. 8*A*, *C*, *E*, table 6).

Bahls Index

Bahls index is a multimetric score based on the relative abundance of diatoms in three categories: sensitive, somewhat tolerant, and tolerant. For this metric, diatom tolerance is based on nutrients, organics, salts, water temperature, toxics, substrate stability, and suspended solids. The resulting score is a scaled value ranging from 1 to 3, with 3 representing a community composed of sensitive taxa and 1 representing a community composed of tolerant taxa; therefore, values of 3 indicate good water-quality conditions and values of 1 represent poor water-quality conditions (Porter, 2008; Bahls, 1993).

Bahls Index values ranged from 2.30 to 2.72 in August 2012 and from 2.03 to 2.42 in April 2013 (fig. 16*D*), and were similar to the index values observed for periphyton communities in the Blue River (2.0–2.5) (Graham and others, 2010).

Bahls index values decreased at all sites between August 2012 and April 2013, indicating a shift to more tolerant diatom communities. The 119th and Tomahawk sites had among the highest Bahls index scores in August 2012 (2.56 and 2.72, respectively) and April 2013 (2.42 and 2.36, respectively). Lower index scores at the sites located downstream from the WWTFs relative to the upstream sites may reflect the influence of wastewater effluent discharge on the diatom communities in August 2012, but among-site differences were not statistically significant (ANOVA: F=3.5, *p*-value=0.06). Among-site differences were statistically significant in April 2013 (ANOVA: F=7.35, *p*-value<0.01; fig. 16*D*), but do not reflect the influence of wastewater effluent discharge. Bahls index values were significantly lower at the Marty and State Line sites (2.03–2.04) in April 2013 than at the other sites (2.28–2.42). Despite these patterns, Bahls index values spanned a narrow range (2.0–2.7), indicative of somewhat tolerant diatom communities at all sites during August 2012 and April 2013.

Periphyton Chlorophyll, Abundance, and Biovolume

Chlorophyll, a light-gathering pigment present in all photosynthetic organisms, often is used to describe algal communities because analysis is simpler and less time consuming than identifying, counting, and measuring algal cells. Periphytic algal abundance reflects the total number of cells present, whereas chlorophyll concentrations and biovolume are indicators of biomass. Periphytic chlorophyll concentrations exceeding 150 mg/m^2 are indicative of undesirable algal conditions (Suplee and others, 2009), and KDHE uses the 150 mg/m^2 threshold as an endpoint for TMDLs (Kansas Department of Health and Environment, 2010). Similar threshold concentrations have not been established for periphytic algal abundance and biovolume.

Periphyton chlorophyll concentrations ranged from 14.4 to 195 mg/m^2 in August 2012 and exceeded the KDHE threshold of 150 mg/m^2 at the College site (table 9), located immediately downstream from the Middle Basin WWTF. Concentrations were between 4 and 21 times larger in April 2013 than August 2012 and exceeded the KDHE threshold at all sites (range=301–846 mg/m^2). Substantially higher periphyton chlorophyll concentrations in spring are typical in Johnson County streams and likely are caused by increased light availability before leaf out of streamside trees (Rasmussen and others, 2009b; Graham and others, 2010; Rasmussen and others, 2012). During August 2012 and April 2013, chlorophyll concentrations were lowest at the 119th site upstream from the Middle Basin WWTF and highest at the College site, immediately downstream from the Middle Basin WWTF (table 9). Chlorophyll concentrations increased by an order of magnitude between the 119th (14.4 mg/m^2) and College (195 mg/m^2) sites in August 2012 and nearly tripled between the two sites in April 2013 (301 and 846 mg/m^2); these differences were statistically significant in August 2012 (ANOVA: F=62.4, *p*-value<0.01), but not April 2013(ANOVA: F=1.51,

Table 9. Mean and standard deviation of periphytic chlorophyll concentration and periphytic algal abundance and biovolume at the Indian Creek study sites during August 2012 and April 2013.

[For each variable, means with either no superscript letters or the same superscript letter across sites are not significantly different. Means and standard deviations are based on three replicate samples at the College and Tomahawk sites and two replicate samples at all other study sites; mg/m^2, milligrams per square meter; billion cells/m^2, billion cells per square meter; mm^3/m^2, cubic millimeters per square meter]

Month	Site	Chlorophyll (mg/m^2)		Abundance (billion cells/m^2)		Biovolume (mm^3/m^2)	
		Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
August 2012	119th	^{abc}14.4	7.00	2.51	1.53	8,130	10,800
	College	195	7.11	23.9	5.55	12,300	3,600
	Marty	^{ab}36.3	3.93	30.6	40.3	8,580	11,030
	Mission Farms	^{a}51.7	12.7	3.85	0.46	1,250	142
	Tomahawk	^{abc}48.9	17.4	8.89	1.65	2,530	643
	State Line	117	24.0	7.15	1.49	9,170	768
April 2013	119th	301	41.1	15.3	4.12	5,160	2,240
	College	846	446	56.8	6.02	19,900	3,550
	Marty	599	122	31.1	6.53	21,200	13,600
	Mission Farms	522	104	34.4	19.3	13,400	8,710
	Tomahawk	448	88.1	46.9	21.3	28,300	28,900
	State Line	570	78.7	106	93.0	45,800	15,400

p-value=0.29). Differences along the upstream-downstream gradient were less pronounced among the other sites. During August 2012, chlorophyll concentrations at the State Line site (117 mg/m^2), immediately downstream from the Tomahawk Creek WWTF, were 2 to 3 times higher than at the upstream Tomahawk site and the Marty and Mission Farms sites (36.3–51.7 mg/m^2). During April 2013, chlorophyll concentrations generally were lower at the upstream sites (301–448), decreased in the downstream direction from the College site (846 mg/m^2), and increased again at the State Line site (570 mg/m^2) (table 9). The pattern in chlorophyll concentrations along the upstream-downstream gradient in Indian Creek generally reflects the patterns observed in nutrient concentrations (fig. 8, table 6), with the highest concentrations downstream from the WWTFs; however, the upstream Tomahawk site had chlorophyll concentrations similar to some of the downstream sites in August 2012 and concentrations at all sites exceeded the KDHE threshold of 150 mg/m^2 in April 2013, suggesting factors other than nutrients also may influence algal biomass in Indian Creek, including streamflow, light conditions, and grazer abundance and community composition (Welch and Lindell, 1992; Allan, 1995; Young and others, 2008).

Periphytic algal abundance and biovolume were 2 to 15 times higher in April 2013 than August 2012 at most sites (table 9). Among-site patterns along the upstream-downstream gradient were not as clear as patterns in chlorophyll, though there were similarities. Periphytic algal abundance was consistently lowest at the 119th site [2.51 billion cells per square meter (billion cells/m^2)], increased by an order of magnitude between the 119th and College sites (23.9 billion cells/m^2) in August 2012, and nearly quadrupled between the two sites in April 2013 (15.3 and 56.8 billion cells/m^2, respectively). During August 2012, periphytic algal abundance was 3 to 10 times higher at the College and Marty sites than any of the other sites. In April 2013, periphytic algal abundance was lowest at the 119th site (15.3 billion cells/m^2), highest at the State Line site (106 billion cells/m^2) and generally similar among the other sites (31.1 to 56.8 billion cells/m^2). Periphytic algal biovolume in August 2012 did not match patterns in chlorophyll and abundance. Biovolume was 3 to 10 times lower at the Mission Farms and Tomahawk sites than the other sites (table 9). April 2013 patterns in biovolume were more consistent. Periphytic algal biovolume was lowest at the 119th site and was nearly 4 times higher at the College site. Among-site differences in periphytic algal abundance and biovolume were not statistically significant [ANOVA: all F<1.60, *p*-value greater than (>) 0.08]. The discrepancy in among-site patterns in August 2012 likely is because of the presence of green algae at some sites. The green algae taxa present were large species, and though not numerically abundant, contributed substantially to periphytic algal biovolume (table 8, appendixes 12 and 13).

Seasonal Periphyton Biomass

Periphytic algal biomass in streams may change rapidly in response to runoff events or changing environmental conditions (Stienmann and others, 2006; Lohman and others, 1992; Murdock and others, 2004). Because of these rapid changes, drawing conclusions about differences in algal biomass among sites based only on a few samples can be misleading (Stienmann and others, 2006); therefore, during August 2011 through September 2012, weekly chlorophyll samples were collected at the Indian Creek sites to determine longer-term patterns in algal biomass in a range of streamflow conditions.

Overall, mean periphyton chlorophyll concentrations ranged from 39 mg/m^2 at the 119th site to 122 mg/m^2 at the College site (fig. 17*A*). Along the upstream-downstream gradient, periphyton chlorophyll concentrations generally were lower at the upstream sites than at the wastewater-influenced sites. This difference was most pronounced at the 119th site (fig. 17); mean periphyton chlorophyll concentration at the 119th site was significantly lower than at the other sites (ANOVA: F=8.4, *p*-value<0.01). The KDHE threshold of 150 mg/m^2 (Kansas Department of Health and Environment, 2010) was occasionally exceeded at all sites. About 2 percent of the samples collected at the 119th site (*n*=57) exceeded 150 mg/m^2. By comparison, 28 percent of the samples collected at the College site (*n*=58) exceeded the KDHE threshold. Exceedance of the KDHE threshold at the other sites ranged from 18 to 21 percent.

Maximum periphyton chlorophyll concentrations at most sites were during winter months (December–March), though high concentrations also occurred in late summer (August–September) (fig. 17*B*). Periphytic chlorophyll concentrations (algal biomass) typically peak in early spring because of increased light availability before leaf emergence (Allan, 1995; Hill and others, 2001). April 2012 chlorophyll concentrations were 6 to 13 times lower than April 2013 concentrations and maximum concentrations during September 2011 through September 2012 were 1.2 to 2.2 times lower than April 2013 concentrations (fig. 17*B*, table 9). Periphytic chlorophyll concentrations in April 2013 were more typical of Johnson County streams than April 2012 concentrations (Rasmussen and others, 2009b; Graham and others, 2010; Rasmussen and others, 2012). Winter data are not available for a similar comparison. Many environmental conditions influence periphytic algal biomass including nutrients, streamflow, water temperature, and grazer abundance and community composition. Based on the continuous water-quality data collected at the State Line site during 2004 through 2013, streamflow during January–April 2012 (67 ft^3/s)was about 23 ft^3/s lower than the period of record mean for those months (90 ft^3/s) and water temperature was about 3 °C higher than the period of record mean for those months (9.3 °C). Generally, lower streamflows and warmer water temperatures would be expected to stimulate algal growth; however, these conditions also may have increased macroinvertebrate grazing (Allan, 1995), possibly

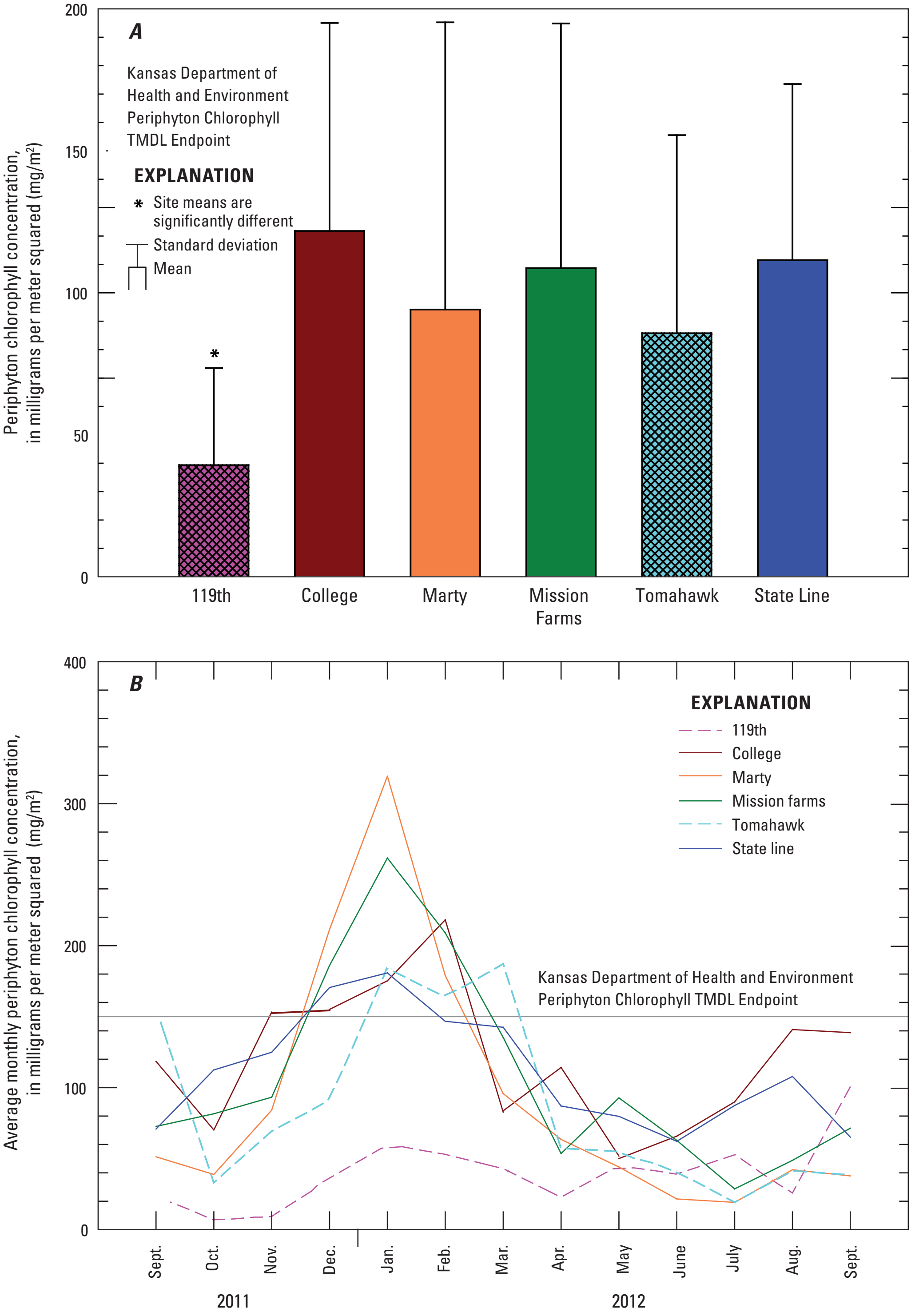


Figure 17. Periphyton chlorophyll concentrations at the Indian Creek study sites during August 2011 through September 2012. *A*, overall mean and *B*, monthly mean. [TMDL, total maximum daily load]

resulting in lower than normal chlorophyll concentrations during April 2012.

Overall, correlations between periphyton chlorophyll concentrations and environmental variables in Indian Creek were weak, but several were statistically significant. Flow regime has a substantial effect on algal biomass because the period between floods dictates the amount of time available for algal accumulation; however, algal biomass may recover rapidly (within days) after flooding (Lohman and others, 1992; Murdock and others, 2004). Periphyton chlorophyll (algal biomass) concentrations were positively related to streamflow conditions during the week before sample collection [Spearman rank-correlation coefficient (rho)=0.33, *p*-value<0.01]. Although the overall correlation with streamflow was positive, chlorophyll concentrations generally were lower when average streamflow during the week before sample collection was higher than 50 ft^3/s (fig. 18), which suggests that streamflows higher than 50 ft^3/s are strong enough to scour attached periphyton from cobbles and may have a substantial influence in observed seasonal and among-site patterns. Nitrate also was positively correlated with periphyton chlorophyll concentrations (rho=0.35, *p*-value<0.01), and reflects the increase in nutrients and algal biomass at sites located downstream from the WWTFs (fig. 17, table 6). Other measured environmental variables that were significantly correlated with periphyton chlorophyll concentrations included water temperature (rho=-0.40, *p*-value<0.01), dissolved oxygen (rho=0.35, *p*-value<0.01), and specific conductance (rho=0.24, *p*-value<0.01).

Macroinvertebrate Communities

Macroinvertebrate community-level responses commonly are used for evaluating biological conditions, long-term monitoring, diagnosis of specific sources and causes of stream impairment, measuring the success of restoration activities, and developing biological criteria in support of water-quality compliance and regulation (Rosenberg and Resh, 1993; Southerland and Stribling, 1995). Macroinvertebrate communities have also been widely used as an indicator of stream quality in urban drainage basins (Paul and Meyer, 2001). Macroinvertebrate community evaluations include examination of changes in dominance or abundance of ecologically important taxa and sensitive taxa that have been eliminated or decreased as a result of changes in stream conditions. Abundance and diversity are used to calculate specific indicator metrics. These metrics provide diagnostic information related to stressor responses and effects on community function.

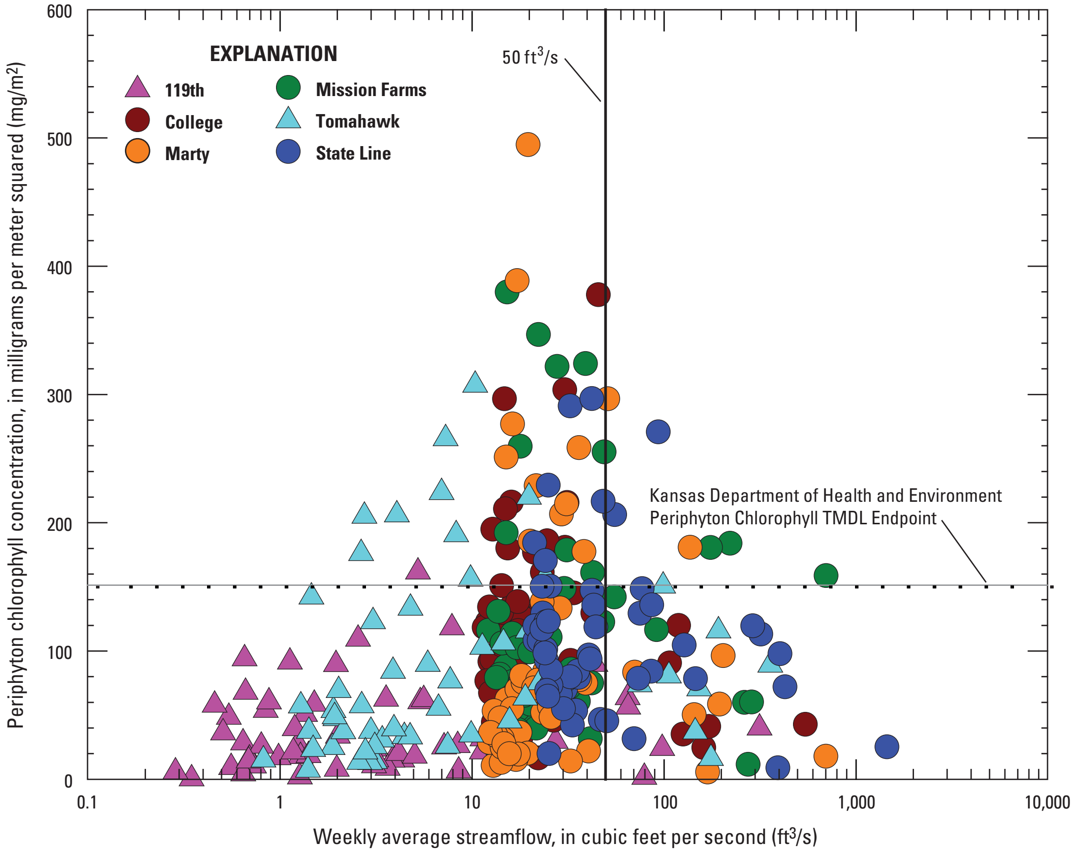


Figure 18. Relation between periphyton chlorophyll concentration and streamflow at the Indian Creek study sites during August 2011 through September 2012. [TMDL, total maximum daily load]

Macroinvertebrate Community Composition

Overall, 130 macroinvertebrate taxa were identified at the six Indian Creek sites in August 2012 and April 2013 (appendix 15). Most taxa (102) were insects; noninsect taxa included Mollusca (mollusks), Annelida (worms and leeches), and Arthropods (malacostracans). About 47 percent of the insect taxa were in the Diptera and Odonata orders, whereas insects typically associated with healthy stream communities (Ephemeroptera, mayflies; Plecoptera, stoneflies; and Trichoptera, caddisflies; referred to as EPT taxa) were only represented by 10 taxa. Between 1 and 7 EPT taxa occurred at each site and relative abundance ranged from 8.4 to 28 percent in August 2012 and 0.5 to 18 percent in April 2013. In addition to these taxa, other aquatic invertebrates including flatworms (Platyhelmenthes), Oligochaeta worms (Families Naididae and Tubificidae), Amphipoda (*Hyalella* sp.), snails (Mollusca), and leeches (Family Erpobdellidae) were common.

Between 31 and 47 taxa were present at each site in August 2012 and between 23 and 34 taxa were present in April 2013 (appendix 15). Individual taxa represented as much as 36 percent of total macroinvertebrate abundance (appendix 16); however, most taxa were rare and represented less than 5 percent of total abundance. In August 2012, damselflies *(Argia* sp., *Enallagma* sp.) and midges (*Polypedilum* sp., *Dicrotendipes* sp., *Chironomus* sp.) were among the most abundant taxa at most sites, whereas midges associated with the genus *Cricotopus* (*Cricotopus/Orthocladius*, *Cricotopus* sp. and *Cricotopus bicinctus)* were among the most dominant organisms at all but the College site in April 2013 (appendix 16). Even though the EPT taxa *Baetis intercalaris* (mayfly), *Fallceon quilleri* (mayfly), and *Cheumatopsyche* sp. (caddisfly) were among the most dominant organisms at some sites, these taxa generally are considered tolerant of organic stream pollution as compared to other taxa within their respective groups (Huggins and Moffet, 1988). The amphipod *Hyalella* sp. was the only dominant taxa present at all sites in April 2013 (appendixes 15, 16). Stoneflies (Plecoptera) were not present at any of the Indian Creek sites during August 2012 or April 2013.

In general, there were no clear among-site patterns in dominant taxa along the upstream-downstream gradient; however, the two sites located immediately downstream from the WWTFs (College and State Line) contained taxa considered tolerant of either organic stream pollution or high nutrient concentrations, especially noninsects such as mollusks (*Physa* sp.), flatworms (Platyhelmenthes), leeches (Erpobdellidae), and aquatic worms (Naididae). In comparing the four most dominant taxa present (appendix 16), these wastewater-affected sites also contained filtering taxa such as blackflies (*Simulium* sp.) and net-spinning caddisflies (*Cheumatopsyche* sp.).

Macroinvertebrate Metrics

Among-site differences in macroinvertebrate communities were evaluated using 34 metrics. These macroinvertebrate metrics include the four KDHE aquatic life support metrics (Kansas Department of Health and Environment, 2008), and additional core metrics used in many State evaluation programs as sensitive and reliable indicators of stream assemblage degradation. There are 8 taxa richness metrics, 15 functional group metrics, 3 tolerance metrics, and 3 other metrics commonly reported in the literature (Barbour and others, 1999). The KDHE aquatic life support metrics are discussed in this section. All 34 metric scores and statistical comparisons among sites are presented in appendix 17.

Aquatic Life Support Metrics

In Kansas, four macroinvertebrate metrics are used as an indicator of the ability of a stream site to support natural aquatic life (Kansas Department of Health and Environment, 2008). The score is an average of the site performance for the four core metrics, with a score of 1, 2, or 3 assigned to each metric value based on KDHE reference criteria. The resulting score determines placement of the stream site into an aquatic life impairment category (fully supporting, partially supporting, or nonsupporting) (table 10). The four core metrics used to determine aquatic life status include the Macroinvertebrate Biotic Index (MBI), the Kansas Biotic Index (KBI), EPT taxa richness, and EPT abundance (percent). Consistent with other Johnson County studies, a fifth metric, percent mussel loss, was not included in the study because this metric requires that a stream site contain at least five mussel species (Poulton and

Table 10. Criteria for four macroinvertebrate metrics used in Kansas to evaluate aquatic life support status of streams (Kansas Department of Health and Environment, 2008).

[MBI, Macroinvertebrate Biotic Index; KBI, Kansas Biotic Index with tolerances for nutrients and oxygen-demanding substances; EPTRich, EPT richness; E, Ephemeroptera; P, Plecoptera; T, Trichoptera; %EPT, percentage of EPT species; <, less than, >, greater than]

Aquatic life support	Score	MBI	KBI	EPTRich	%EPT	Mean score
Fully supporting	3	<4.51	<2.61	>12	>48	>2.49
Partially supporting	2	4.51–5.39	2.61–2.99	8–12	31–47	1.5–2.49
Nonsupporting	1	>5.39	>2.99	<8	<31	1.0–1.49

others, 2007; Rasmussen and others, 2009b; Graham and others, 2010; Rasmussen and others, 2012).

Macroinvertebrate Biotic Index

The MBI is used to evaluate the effects of oxygen-demanding substances, nutrients, and organic enrichment on macroinvertebrate populations. It is a family-level biotic index that uses tolerance values ranging from 1 to 11 for insect and mollusk taxa, with smaller values corresponding to less tolerance and a lesser degree of stream degradation (Davenport and Kelly, 1983). There were no clear patterns in MBI values along the upstream-downstream gradient (fig. 19*A*; appendix 17). The State Line site, located downstream from the Middle Basin and Tomahawk Creek WWTFs (fig. 1), had significantly higher MBI values (6.41 to 6.46) than most other sites in August 2012 (*p*-value<0.01) and April 2013 (*p*-value=0.04); however, in August 2012, the MBI at the upstream 119th site (5.92) also was significantly higher than all other sites except State Line (*p*-value<0.01). The MBI values were similar among the other sites and ranged from 5.30 to 5.92. Based on the MBI, none of the sites were fully supporting of aquatic life and most were nonsupporting (table 10).

Kansas Biotic Index

The KBI was specifically developed for Kansas and uses aquatic organism tolerances to nutrients and oxygen-demanding substances (Huggins and Moffet, 1988). It is a genus-level biotic index calculated in a similar manner as the MBI, with a scoring range of 0 to 10. Small values indicate less tolerance and minimal biological degradation. The KBI values ranged from 2.55 to 3.01 in August 2012 and were generally smaller than in April 2013 when KBI values ranged from 3.14 to 3.46 (appendix 17). There were no clear patterns in KBI values along the upstream-downstream gradient (fig. 19*B*), though in August 2012, the KBI was lower at the upstream 119th site than at the downstream State Line site. In April 2013, the College and Marty sites had significantly higher (*p*-value=0.01) KBI values than either the Mission Farms site or the upstream Tomahawk site. Based on the KBI, only the 119th site in August 2012 was fully supporting of aquatic life (fig. 19*B*).

Ephemeroptera, Plecoptera, and Trichoptera Taxa Richness

The EPT taxa richness is the number of distinct taxa belonging to the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies). Most species belonging to each of these orders are considered to be intolerant of stressors and generally larger numbers of species in these groups indicate higher water quality (Barbour and others, 1999). In August 2012, EPT richness was lower at the College and State Line sites, immediately downstream from the WWTFs, though among-site differences were not statistically significant (*p*-value=0.07); there were two to four more EPT taxa at the sites located either upstream or farther downstream from the WWTFs (fig. 19*C*, appendix 17). The EPT richness in April 2013 was lower than in August 2012 and there were no clear patterns along the upstream-downstream gradient. In April 2013, EPT richness was significantly higher (*p*-value<0.01) at the Tomahawk, Mission Farms, and Marty sites; however, there were generally only 1 to 3 taxa present at all sites (fig. 19*C*, appendix 17). Based on EPT richness, all of the study sites were nonsupporting of aquatic life during August 2012 and April 2013 (fig. 19*C*).

Percentage of Ephemeroptera, Plecoptera, and Trichoptera

The percent EPT metric is the relative abundance of organisms belonging to the orders Ephemeroptera (mayflies), Plecoptera (stoneflies), and Trichoptera (caddisflies) expressed as a percentage of the total number in each sample. It provides information about relative abundance of the three sensitive (stressor intolerant) orders of aquatic insects without information about their richness, so abundant populations of a few species can result in high values. The percentage of EPT ranged from 9.2 to 26 in August 2012. Percentage EPT was lower at all sites in April 2013 and ranged from 0.45 to 13 (fig. 19*D*, appendix 17). There were no clear patterns in percentage EPT along the upstream-downstream gradient. In August 2012, the two upstream sites (119th and Tomahawk) and the State Line site were significantly lower (*p*-value=0.03) than other sites, whereas in April 2013, the Tomahawk site had significantly higher (*p*-value<0.01) values than other sites. Similar to the EPT richness metric, percentage EPT values indicated conditions nonsupporting of aquatic life at all sites in August 2012 and April 2013 (fig. 19*D*).

Aquatic Life Support Status

Kansas Department of Health and Environment aquatic life support scores ranged from 1.0 to 1.5 and indicated conditions nonsupporting of aquatic life at all sites, with the exception of Mission Farms in August 2012, which was partially supporting (fig. 19*E*). In previous assessments, Indian Creek study sites always had nonsupporting aquatic life support scores, regardless of location relative to WWTFs (Poulton and others, 2007; Rasmussen and others, 2009b, 2012). By comparison, sites in the nearby upper Blue River Basin, which is influenced by wastewater but has less urban development, typically are partially supporting of aquatic life (Graham and others, 2010). The small range of scores and conditions nonsupporting of aquatic life at all sites indicates factors other than wastewater are affecting macroinvertebrate communities in Indian Creek.

Other urban influences that affect environmental conditions may negatively affect macroinvertebrates. For example, Rasmussen and others (2009b and 2012) determined that in Johnson County, the density of stormwater outfall points adjacent to streams, specific conductance of water, and PAH concentrations in streambed sediment were negatively correlated with biological conditions. The PAHs occurred at all Indian Creek study sites at concentrations large enough to cause adverse effects on aquatic biota (appendix 9). Chloride

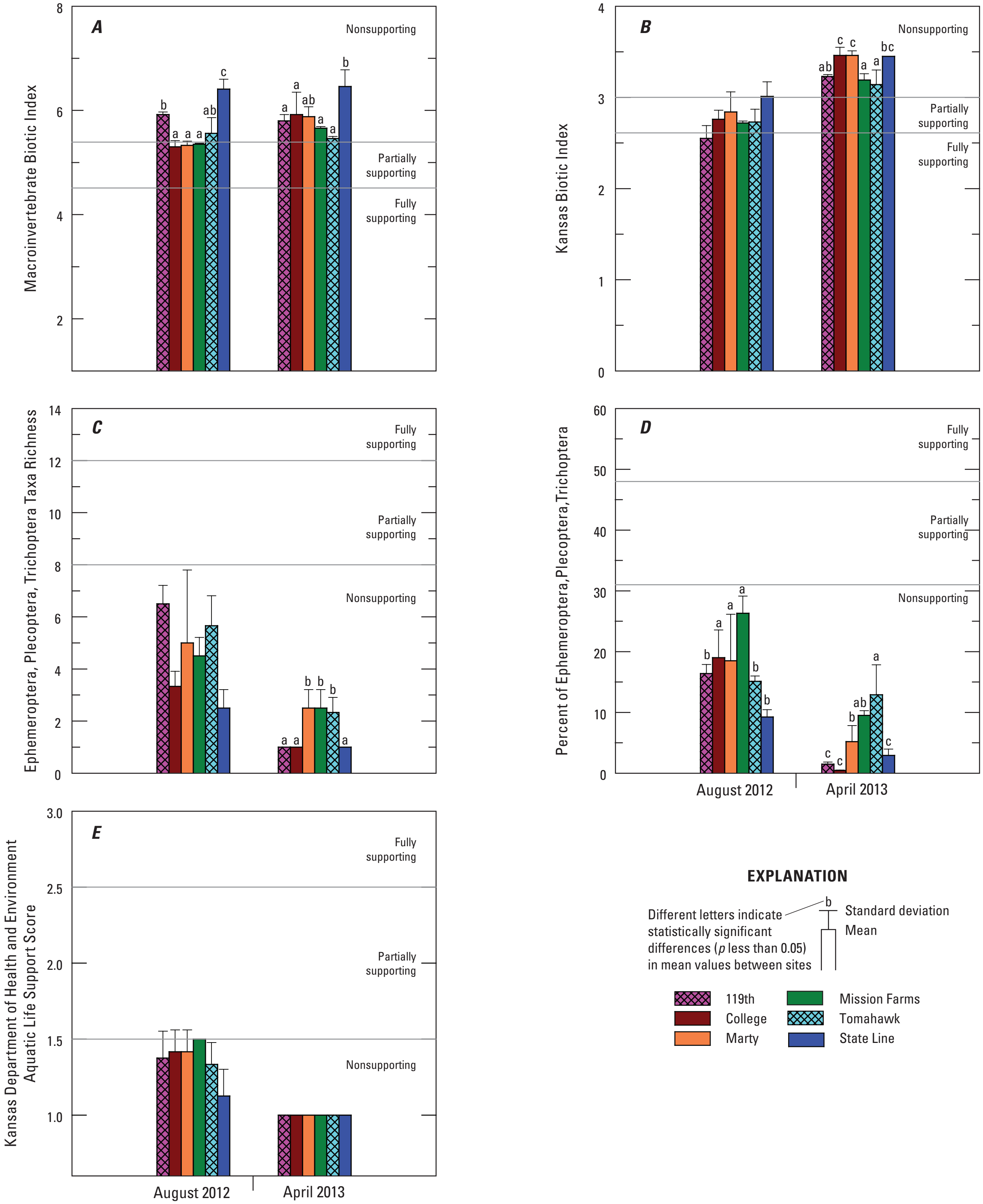


Figure 19. Macroinvertebrate aquatic life support metrics at the Indian Creek study sites during August 2012 and April 2013. *A*, Macroinvertebrate Biotic Index; *B*, Kansas Biotic Index; *C*, Ephemeroptera, Plecoptera, Trichoptera Taxa Richness; *D*, Percent of Ephemeroptera, Plecoptera, Trichoptera; and *E*, Kansas Department of Health and Environment Aquatic Life Support Score.

may also have adverse effects on aquatic biota (Corsi and others, 2010). As discussed for the periphyton saprobidity indices, chloride concentrations were elevated during the months before sample collection in April 2013, likely because of road salt applications for de-icing. Chloride at concentrations above the acute and chronic thresholds may have contributed to the loss of richness and abundance of EPT taxa between the August 2012 and April 2013. Elevated chloride concentrations may persist for extended periods of time after road salt applications (Kaushal and others, 2005), and may also influence macroinvertebrate communities at other times of the year.

Stream Metabolism

Stream metabolism, a measure of ecosystem function, can be an indicator of stream health because function is affected by a combination of physical, chemical, and biological characteristics, all of which are embedded in metabolism rates (Mulholland and others, 2005; Fellows and others, 2006; Young and others, 2008). Stream metabolism is an estimate of how much carbon is produced and/or consumed during a period of time. Diel variation in dissolved oxygen concentration commonly is used to estimate stream metabolism. During steady streamflow conditions, changes in dissolved oxygen concentration result from photosynthesis (primary production), aerobic respiration (cellular processes that require oxygen to generate energy), and gas exchange with the atmosphere (reaeration; Lewis, 2006). Calculated stream metabolism variables include GPP, CR, NEP, and P/R (Bales and Nardi, 2007). Combined, these variables can indicate an ecosystem-level response to changing environmental conditions. The GPP, CR, and NEP are expressed as grams of oxygen per meter squared per day (g $O_2/m^2/d$). There is some uncertainty associated with reaeration coefficient estimation; therefore, relative differences in metabolism rates among sites should be emphasized rather than absolute values of GPP, CR, and NEP. The GPP and CR are discussed in this section. Data for all four calculated variables are presented in appendix 18.

There currently (2014) are no established procedures or criteria for using stream metabolism estimates to assess stream health; however, Young and others (2008) proposed a preliminary framework for assessing functional stream health using GPP and CR (table 11) based on meta-analysis of published available data. This framework proposes criteria-based ratios describing relative differences in GPP or CR between a test site and a reference site. Young and others (2008) define a test site as a site that is potentially affected and a reference site as a site that is more pristine. The downstream College, Marty, Mission Farms, and State Line sites were considered the test sites and the upstream 119th site was considered the reference site for the Indian Creek study. Use of the 119th site as a reference site for this analysis does not imply that functional stream health is not impaired at this urban site relative to more pristine sites in Johnson County or elsewhere. Rather, all comparisons of functional stream health are relative to the upstream 119th site and reflect changes along the upstream-downstream gradient. The preliminary criteria proposed by the framework are based on a global range of data and unimpaired reference sites. Additional research is required to develop more region-specific criteria and more specific criteria for comparing relative differences among impaired sites; however, this framework provides a useful method of comparing relative functional stream health upstream and downstream from the WWTFs that discharge to Indian Creek.

Table 11. Framework and ratio criteria proposed by Young and others (2008) for assessing functional stream health using stream metabolism data.

[GPP, gross primary production; t, test site; r, reference site; CR, community respiration; <, less than; >, greater than]

Ecosystem function	GPP_t/GPP_r	CR_t/CR_r
No impairment	<2.5	0.4–1.6
Mildly impaired	2.5–5.0	0.2–0.4 or 1.6–2.7
Severly impaired	>5.0	<0.2 or >2.7

Gross Primary Production

Gross primary production (GPP) is net primary productivity by autotrophs minus respiration losses. Median GPP for all sites was 0.70 g $O_2/m^2/d$ and ranged from 0 to 10.0 g $O_2/m^2/d$ (appendix 18). This overall GPP range falls within ranges reported for urban streams in eight regions, including Kansas (0.1–11.9 g $O_2/m^2/d$; Bernot and others, 2010) and a continuously monitored suburban stream in Ohio (0.001–12.5 g $O_2/m^2/d$; Beaulieu and others, 2013), but exceeds the range reported in the upper Blue River at all sites, regardless of urbanization or wastewater influences, by a factor of about 2 (Graham and others, 2010).

The GPP is influenced by light availability, hydrology, water temperature, turbidity, and nutrients (Young and Huryn, 1996; Lamberti and Steinman, 1997; Mulholland and others, 2001; Uehlinger, 2006; Roberts and others, 2007; Bernot and others, 2010). In Indian Creek, GPP was positively correlated with nitrate (rho=0.55, *p*-value<0.01), streamflow (rho=0.37, *p*-value<0.01), and water temperature (rho=0.30, *p*-value<0.01,). Light, specific conductance, and turbidity also were significantly (*p*-value<0.01), and positively, correlated with GPP in Indian Creek, but relations were not as strong (all rho<0.20). These correlations are similar to those variables that were significantly correlated with algal biomass (periphyton chlorophyll concentrations) in Indian Creek, demonstrating the inter-relationship between the standing crop of algal biomass and primary production.

Overall, seasonal median GPP was approximately 4.3 times larger in spring (1.30 g $O_2/m^2/d$) than in fall (0.30 g $O_2/m^2/d$) (appendix 18). Median summer and winter

GPP estimates were similar (0.80 and 0.90 g $O_2/m^2/d$, respectively). Among sites, seasonal GPP maxima were during spring at most sites except College, which was highest in winter, and State Line, which was highest in summer (fig. 20*A*, appendix 18). Seasonal minima at all sites were in the fall. Other studies have documented similar results, with GPP typically reaching annual maxima in spring (Acuna and others, 2004; Houser and others, 2005; Uehlinger, 2006; Graham and others, 2010; Beaulieu and others, 2013). Seasonal spring maxima in GPP likely are because of longer day length and associated increases in light and water temperature. Light limitation because of leaf litter inputs and low water temperatures may contribute to decreased GPP during fall months.

Overall median GPP was highest at the College site (4.25 g $O_2/m^2/d$), located immediately downstream from the Middle Basin WWTF, and lowest at the 119th, Tomahawk, and Mission Farms sites (0.20 to 0.40 g $O_2/m^2/d$) (appendix 18). Seasonally, median GPP at the College site was always at least 2 times higher than any of the other sites (fig. 20*A*; appendix 18). The GPP at the State Line site also was always higher than at the other sites, with the exception of Marty in winter. Patterns along the upstream-downstream gradient were generally consistent among seasons. The GPP increased by a factor of about 10 between the 119th and College sites and then decreased in the downstream direction. By the Mission Farms site, GPP was similar to the two upstream sites. The GPP increased by a factor of about 6 between the Mission Farms and State Line sites. Similarly, in the upper Blue River, GPP downstream from the WWTF was about 2.5 times higher than at the upstream site (Graham and others, 2010). Other studies have also documented higher GPP at wastewater-influenced sites (Bott and others, 2006; Gücker and others, 2006; Yates and others, 2012), likely because of increased growth of aquatic plants and algae stimulated by elevated nutrient concentrations. Patterns in GPP along the upstream-downstream gradient correspond to patterns in nutrient concentrations (fig. 6*F*, 8, table 5) and algal biomass (fig. 17, table 9).

Overall median GPP ratios indicated severe impairment of functional stream health at the College site, immediately downstream from the Middle Basin WWTF, and no impairment at the other downstream sites relative to the upstream 119th site (table 12). Seasonally, median GPP ratios at the College site were always indicative of severe impairment relative to the upstream 119th site, except for spring, which had ratios indicative of mild impairment. By comparison, median seasonal GPP ratios at the Mission Farms site were always indicative of no impairment relative to the upstream 119th site. Median seasonal GPP ratios at the Marty and State Line sites indicated mild impairment in summer and fall and no impairment relative to the upstream 119th site in spring and winter. In the upper Blue River, annual and seasonal median GPP ratios at the wastewater-influenced site indicated normal functional stream health relative to the upstream 119th site, except during summer when the GPP ratio was indicative of mild impairment (Graham and others, 2010). Indian Creek demonstrates more severe impairment than the upper Blue River downstream from the WWTF, possibly because the effluent flow from the Middle Basin WWTF (about 15 ft^3/s) was about double the flow from the Blue River Main WWTF (about 8 ft^3/s) during the study period. The Indian Creek Basin also is substantially more urban (greater than 80 percent urban at all sites) than the upper Blue River Basin (less than 40 percent urban at all sites) and other urban influences may have affected stream health at the downstream sites relative to the upstream 119th site, though patterns along the upstream-downstream gradient indicated wastewater influence. Severe impairment at the College site and mild or no impairment relative to the upstream 119th site at the other downstream sites indicated that wastewater influence on functional stream health in Indian Creek decreases as distance from the WWTFs increases. For example, GPP at the Mission Farms site, located about 9.5-km downstream from the Middle Basin WWTF, was similar to GPP at the two upstream study sites.

Community Respiration

Community respiration (CR) includes respiration by autotrophs (photosynthetic organisms such as algae) and heterotrophs (non-photosynthetic organisms such as bacteria, macroinvertebrates, and fish). Median CR for all sites was 2.19 g $O_2/m^2/d$ and ranged from 0 to 28.5 g $O_2/m^2/d$ (appendix 18). This overall CR range exceeds the range reported for urban streams in eight regions, including Kansas (0.5–17.9 g $O_2/m^2/d$; Bernot and others, 2010) and a continuously monitored suburban stream in Ohio (0.39–12.96 g $O_2/m^2/d$; Beaulieu and others, 2013), as well as the range reported in the upper Blue River by a factor of about 6 (Graham and others, 2010). The range in CR estimates also exceeds the top 5 percent of CR values in a recent synthesis of ecosystem metabolism (22.7 g $O_2/m^2/d$; Hoellein and others, 2013); however, the upper CR range does fall within the range reported for 1 year of continuous monitoring of a midwestern agricultural stream (0.9–34.8 g $O_2/m^2/d$; Griffiths and others, 2013), and approximately 1 year of continuous monitoring of streams in northern Spain (6.3–42.6 g $O_2/m^2/d$; Izagirre and others, 2008). High respiration rates in streams receiving untreated or partially treated wastewater discharges may be due to nutrient inputs (Izagirre and others, 2008).

Like GPP, CR is influenced by hydrology, water temperature, turbidity, and nutrients (Mulholland and others, 2001; Hill and others, 2000; Uehlinger, 2000; Roberts and others, 2007; Izagirre and others, 2008; Bernot and others, 2010). The CR was positively correlated with GPP (rho=0.65, *p*-value<0.01) and relations with environmental variables were similar. The CR in Indian Creek was positively correlated with nitrate (rho=0.53, *p*-value<0.01), streamflow (rho=0.38, *p*-value<0.01), and water temperature (rho=0.32, *p*-value<0.01) and significantly (*p*-value<0.01), but less strongly correlated with light, specific conductance, and turbidity (all rho<0.20). Positive correlations between CR, water temperature, and nitrate have been documented in other

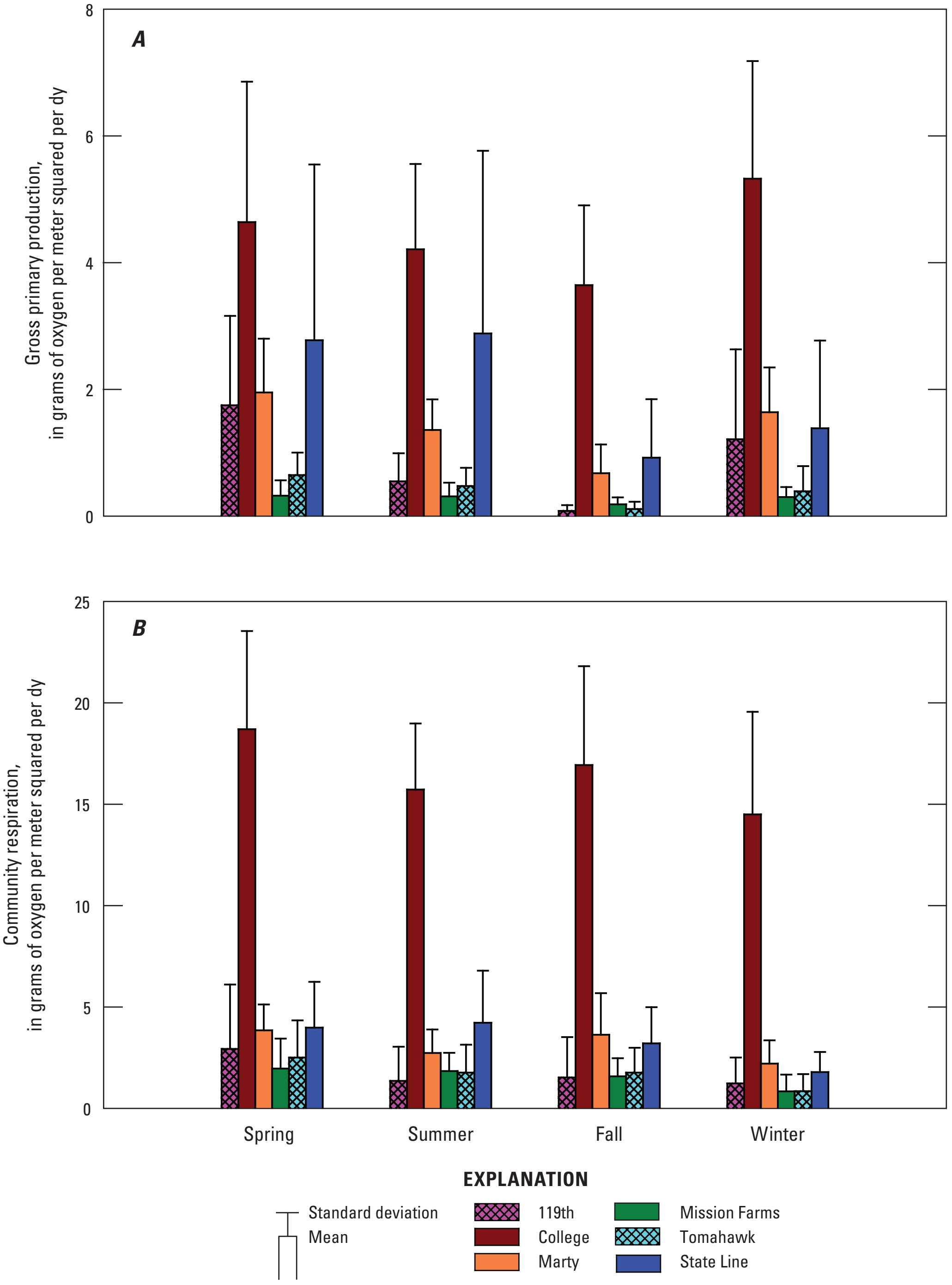


Figure 20. Seasonal patterns in mean gross primary production and community respiration at the Indian Creek study sites during July 2011 through June 2013. *A*, gross primary production and *B*, community respiration.

Table 12. Seasonal and overall summary of functional stream health ratios at the Indian Creek study sites during July 2011 through June 2013.

[Impact assessment based on Young and others (2008) proposed ratio criteria; n, number of observations]

Time period	College				Marty				Mission Farms				State Line			
	College:119th ratio			Ecosystem function	Marty:119th ratio			Ecosystem function	Mission Farms:119th ratio			Ecosystem function	State Line:119th ratio			Ecosystem function
	n	Range	Median		*n*	Range	Median		*n*	Range	Median		*n*	Range	Median	
Gross primary production																
Summer	156	0–62.0	9.18	Severly impaired	156	0–22.0	2.92	Mildly impaired	156	0–8.00	0.61	No impairment	156	0–91.0	4.00	Mildly impaired
Fall	90	0–66.0	27.2	Severly impaired	90	0–19.0	4.50	Mildly impaired	90	0–7.00	1.00	No impairment	90	0–80.0	5.00	Mildly impaired
Winter	146	0–92.0	6.17	Severly impaired	146	0–16.0	2.09	No impairment	146	0–7.00	0.25	No impairment	146	0–10.0	1.69	No impairment
Spring	141	0–23.5	2.82	Mildly impaired	141	0–9.00	1.32	No impairment	141	0–2.33	0.16	No impairment	141	0–7.33	1.53	No impairment
July 2011–June 2013	533	0–92.0	7.14	Severly impaired	533	0–22.0	2.33	No impairment	533	0–8.00	0.33	No impairment	533	0–91.0	2.00	No impairment
Community respiration																
Summer	159	0–835	20.4	Severly impaired	159	0–120	3.59	Severly impaired	159	0–60.0	2.38	Mildly impaired	159	0–432	3.77	Severly impaired
Fall	165	0–812	18.5	Severly impaired	165	0–116	3.26	Severly impaired	165	0–50.5	1.36	No impairment	165	0–207	2.49	Mildly impaired
Winter	150	0–294	16.7	Severly impaired	150	0–67.7	2.51	Mildly impaired	150	0–25.7	0.64	No impairment	150	0–52.6	1.90	Mildly impaired
Spring	142	0–206	6.56	Severly impaired	142	0–109	1.50	No impairment	142	0–62.0	0.73	No impairment	142	0–154	1.51	No impairment
July 2011–June 2013	616	0–835	15.7	Severly impaired	616	0–120	2.65	Mildly impaired	616	0–62.0	1.17	No impairment	616	0–432	2.15	Mildly impaired

streams across a range of land uses (Bernot and others, 2010; Beaulieu and others, 2013).

Overall seasonal median CR was highest in spring (3.15 g $O_2/m^2/d$) and lowest in winter (1.41 g $O_2/m^2/d$; appendix 18). Median summer and fall CR estimates were similar (2.27 g and 2.06 g $O_2/m^2/d$, respectively). Other studies have documented similar results, with CR typically reaching annual maxima in the spring and minima in winter (Uehlinger, 2006; Graham and others, 2010). Seasonal patterns in CR are closely related to water temperatures because metabolic activity generally increases with increasing water temperature, though seasonal water temperature maxima may stress some aquatic organisms (Sinsabaugh, 1997; Hill and others, 2000).

The College site had the highest median CR value (16.2 g $O_2/m^2/d$) and the 119th, Tomahawk, and Mission Farms sites had the lowest CR values (0.94 to 1.38 g $O_2/m^2/d$) (appendix 18). Seasonally, median CR at the College site was always at least 3.6 times higher than at any of the other sites (fig. 20*B*, appendix 18). The CR at the Marty and State Line sites also was consistently higher than at the other sites. Patterns along the upstream-downstream gradient were consistent among seasons and matched patterns observed in GPP. The CR increased by a factor of about 17 between the 119th and College sites and then decreased in the downstream direction before increasing again at the State Line site (fig. 20*B*). A similar pattern was observed in the upper Blue River, though the magnitude of the increase between the upstream and downstream sites was not as large; CR was about 1.3 times higher downstream from the WWTF than at the upstream site (Graham and others, 2010).

Overall median CR ratios indicated severe impairment of functional stream health at the College site, immediately downstream from the Middle Basin WWTF, mild impairment at the Marty and State Line sites, and no impairment at the Mission Farms site relative to the upstream 119th site (table 12). Seasonally, median CR ratios at the College site were always indicative of severe impairment relative to the upstream 119th site. At the Marty and State Line sites, CR ratios indicated severe impairment during summer and either mild or severe impairment during all other seasons except spring, which had ratios indicative of no impairment relative to the upstream 119th site. With the exception of summer, which had CR ratios indicative of mild impairment relative to the upstream 119th site, ratios at the Mission Farms site indicated no impairment. Like GPP, CR ratios indicated more severe impairment in Indian Creek than the upper Blue River, where the downstream site was only mildly impaired relative to the upstream site during summer (Graham and others, 2010). Patterns in CR ratios along the upstream-downstream gradient indicate less severe impairment relative to the 119th site as distance from the Middle Basin WWTF increases.

Effects of Wastewater Effluent Discharge on Environmental and Biological Conditions of Indian Creek

Indian Creek is one of the most urban drainage basins in Johnson County, Kans., and environmental and biological conditions are affected by contaminants from point and other urban sources (Rasmussen and others, 2009b, 2012; Rasmussen and Gatotho, 2014). Contaminants from point and other urban sources affect streams by altering hydrology, stream habitat, water chemistry, and biological communities (Welch and Lindell, 1992; U.S. Environmental Protection Agency, 1997; Paul and Meyer, 2001; Cuffney and others, 2010; Poff and others, 2010). The complexity of altered stream systems, biological processes, contaminant sources and transport, and biological responses in urban drainage basins can make it difficult to separate the influence of point and other urban contaminants on environmental and biological conditions. For this study, two urban sites without wastewater influences were compared to four sites located downstream from wastewater effluent discharges. Land use in the entire Indian Creek Basin is primarily urban, allowing a comparison of environmental and biological conditions along an upstream-downstream gradient with varying degrees of wastewater influence but little change in urban land use.

A key goal of the Kansas nutrient reduction plan is a 30-percent reduction in annual total nitrogen and phosphorus loads exported from the State (Kansas Department of Health and Environment, 2004); therefore, KDHE established nutrient concentration goals in wastewater effluent as part of the Kansas Surface Water Nutrient Reduction Plan. After the addition of biological nutrient removal to the Middle Basin WWTF in 2010, annual mean total nitrogen concentrations in effluent decreased by about 46 percent, but the goal concentration of 8.0 mg/L was still exceeded. Total phosphorus goal concentrations of 1.5 mg/L were achieved at the Middle Basin WWTF after the addition of biological nutrient removal to treatment processes and at the Tomahawk Creek WWTF after the addition of chemically enhanced primary treatment in 2009. Annual total nitrogen and phosphorus loads from the Middle Basin WWTF decreased by 42 and 54 percent, respectively, even though effluent volume increased by 11 percent. Similarly, annual total phosphorus loads from the Tomahawk Creek WWTF also decreased by 54 percent despite a 33-percent increase in effluent volume. During 2010 through 2013, annual discharge from the Middle Basin WWTF was about 75 percent of permitted design capacity. Annual nutrient loads likely will increase when the facility is operated at design capacity; however, estimated potential maximum nutrient loads were 27 to 38 percent lower than before capacity upgrades and the addition of biological nutrient removal to treatment processes.

Water-quality data have been collected at the State Line site, located about 13 kilometers downstream from the Middle Basin WWTF and 2.3 kilometers downstream from the Tomahawk Creek WWTF, since 2004, allowing a comparison of water-quality conditions at the site before and after changes in treatment processes at the WWTFs. Water-quality differences at the State Line site were small between the before- and after-upgrade periods, and many observed differences likely were because of among-year variability in weather and streamflow conditions. The most notable difference was in total phosphorus concentrations. Median total phosphorus concentrations during below-normal and normal streamflow conditions were about 43 percent lower after changes in treatment processes were implemented, reflecting decreases in effluent phosphorus concentrations at both WWTFs. A similar decrease in total nitrogen concentrations was not observed, likely because total nitrogen concentrations only decreased in Middle Basin effluent, and wastewater contributed a higher percentage of streamflow when nutrient samples were collected during the after-upgrade period.

The effects of wastewater effluent on the water quality of Indian Creek were most evident during below-normal and normal streamflows (about 75 percent of the time), when wastewater effluent represented about 24 percent or more of total streamflow. Effluent from the two WWTFs caused changes in stream-water quality that may affect biological community structure and ecosystem processes, including higher concentrations of bioavailable nutrients (nitrate and orthophosphorus) and warmer water temperatures during winter months. Concentrations of nutrients downstream from the Middle Basin and Tomahawk Creek WWTFs always exceeded ecoregion-based criteria, even after changes in treatment processes decreased wastewater effluent total nutrient concentrations. Concentrations of nutrients and other water-quality constituents at the downstream sites in Indian Creek are among the highest reported from other stream sites in Johnson County. By comparison, nutrient concentrations at the upstream sites during below-normal and normal streamflows are among the lowest reported from other stream sites in Johnson County, regardless of the urbanization in the Indian Creek Basin (Lee and others, 2005; Poulton and others, 2007; Graham and others, 2010; Rasmussen and others, 2008, 2009b, 2012, 2014).

The influence of other urban activities also caused changes in stream-water quality that may affect biological community structure and ecosystem processes, including higher turbidities downstream from construction areas and higher specific conductance and chloride concentrations during winter months. Wastewater effluent discharge increased specific conductance and chloride concentrations in Indian Creek; however, the largest increases were during winter months and likely are linked to road salt applications for deicing. At concentrations in excess of the EPA acute criterion (860 mg/L), chloride may be toxic to aquatic organisms and cause loss of sensitive taxa in aquatic communities (U.S. Environmental Protection Agency, 1988; Corsi and others, 2010). In contrast to other studies in Johnson County (Rasmussen and others, 2009b, 2012; Graham and others, 2010), periphyton and macroinvertebrate communities at all sites during spring 2013 indicated poorer water-quality conditions than during summer 2012. Typically, periphyton and macroinvertebrate communities are indicative of poorer water-quality conditions during summer because of the stress imposed by seasonal low-flow conditions and high water temperatures. Chloride concentrations exceeded acute (860 mg/L) and chronic (230 mg/L) exposure criteria (U.S. Environmental Protection Agency, 1988) at all Indian Creek study sites, regardless of wastewater influence, for weeks or months during winter 2012–13, and may have had an effect on biological community structure during spring 2013.

Streambed sediment quality may influence the biological condition of Johnson County streams (Rasmussen and others, 2009b, 2012). Wastewater effluent discharge likely influenced streambed sediment quality in Indian Creek. Nutrient concentrations were higher downstream from the WWTFs and there were several organic wastewater-indicator compounds that were only detected at the downstream sites. Urban factors associated with runoff also likely influenced streambed sediment quality. The PAHs are of particular concern for benthic community diversity, and were detected at all Indian Creek study sites. The PAH concentrations in streambed sediment exceeded probable effects concentrations at the three most downstream sites in the drainage basin.

Habitat conditions in Indian Creek generally declined along the upstream-downstream gradient; however, with the possible exception of riffle-substrate fouling, wastewater effluent did not have a measurable effect on in-stream habitat conditions at the downstream sites. General decline in habitat conditions along the upstream-downstream gradient likely was caused by the cumulative effects of urbanization with increasing drainage basin size. Riffle-substrate fouling generally was higher at the sites located downstream from the WWTFs. Increased periphytic algal biomass and the occurrence of nuisance filamentous algae at the downstream sites likely contributed to increased riffle-substrate fouling, but patterns in riffle substrate fouling scores along the upstream-downstream gradient did not reflect patterns in algal biomass. Other factors, such as accumulation of sediment, likely also contributed to riffle-substrate fouling at the downstream sites. Canopy cover, which influences in-stream light conditions, also decreased along the upstream-downstream gradient, likely because of the natural widening of the stream channel as more tributaries flow into Indian Creek (Vannote and others, 1980; Allan, 1995).

Periphyton community composition at all sites was indicative of somewhat degraded, eutrophic conditions with small to moderate amounts of organic enrichment (Bahls, 1993; Porter, 2008). Despite this overall similarity, periphyton community composition was influenced by wastewater effluent discharges into Indian Creek. The relative abundance of eutrophic and nitrogen-heterotrophic diatoms, indicative of nutrient enrichment, was higher at the downstream sites than the upstream sites. Conversely, the relative abundance of oligosaprobic and beta-meso saprobic diatoms, indicative of unpolluted conditions, was higher at the upstream sites than the downstream sites.

Algal biomass, as estimated by chlorophyll, and primary production were lowest at the upstream sites and highest immediately downstream from the WWTFs, indicating conditions for algal growth were more favorable at the downstream sites. Algal biomass occasionally exceeded the KDHE threshold of 150 mg/m^2 at all sites, but at the College site, located immediately downstream from the Middle Basin WWTF, the threshold was exceeded about 28 percent of the time during August 2011 through September 2012. The increase in primary production was substantial enough to indicate mild to severe impairment at the College site relative to the upstream 119th site year-round and mild impairment at the State Line site during summer and fall. Algal growth and primary production commonly increase downstream from WWTFs because of the constant source of bioavailable nutrients (Welch and others, 1992; Lewis and others, 2002; Dyer and others, 2003; Bott and others, 2006; Gücker and others, 2006; Yates and others, 2012). Increased periphytic algal biomass and primary production at the downstream sites may be a direct response to nutrient enrichment, as indicated by the positive correlation with nitrate. There are other factors that affect algal biomass and primary production in streams that may have affected algal growth in Indian Creek, including light, water temperature, streamflow, and grazer abundance (Welch and Lindell, 1992; Allan, 1995; Young and others, 2008).

Light is a key factor limiting algal growth and primary production in temperate streams (Allan, 1995; Hill and others, 2001; Young and others, 2008). Algal biomass at the 119th site was substantially lower than any of the other Indian Creek study sites, including the upstream Tomahawk site. Decreased light conditions may have limited algal biomass at the 119th site; light intensity was lower at the 119th site than at the other Indian Creek sites, likely because of increased canopy cover. By comparison, algal biomass at the upstream Tomahawk site, which had similar water-quality conditions to the 119th site but higher light intensity, was 2 times higher than at the 119th site. Despite differences in algal biomass, primary production was similar between the two upstream sites.

Water temperature affects the growth and metabolic rates of aquatic organisms, with higher water temperatures causing higher rates (Welch and Lindell, 1992). Primary production was positively correlated with water temperature in Indian Creek, but algal biomass had a negative correlation. This difference may be caused by consumption by grazers that reduce the standing crop of algal biomass but not the amount of biomass being produced. Peak primary production was during spring at all sites except College, where peak production was during winter. Water temperatures at the College site were substantially higher than other sites during winter because of the WWTF effluent discharge. Warmer winter water temperatures at this site may have stimulated production.

During low-flow conditions, increases in streamflow may enhance nutrient uptake and growth of algal periphyton (Welch and Lindell, 1992). Streamflow at the downstream sites was always higher than the upstream sites because of wastewater effluent contributions and may have been sufficient to enhance uptake and stimulate algal growth. At all Indian Creek study sites, algal biomass, represented by periphyton chlorophyll concentration, generally increased with streamflows until around 50 ft^3/s; at higher streamflows, algal biomass decreased.

Macroinvertebrate grazers may effectively decrease algal biomass in streams, even under nutrient enriched conditions (Welch and Lindell, 1992). Some macroinvertebrates have developed a specific feeding strategy to remove algae and other periphyton from surfaces by scraping (Cummins, 1974; Barbour and others, 1999). The relative abundance of scrapers did not indicate clear patterns along the upstream-downstream gradient in Indian Creek (appendix 17); however, the approach used to evaluate macroinvertebrate communities in this study was semiquantitative, and does not allow a meaningful comparison of the number of organisms present at each site. More scrapers may have been present at the upstream sites even though relative abundance did not indicate clear among-site patterns.

Macroinvertebrate communities indicated impairment at all sites in Indian Creek. The KDHE aquatic life support scores indicated conditions nonsupporting of aquatic life, regardless of wastewater influences. The Mission Farms site, located about 9.5 kilometers downstream from the Middle Basin WWTF, was partially supporting of aquatic life in August 2012. Although macroinvertebrate communities indicated degraded conditions at all sites, a few metrics indicated some patterns along the upstream-downstream gradient. For example, in August 2012, EPT richness was highest at the upstream sites and lowest at the sites located immediately downstream from the WWTFs. Common wastewater effluent constituents such as nutrients, chloride, trace metals, and organic wastewater-indicator compounds in water and sediments may be important in structuring macroinvertebrate community composition downstream from WWTFs (Birge and others, 1989; Dickson and others, 1992; Diamond and Daley, 2000; Dyer and Wang, 2002; Camargo and Álonso, 2006). However, macroinvertebrate communities also are sensitive to the effects from urbanization and contaminants from other urban sources, and loss of sensitive taxa begin to occur at low levels of urban land use (Booth and Jackson, 1997; Richards and others, 1996; Roth and others, 1996; Roy and others, 2003; Brown and others, 2009). Several environmental conditions associated with urbanization were documented at all Indian Creek study sites including degraded habitat conditions, elevated chloride concentrations, and PAHs in streambed sediment. Because macroinvertebrate communities indicated severe impairment at all Indian Creek sites, wastewater and other urban factors that influence hydrology, water quality, and habitat quality likely had a substantial influence on the biological conditions of Indian Creek.

Evaluation of functional stream health is complementary to traditional water-quality and biological monitoring approaches, because measures of ecosystem function, such as stream metabolism, integrate the influence of physical, chemical, and biological stressors. Environmental stressors may affect habitat, water quality, and/or biological communities (ecosystem structure) but not overall ecosystem function, ecosystem function but not structure, or both; therefore, comprehensive assessments of stream impairment need to include measures of ecosystem structure and function (Mullholland and others, 2005; Fellows and others, 2006; Young and others, 2008). Stream metabolism was calculated for most days during July 2011 through June 2013, allowing the evaluation of primary production and community respiration along the upstream-downstream gradient at a temporal resolution that is not feasible for more traditional biological monitoring approaches.

Overall, functional stream health at the College site was severely impaired and the Marty and State Line sites were mildly impaired relative to the upstream 119th site. College was the only site that was impaired during all seasons; the Marty and State Line sites were not impaired relative to the upstream 119th site during spring. The College site was located about 1.0 km downstream from the Middle Basin WWTF, and wastewater effluent contributed a larger part of streamflow at the College site than at any other downstream site. The State Line site was located further downstream (about 2.4 km) from a WWTF than the College site, and wastewater contributions to streamflow were about 32 percent less; therefore, wastewater-associated effects on environmental and biological conditions and on functional stream health were highest at the College site.

Seasonally, all sites except Mission Farms were impaired relative to the upstream 119th site during summer and fall based on primary production ratios. Based on community respiration ratios, all sites were severely impaired during summer, except for Mission Farms, which was mildly impaired relative to the upstream 119th site during summer. Biological communities typically experience increased stress during summer because of seasonal low-flow conditions and high water temperatures. Wastewater effluent likely represented more than one-half of the streamflow at the downstream Indian Creek study sites during most of the summer, thereby having a substantial influence on water-quality conditions and causing additional stress on biological communities. Differences in environmental and biological conditions along the upstream-downstream gradient likely were more extreme during summer than other times of the year, resulting in seasonal impairment of functional stream health at some sites.

Streams may recover downstream from WWTF effluent discharges through natural dilution and biological uptake and degradation processes. The distance a stream takes to recover depends on a variety of factors including streamflow, effluent volume and composition, water temperature, and pH (Miller, 1991). Patterns in several environmental and biological variables along the upstream-downstream gradient in Indian Creek indicated some stream recovery.

Nutrient concentrations were highest immediately downstream from the Middle Basin WWTF and decreased in the downstream direction until effluent from the Tomahawk Creek WWTF entered the stream and concentrations increased again. The decrease in nutrient concentrations along the upstream-downstream gradient between the College site, located about 1.0 km downstream from the Middle Basin WWTF, and the Mission Farms site, located about 9.5 km downstream, indicates that nutrients are being diluted and/or utilized by biological processes in Indian Creek; however, the distance between the Middle Basin and Tomahawk Creek WWTFs is not sufficient to allow dilution and biological processes to decrease nutrients to the more natural concentrations observed at the upstream sites. Streambed sediment phosphorus concentrations were highest at the sites located immediately downstream from the WWTFs. At the Mission Farms site, sediment phosphorus concentration was similar to the upstream sites, indicating that nutrient cycling along the 8.5-km reach between the College and Mission Farms sites may have been sufficient to decrease sediment phosphorus concentrations to levels observed at the upstream sites. Several organic wastewater-indicator compounds also indicated similar increases and decreases along the upstream-downstream gradient with respect to the WWTFs.

Algal periphyton biomass and community metrics and a few macroinvertebrate community metrics also indicated patterns along the upstream-downstream gradient. Generally, the largest differences were between the upstream sites and the sites located immediately downstream from the WWTFs and some metrics indicated improvement in condition as distance from the Middle Basin WWTF increased. Primary production, community respiration, and functional stream health ratios provide the clearest indication of some stream recovery from wastewater influences along the upstream-downstream gradient. Primary production and community respiration followed the same pattern as nutrients; values increased between the 119th and College sites, decreased in the downstream direction to the Mission Farms site, and then increased again at the State Line site. Estimates of primary production and community respiration at the downstream Mission Farms site generally were similar to estimates at the upstream sites. Overall, functional stream health ratios reflected this pattern, with severe impairment at the College site relative to the upstream 119th site, mild impairment at the Marty site, no impairment at the Mission Farms site, and mild impairment at the State Line site. The overall similarity in stream metabolism metrics and lack of impairment relative to the upstream 119th site at the Mission Farms site indicates that ecosystem processes along the 8.5-km reach of Indian Creek between the College and Mission Farms sites may have been sufficient to restore functional stream health to conditions similar to those at the urban 119th site located upstream from the WWTFs.

A complex range of physical, chemical, and biological factors may potentially affect biological community composition and ecosystem processes, and these factors may vary seasonally (Robinson and Minshall, 1986; Welch and Lindell, 1992; Allan, 1995; Linke and others, 1999; Hill and others, 2001). Cause-and-effect relations are difficult to determine without conducting manipulative field and/or laboratory experiments through a range of spatial and temporal conditions. This complexity makes it difficult to determine which environmental factors most affect biological conditions and ecosystem function in Indian Creek; however, results from this study indicate that wastewater effluent likely influenced algal periphyton biomass and community composition, primary production, and community respiration in Indian Creek. The mechanisms causing the changes in these biological variables are unclear, though elevated nutrient concentrations were positively correlated with algal biomass, primary production, and community respiration. Results from this study also indicate that urban influences, other than wastewater effluent discharge, control macroinvertebrate community structure in Indian Creek.

Changes in treatment processes at the Middle Basin and Tomahawk Creek WWTFs improved wastewater effluent quality and decreased nutrient loads, but the wastewater effluent discharges still had negative effects on the environmental and biological conditions at downstream Indian Creek sites. Wastewater effluent discharge into Indian Creek likely contributed to changes in measures of ecosystem structure (streamflow, water and streambed-sediment chemistry, algal biomass, and algal periphyton community composition) and function (primary production and community respiration) along the upstream-downstream gradient. Wastewater effluent discharges maintained streamflows and increased nutrient concentrations, algal biomass, primary production, and community respiration at the downstream sites. Functional stream health was severely impaired downstream from the Middle Basin WWTF and mildly impaired downstream from the Tomahawk Creek WWTF relative to the urban 119th upstream site. As distance from the Middle Basin WWTF increased, nutrient concentrations, algal biomass, primary production, and community respiration decreased, and by 9.5 km downstream from the discharge, functional stream health was no longer impaired relative to the urban upstream site. Therefore, although wastewater effluent caused persistent changes in environmental and biological conditions and functional stream health at sites located immediately downstream from WWTF effluent discharges, some recovery to conditions more similar to the urban upstream site occurred within a relatively short distance.

Summary

Indian Creek is one of the most urban drainage basins in Johnson County, Kansas, and environmental and biological conditions are affected by contaminants from point and other urban sources. The Johnson County Douglas L. Smith Middle Basin Wastewater Treatment Facility (WWTF) (hereafter referred to as the “Middle Basin”) is the largest point-source discharge on Indian Creek. A second WWTF, the Tomahawk Creek WWTF, discharges into Indian Creek about 11 kilometers (km) downstream from the Middle Basin WWTF. In summer 2010, upgrades to increase capacity from 18.6 to 22.4 cubic feet per second (ft^3/s) and include biological nutrient removal at the Middle Basin WWTF were completed. There have been no recent infrastructure changes at the Tomahawk Creek WWTF; however, during 2009, chemically enhanced primary treatment was added to the treatment process for better process settling before disinfection and discharge with the added effect of enhanced phosphorus removal. The U.S. Geological Survey, in cooperation with Johnson County Wastewater, assessed the effects of wastewater effluent on environmental and biological conditions of Indian Creek by comparing two upstream sites to four sites located downstream from the WWTFs using data collected during June 2004 through June 2013.

The purpose of this report is to describe the effects of wastewater effluent discharge and facility upgrades on the environmental and biological conditions in Indian Creek, downstream from the Middle Basin and Tomahawk Creek WWTFs. This report includes (1) an evaluation of streamflow and water-quality conditions before and after upgrades and upstream and downstream from the WWTFs using previously and newly collected discrete and continuous data, (2) estimates of total nutrient concentrations and loads upstream and downstream from the WWTFs using regression models developed using discrete and continuous data, (3) evaluation of streambed-sediment chemistry, (4) habitat assessment, and (5) a comparison of algal periphyton and macroinvertebrate community metrics and ecosystem function (primary production and community respiration) along the upstream-downstream gradient. Evaluation of environmental and biological data allows assessment of the physical, chemical, and resulting ecological effects of wastewater effluent discharges in an urban area.

Five sites along a 15.4-km reach of Indian Creek and one site on Tomahawk Creek, the largest tributary to Indian Creek, were included in the study. The 119th and Tomahawk sites are located upstream from WWTF effluent discharges. The College, Marty, and Mission Farms sites are located 1.0, 5.1, and 9.5-km, respectively, downstream from the Middle Basin WWTF effluent discharge. The State Line site is located 13-km downstream from the Middle Basin WWTF effluent discharge and 2.3-km downstream from the Tomahawk Creek WWTF effluent discharge. Previously collected streamflow data were available for the Marty and State Line sites and previously collected water-quality (discrete and continuous) data were available for the State Line site. Continuous water-quality monitors were operated at all six sites from July 1, 2011, through June 30, 2013 and discrete water-quality samples were collected at all six sites from June 1, 2011, through June 30, 2013. Water-quality, algal periphyton, and macroinvertebrate samples were collected from all six sites during below-normal streamflow conditions in August 2012 and normal to slightly above-normal streamflow conditions in April 2013. In addition, habitat conditions were assessed in July 2012 and sediment-quality samples were collected in April 2013.

The contribution of wastewater effluent to streamflow at the downstream sites ranged from negligible (less than 1 percent) during large runoff events to nearly 100 percent during the lowest streamflows. Wastewater effluent represented more than 90 percent of total streamflow about 38 percent and 19 percent of the time at the Marty and State Line sites, respectively, during the study period (January 2004 through December 2013). Capacity upgrades from 18.6 to 22.4 ft^3/s at the Middle Basin WWTF did not have a substantial influence on the wastewater effluent contribution to streamflows in Indian Creek.

The Middle Basin and Tomahawk Creek wastewater effluent discharges caused changes in water temperature and the concentration of some water-quality constituents that may affect biological community structure and function, including higher concentrations of bioavailable nutrients (nitrate and orthophosphorus). Other urban sources of contaminants also caused changes in the concentration of some water-quality constituents, including specific conductance and chloride concentrations. Wastewater effluent caused downstream sites to be warmer during the winter and cooler during the summer than upstream sites; the influence of effluent on stream-water temperature was most pronounced during the winter and at the College site, immediately downstream from the Middle Basin WWTF. The effects of wastewater effluent on the water quality of Indian Creek were most evident during below-normal and normal streamflows (about 75 percent of the time), when wastewater effluent contributed more than 24 percent to total streamflow. Nutrient concentrations changed more than other measures of water chemistry as a result of the effect of wastewater effluent. Total and inorganic nutrient concentrations at the downstream sites during below-normal and normal streamflows were 10 to 100 times higher than at the upstream sites, and were highest at the sites located immediately downstream from the WWTFs. Wastewater effluent discharge increased specific conductance and chloride concentrations of Indian Creek; however, the largest increases were during winter months and likely were caused by road salt applications for de-icing. Chloride concentrations exceeded acute and chronic exposure criteria at all Indian Creek study sites, regardless of wastewater influence, for weeks or months during winter.

After the addition of biological nutrient removal to the Middle Basin WWTF in 2010, annual mean total nitrogen concentrations in effluent decreased by 46 percent, but the National Pollutant Discharge Elimination System (NPDES) wastewater effluent permit goal concentration of 8.0 milligrams per liter (mg/L) was still exceeded. The NPDES wastewater effluent permit goal total phosphorus concentration of 1.5 mg/L was achieved at the Middle Basin WWTF after the addition of biological nutrient removal in 2010 and at the Tomahawk Creek WWTF after the addition of chemically enhanced primary treatment in 2009. Annual total nitrogen and phosphorus loads from the Middle Basin WWTF decreased by 42 and 54 percent, respectively, even though effluent volume increased by 11 percent. Annual total phosphorus loads from the Tomahawk Creek WWTF decreased by 54 percent despite a 33-percent increase in effluent volume. During 2010 through 2013, annual discharge from the Middle Basin WWTF was about 75 percent of permitted design capacity. Annual nutrient loads likely will increase when the facility is operated at design capacity; however, estimated potential maximum nutrient loads were 27 to 38 percent lower than before capacity upgrades and the addition of biological nutrient removal to treatment processes.

Water-quality differences at the State Line site were small between the before- and after-upgrade periods. The most notable difference was in total phosphorus concentrations. Median total phosphorus concentrations during below-normal and normal streamflow conditions were about 43 percent lower after changes in treatment processes were implemented, reflecting decreases in effluent phosphorus concentrations at both WWTFs. A similar decrease in total nitrogen concentrations was not observed, likely because total nitrogen concentrations only decreased in Middle Basin effluent, and wastewater contributed a higher percentage of streamflow when nutrient samples were collected during the after-upgrade period.

Nutrient loads at the downstream State Line site were estimated during 2005 through 2012 and nutrient loads at all sites were estimated during July 2011 through June 2013 based on regression models developed using discrete and continuous data. During 2005 through 2012, total nitrogen and total phosphorus from the WWTFs contributed between about 30 and nearly 100 percent to annual nutrient loads in Indian Creek depending on streamflow conditions. Most of the total nitrogen typically comes from wastewater effluent except during years with the highest streamflows; most of the total phosphorus typically comes from wastewater effluent during dry years and from other urban sources during wet years. During July 2011 through June 2013, total nutrient loads increased along the upstream-downstream gradient, with the largest increases between sites located immediately upstream and downstream from the WWTFs. The contribution of wastewater to total nutrient loads was highest at the College site and lowest at the State Line site. Monthly total phosphorus and nitrogen loads from the WWTFs ranged from about 4 and 20 percent, respectively, when streamflow was dominated by stormwater runoff (typically spring and early summer), to nearly 100 percent during drier months (typically late summer).

Nutrient concentrations in streambed sediment were highest downstream from the WWTFs. Polyaromatic hydrocarbons (PAHs) were detected at all Indian Creek study sites and exceeded probable effects concentrations at the three most downstream sites in the drainage basin, indicating urban factors associated with runoff may be influencing sediment quality at these sites. Eleven organic wastewater-indicator compounds were detected only at the downstream sites; of these compounds, five had clear patterns with respect to the WWTFs.

Light intensity was generally lowest at the 119th site and highest at the State Line site. The difference in light conditions among sites reflects the decrease in canopy cover along the upstream-downstream gradient. Total habitat scores indicated suboptimal and marginal conditions at all sites, and generally decreased in the downstream direction. The individual habitat variables with the largest among-site differences in score were percentage of altered banks, riffle-substrate fouling, and substrate cover and diversity. Scores for these variables generally decreased along the upstream-downstream gradient, with the highest scores at the 119th or Tomahawk sites and the lowest at the State Line site.

Overall periphyton community composition at all sites was indicative of somewhat degraded, eutrophic conditions with small to moderate amounts of organic enrichment. Patterns in periphyton metrics along the upstream-downstream gradient reflected the patterns observed in nutrient concentrations. The relative abundance of eutrophic and nitrogen-heterotrophic diatoms, indicative of nutrient enrichment, increased immediately downstream from the WWTFs and generally decreased as distance from WWTF effluent discharge increased. The relative abundance of oligosaprobic and beta-mesosaprobic diatoms, indicative of unpolluted conditions, followed the opposite pattern with decreases immediately downstream from the WWTFs and increases as distance from WWTF effluent discharge increased.

Periphytic algal biomass, as estimated by chlorophyll, and primary production were lowest at the upstream sites and highest immediately downstream from the WWTFs, indicating conditions for algal growth were more favorable at the downstream sites. Increased algal biomass and primary production at the downstream sites may be a direct response to nutrient enrichment at these sites. Patterns along the upstream-downstream gradient generally matched patterns in nutrient concentration, and algal biomass and primary production were positively correlated with nitrate. Many other factors also affect algal growth. Increased light because of decreased canopy cover, increased streamflow, increased water temperatures during winter, and changes in scraper abundance at the downstream sites all may have contributed to the increases in algal biomass and primary production at the downstream sites.

Macroinvertebrate communities indicated impairment at all Indian Creek sites. The Kansas Department of Health and Environment (KDHE) aquatic life support scores indicated conditions nonsupporting of aquatic life, regardless of wastewater influences. Macroinvertebrate communities also are sensitive to the effects of urbanization and contaminants from other urban sources on streams, and loss of sensitive taxa begins to occur at low levels of urban land use. Because macroinvertebrate communities indicated severe impairment at all Indian Creek sites, wastewater and other urban factors that influence hydrology, water quality, and habitat quality likely had a substantial influence on the biological conditions of Indian Creek.

Primary production and community respiration were consistently higher at the sites located immediately downstream from the WWTFs than the upstream sites, regardless of season. There were clear patterns along the upstream gradient; primary production and community respiration increased between the 119th and College sites, decreased in the downstream direction to the Mission Farms site, and then increased again at the State Line site. Estimates of primary production and community respiration at the downstream Mission Farms site were generally similar to estimates at the upstream sites. Functional stream health was evaluated using a preliminary framework based on primary production and community respiration. Overall functional stream health ratios indicated severe impairment at the College site, mild impairment at the Marty site, no impairment at the Mission Farms site, and mild impairment at the State Line site relative to the upstream 119th site. Seasonally, all sites except Mission Farms were impaired relative to the upstream 119th site during summer and fall based on primary production ratios. Based on community respiration ratios, all sites were severely impaired relative to the upstream 119th site during summer, except for Mission Farms, which was mildly impaired. Differences in environmental and biological conditions along the upstream-downstream gradient likely were more extreme during summer than other times of the year, resulting in seasonal or more severe impairment of functional stream health relative to the urban upstream site.

A complex range of physical, chemical, and biological factors may potentially affect biological community composition and ecosystem processes, and these factors may vary seasonally. Cause-and-effect relations are difficult to determine without conducting manipulative field and/or laboratory experiments through a range of spatial and temporal conditions. This complexity makes it difficult to determine which environmental factors most affect biological conditions and ecosystem function in Indian Creek; however, results from this study indicate that wastewater effluent likely influenced algal periphyton biomass and community composition, primary production, and community respiration in Indian Creek. The mechanisms causing the changes in these biological variables are unclear, though elevated nutrient concentrations were positively correlated with algal biomass, primary production, and community respiration. Results from this study also indicate that urban influences, other than wastewater effluent discharge, control macroinvertebrate community structure in Indian Creek.

Changes in treatment processes at the Middle Basin and Tomahawk Creek WWTFs improved wastewater effluent quality and decreased nutrient loads, but the wastewater effluent discharges still had negative effects on the environmental and biological conditions at downstream Indian Creek sites. Wastewater effluent discharge into Indian Creek likely contributed to changes in measures of ecosystem structure (streamflow, water and streambed-sediment chemistry, algal biomass, and algal periphyton community composition) and function (primary production and community respiration) along the upstream-downstream gradient. Wastewater effluent discharges maintained streamflows and increased nutrient concentrations, algal biomass, primary production, and community respiration at the downstream sites. Functional stream health was severely impaired downstream from the Middle Basin WWTF and mildly impaired downstream from the Tomahawk Creek WWTF relative to the urban upstream site. As distance from the Middle Basin WWTF increased, nutrient concentrations, algal biomass, primary production, and community respiration decreased, and by 9.5 km downstream from the discharge, functional stream health was no longer impaired relative to the urban upstream site. Therefore, although wastewater effluent caused persistent changes in environmental and biological conditions and functional stream health at sites located immediately downstream from WWTF effluent discharges, some recovery to conditions more similar to the urban upstream site occurred within a relatively short distance.

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