Prepared in cooperation with the Kansas Department of Health and Environment

Sediment Oxygen Demand in Eastern Kansas Streams, 2014 and 2015

Scientific Investigations Report 2016–5113

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

Cover. Front: Sediment oxygen demand deployments on Little Arkansas River, November 18, 2014. Photograph taken by Lindsey R. King, U.S. Geological Survey.

Back, right: Research hydrologist and hydrologic technician performing a trial run of sediment oxygen demand deployments on the Kansas River at De Soto, May 30, 2014. Left: Preparations for Sediment Oxygen Demand deployments on the Kansas River at De Soto, August 20, 2014. Photographs taken by Guy M. Foster, U.S. Geological Survey.

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SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Conversion Factors

[International System of Units to Inch/Pound]

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
micrometer	0.001	millimeter
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)

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

$$°F = (1.8 \times °C) + 32.$$

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Abbreviations

ADV	acoustic Doppler velocimeter
°C	degrees Celsius
DO	dissolved oxygen
EPA	U.S. Environmental Protection Agency
KDHE	Kansas Department of Health and Environment
LOI	loss on ignition
NLCD	National Land Cover Database
NWIS	National Water Information System
SOD	sediment oxygen demand
TMDL	total maximum daily load
USGS	U.S. Geological Survey

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Abstract

Dissolved oxygen concentrations in streams are affected by physical, chemical, and biological factors in the water column and streambed, and are an important factor for the survival of aquatic organisms. Sediment oxygen demand (SOD) rates in Kansas streams are not well understood. During 2014 and 2015, the U.S. Geological Survey, in cooperation with the Kansas Department of Health and Environment, measured SOD at eight stream sites in eastern Kansas to quantify SOD rates and variability with respect to season, land use, and bottom-sediment characteristics. Sediment oxygen demand rates (SOD_T) ranged from 0.01 to 3.15 grams per square meter per day at the ambient temperature of the measurements. The summer mean SOD rate was 3.0-times larger than the late fall mean rate, likely because of increased biological activity at warm water temperatures. Given the substantial amount of variability in SOD rates possible within sites, heterogeneity of substrate type is an important consideration when designing SOD studies and interpreting the results. Sediment oxygen demand in eastern Kansas streams was correlated with land use and streambed-sediment characteristics, though the strength of relations varied seasonally. The small number of study sites precluded a more detailed analysis. The effect of basin land use and streambed sediment characteristics on SOD is currently (2016) not well understood, and there may be many contributing factors including basin influences on water quality that affect biogeochemical cycles and the biological communities supported by the stream.

Introduction

Dissolved oxygen (DO) is an important factor for the survival of aquatic organisms. Kansas aquatic life support criteria require that dissolved oxygen concentrations are not less than 5.0 milligrams per liter (mg/L) (Kansas Department of Health and Environment, 2015). In 2014, 175 Kansas streams were listed as impaired because of low DO levels (U.S. Environmental Protection Agency, 2014). Physical, chemical, and biological factors in the water column and the streambed affect ambient in-stream DO concentrations to varying degrees depending on individual stream characteristics (Allan, 1995). In late summer, Kansas streams typically report seasonal low flows and warm temperatures, conditions that frequently result in low DO concentrations because of the lower solubility of oxygen at higher temperatures, and the influence of biological activity (Graham and others, 2010; Rasmussen and Gatotho, 2013; Graham and others, 2014). Sediment oxygen demand (SOD) also may contribute to low dissolved oxygen concentrations in Kansas streams. Sediment oxygen demand may account for more than 50 percent of total DO depletion in certain rivers and lakes in the United States (Veenstra and Nolen, 1991). Currently (2016), little to no empirical SOD data have been published on Kansas streams.

Sediment oxygen demand is the rate of water column DO depletion at the sediment-water interface caused by the biological and chemical uptake of DO (Heckathorn and Gibs, 2010; Rounds and Doyle, 1997). Sediment oxygen demand at or near the sediment-water interface typically is caused by the decomposition of organic material, whereas deeper in the sediment SOD is more likely to be driven by chemical oxidation reactions (Rounds and Doyle, 1997). The extent to which SOD plays a role in ambient stream DO concentrations is dependent on physical characteristics and environmental factors such as temperature and precipitation (Bowie and others, 1985).

The Kansas Department of Health and Environment (KDHE) Watershed Planning, Monitoring, and Assessment Section responsibilities include implementation of the Clean Water Act of 1972 and development of statewide surface water quality standards (Kansas Department of Health and Environment, 2015). Understanding the variability of SOD in Kansas streams will allow for better assessment of the causes of DO impairment and development of DO total maximum daily load (TMDL) requirements. During 2014 and 2015, the U.S. Geological Survey (USGS), in cooperation with KDHE, measured SOD rates at eight stream sites in eastern Kansas to quantify SOD rates and variability with respect to season, land use, and bottom-sediment characteristics.

Purpose And Scope

The purpose of this report is to describe SOD measurements made at eight eastern Kansas streams during late summer (annual DO minima) and late fall (annual DO maxima) in 2014 and 2015. Relations between SOD and seasonality, land use, and bottom-sediment characteristics also are described in this report. Measurement of SOD in Kansas streams will provide KDHE data with which to assess DO TMDL requirements and improve model development.

Description Of Study Area

Eight SOD study sites were selected based on drainage basin size, land use (fig. 1*A*; table 1), and DO impairment, and generally represent the range of environmental conditions found in eastern Kansas streams (Kansas Department of Health and Environment, written commun., 2013). Where possible, SOD study sites were located at or near existing USGS streamgage sites. Sediment oxygen demand study sites include the Kansas River at De Soto; Kansas River at Wamego; Indian Creek at Indian Creek Parkway, Overland Park; Pottawatomie Creek near Scipio; Marmaton River near Fort Scott; Little Arkansas River at Valley Center; Walnut River near Augusta; and Grouse Creek near Silverdale (fig 1; table 1).

The drainage area for each SOD sampling site was delineated using the location of the SOD sampling site, not the drainage area of the nearest USGS streamgage, sometimes resulting in small differences between published streamgage drainage area values and those used in this report. These drainage area data are stored in the USGS National Water Information System (NWIS) database available at http://dx.doi.org/10.5066/F7P55KJN. Land use was calculated from the National Land Cover Database (NLCD) 2011 Land Cover (Fry and others, 2011) for each drainage basin (table 1). Similar to drainage area, land use delineation applies to the location of the SOD sampling site, not to the nearest USGS streamgage.

Drainage areas of the SOD study sites (table 1) ranged from 94.8 square miles (mi^2) (Indian Creek) to 59,576 mi^2 (De Soto) (table 1). Most study sites had drainage areas less than 460 mi^2, with the exception of the Little Arkansas site, which had an intermediate drainage area (1,327 mi^2) and the De Soto and Wamego sites, which had large drainage areas (greater than 55,000 mi^2). Land use among SOD study sites ranged from predominantly agricultural (grasslands, pasture and cropland) to predominantly urban (developed; table 1). Agricultural land use was dominant at most sites, but agricultural uses among sites represented a varied mix of grasslands, pasture, and cropland. Dominant (greater than 60 percent of basin land use) agricultural land uses included grassland (Grouse and Walnut), cropland (Little Arkansas), a combination of pasture, cropland, and grassland (Marmaton and Pottawatomie), and cropland and grassland (De Soto and Wamego). Indian Creek was the only urban study site, and developed land represented 95 percent of land use (table 1).

In 2014, reaches of Pottawatomie, Marmaton, and Walnut were listed by KDHE as having DO impairments (Kansas Department of Health and Environment, 2014). Many of the other study sites (De Soto, Wamego, Indian Creek, and Little Arkansas) occasionally report DO concentrations less than 5 mg/L (Kansas Real-Time Water Quality; http://nrtwq.usgs.gov/ks/). All of the study streams have reaches with bacteria impairments, and except for Pottawatomie and Grouse Creeks, also have reaches with nutrient impairments (Kansas Department of Health and Environment, 2014). Treated wastewater effluent typically makes up most of the streamflow at Indian Creek (Graham and others, 2014).

Methods

The SOD data were collected during mostly below-normal streamflow conditions (less than 25th percentile) based on the streamflow statistics for the period of record at the nearest USGS streamgage, available through NWIS (http://dx.doi.org/10.5066/F7P55KJN). Exceptions were at Wamego in August 2015 and Indian Creek in December 2015 when streamflows were above normal (greater than 75th percentile) and Indian Creek during September 2015 when streamflow was normal (between 25th and 75th percentiles). Streamflow was measured at Walnut using standard USGS methods (Turnipseed and Sauer, 2010), but insufficient long-term historical streamflow data existed (less than 10 years) for streamflow statistics to be computed. Streamflow and other ancillary data collected during SOD chamber deployments are available in King and others (2016) (http://dx.doi.org/10.5066/F7610XG8). Sediment oxygen demand data were collected during late summer (August and September), coinciding with warm and dry periods when Kansas streams typically report annual DO minima, and late fall (November and December), coinciding with cold and wet periods when Kansas streams typically report annual DO maxima (Wetzel, 2001; Rasmussen and Gatotho, 2013; Stone and others, 2013). Sediment oxygen demand deployments at De Soto, Little Arkansas, Marmaton, and Pottawatomie were completed in August and November of 2014; SOD deployments at Wamego, Indian Creek, Grouse, and Walnut were completed in August/September and December of 2015.

Sediment Oxygen Demand Chambers

The SOD chambers constructed for this study followed the design used by Heckathorn and Gibs (2010). Large aluminum stock pots (originally 94.6 liters/100 quarts) were modified into chambers to mount a multiparameter water-quality monitor (YSI EXO2; Yellow Springs Instruments, 2014) and the chamber edges pushed into the sediment to seal it to the streambed (fig. 2). Cast iron, powder coated flanges and 3-inch

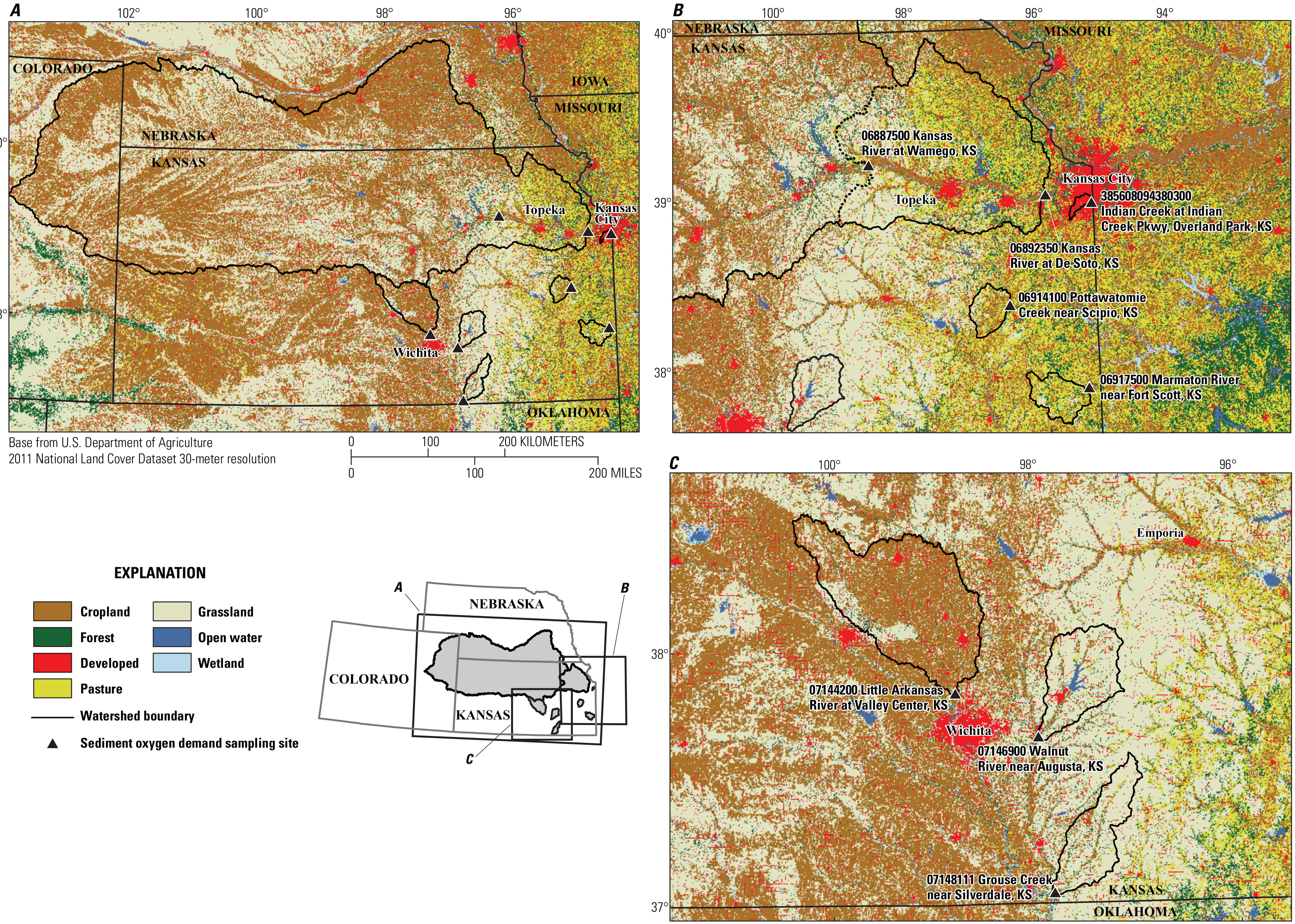

Figure 1. Sediment oxygen demand study sites in eastern Kansas. *A*, Location of sediment oxygen demand (SOD) study sites, land use, and drainage basins; *B*, enlarged area showing location of Kansas River at De Soto, Kansas River at Wamego, Indian Creek, Pottawatomie Creek, and Marmaton River SOD study sites, land use, and drainage basins; *C*, enlarged area showing location of Little Arkansas River, Walnut River, and Grouse Creek SOD study sites, land use, and drainage basins.

Table 1. Location and description of sediment oxygen demand study sites in eastern Kansas, including drainage area and land use.

U.S. Geological Survey site ID	U.S. Geological Survey site number	Short site name	Drainage area (square mile)	Percent land use[1]						
				Open Water	Developed	Forest	Grass-land	Pasture	Crop-land	Wet-lands
Kansas River at De Soto, Kansas	06892350	De Soto	59,576	1	4	2	39	3	49	1
Kansas River at Wamego, Kansas	06887500	Wamego	55,280	1	4	3	40	1	52	1
Indian Creek at Indian Creek Parkway, Overland Park, Kansas	385608094380300	Indian Creek	94.8	0	95	2	0	1	1	0
Pottawatomie Creek near Scipio, Kansas	06914100	Pottawatomie	343	1	3	7	18	38	32	1
Marmaton River near Fort Scott, Kansas	06917500	Marmaton	388	1	4	13	15	53	14	1
Little Arkansas River at Valley Center, Kansas	07144200	Little Arkansas	1,327	1	7	3	22	0	66	1
Walnut River near Augusta, Kansas	07146900	Walnut	452	4	6	3	76	2	7	2
Grouse Creek near Silverdale, Kansas	07148111	Grouse	392	1	4	5	78	3	8	2

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

diameter cast iron pipes were used to mount the water-quality monitor, and neoprene sheets were used to seal the water-quality monitor onto the chamber. Cast iron provided extra weight to the chambers, which helped maintain their placement and seal on the streambed. Four holes were drilled on top of the chamber, which allowed air to escape during deployment; these holes were plugged by rubber stoppers during data collection.

Stream velocity may affect the amount of time a parcel of water is exposed to the streambed and therefore the actual effect of SOD on ambient DO concentrations. Some SOD studies have used water recirculation pumps in the chambers to mimic the effect of stream velocity, though the potential effect on SOD rate is likely small when stream velocity is less than the velocity required to resuspend bottom sediment (Doyle and Rounds, 2003). Without in-chamber recirculation, there is the potential for DO gradients to form from the sediment-water interface upward towards the DO sensor, causing underestimation of SOD rates in streams with higher velocities. Heckathorn and Gibbs (2010) noted a concern that in-chamber circulation potentially could affect the chamber's seal to the streambed. Similar to Heckathorn and Gibs (2010), the chambers used in this study were not equipped with a means to recirculate water inside the chamber. The optical DO sensor used (YSI EXO2) does not require flowing water to produce accurate readings of concentrations of low-dissolved oxygen, and there was concern that any recirculation of the water would suspend the fine sediments typical of eastern Kansas streams. Potential error in SOD measurements where sediments are resuspended may be substantial (Doyle and Rounds, 2003). Therefore, a turbidity sensor was included on the water-quality monitor to monitor settling and resuspension of sediments within the chamber.

A control chamber was constructed in the same way as the regular chambers with one exception. The control chamber had an aluminum plate welded to the bottom to isolate a parcel of water from both the stream bottom and ambient stream water, allowing measurement of oxygen depletion of the water column (Rounds and Doyle, 1997). The control chamber data allowed for correction of measured SOD rates by subtracting oxygen depletion by water column processes from oxygen depletion by SOD processes (Rounds and Doyle, 1997).

Sediment Oxygen Demand Deployments

Study sites were selected to be generally representative of streambed characteristics. Ideal locations for chamber placement are sites with fine-grained sediments, water depth sufficient to submerge the chamber, and low stream velocity (Wilson, 2014). Bottom sediments including silt, clay, and sand are preferred locations for the chambers to create a seal. To achieve a seal, the edges of the chambers were pushed into the streambed sediment as far as practical, to depths ranging from 5.2 inches on soft bottoms, to less than a tenth of an inch on coarser substrates. Sediment larger than fine gravel (greater than 0.25 millimeters) increases the chance of ambient water leaking into the chamber (Wilson, 2014).

At each SOD study site, two replicate chambers and a control chamber equipped with calibrated multiparameter

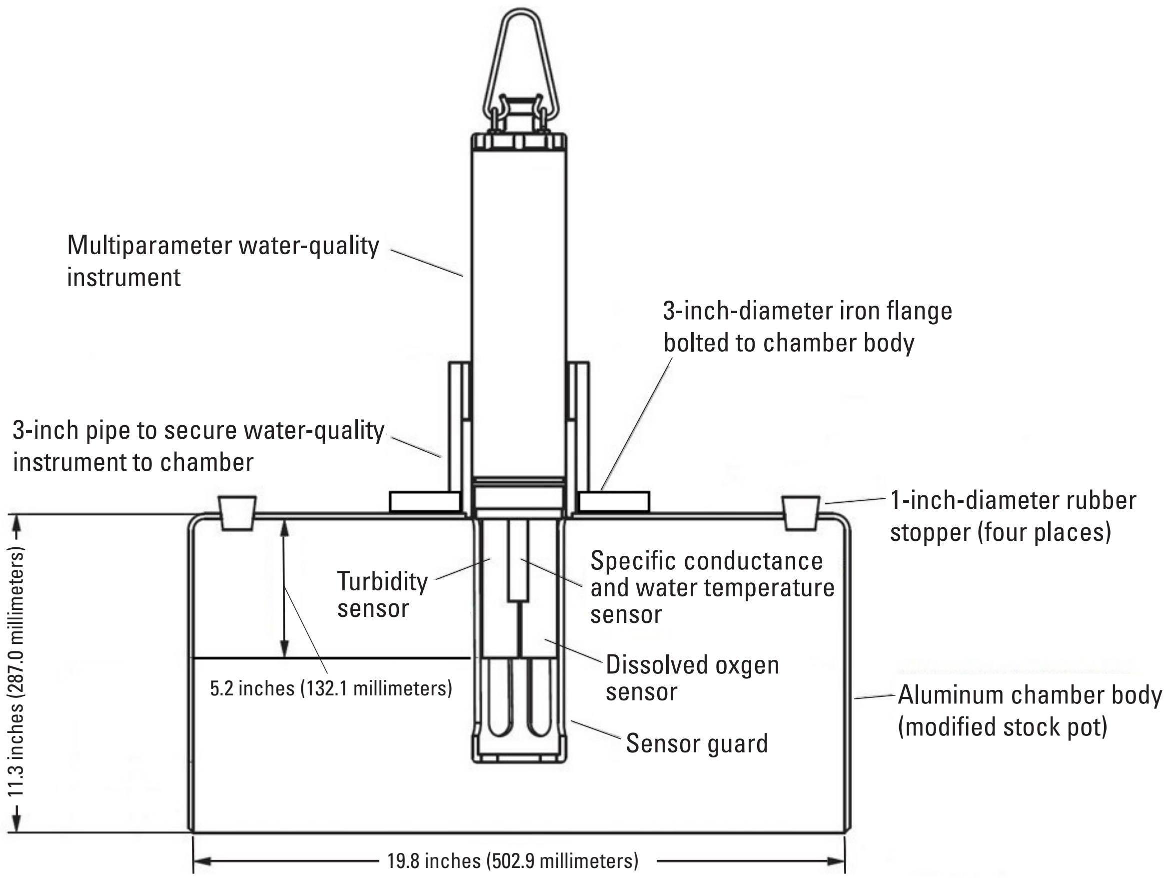

Figure 2. Schematic diagram of sediment oxygen demand chamber (modified from Heckathorn and Gibs, 2010); measurements are given in inches; measurements in parentheses are in millimeters.

water-quality monitors (herein referred to as A, B, and control chambers) were submerged and inserted into (A and B) or placed on (control) the streambed at the best possible location (fig. 3). Care was taken to avoid disturbing bottom sediments as much as possible. The seal between chamber and streambed is critical to isolate the conditions in the chamber from the environment. Once submerged, sealed to the streambed, and any air evacuated, the chambers were plugged with rubber stoppers to prevent any exchange of water with the stream. The A and B chambers were not necessarily placed on the same substrate types and are therefore not true replicate chambers. The control chamber was placed near the A and B chambers to ensure similar temperature conditions during deployment. Water-quality monitors were equipped with optical DO, turbidity, water temperature, pH, specific conductance, and total algae (total chlorophyll-*a* and phycocyanin) sensors. To measure ambient stream conditions a water-quality monitor equipped with the same set of sensors also was deployed outside the chamber in the water column as close to the SOD chambers as possible. This report focuses on DO, turbidity, and water temperature data. All data collected as part of this study are available in King and others (2016) (http://dx.doi.org/10.5066/F7610XG8).

All water-quality monitors measured DO, turbidity, water temperature, pH, specific conductance, and total algae (total chlorophyll-*a* and total phycocyanin) in the water column near the sediment-water interface, every 30 seconds throughout the deployment. The centralized wiper on the YSI EXO2 was programmed to wipe every 5 minutes. Dissolved oxygen concentrations were checked hourly to monitor DO depletion in the A, B, and control chambers, as well as changes in ambient stream conditions. Deployments were continued until DO was depleted by 2 mg/L in the chambers or a consistent minimum DO was achieved. Deployments typically lasted for about 5 to 6 hours.

The final volume in the chambers during deployments was computed by taking into account the depth of insertion of the chamber's edges into the sediment as well as the water displaced by the water-quality monitor (0.176 liters). The final volume varied between 30.6 and 56.9 liters (table 2). Chamber insertion depth was measured at the beginning of each deployment and hourly thereafter at four points, vertically around the

Figure 3. Sediment oxygen demand (SOD) chamber deployment. *A*, removal of control chamber at the Kansas River at De Soto, Kansas site. Photograph by J. Gonzalez. *B*, Chambers during a deployment at the Indian Creek at Indian Creek Parkway, Overland Park, Kansas site. Photograph by L.R. King; and *C*, Top view of an SOD chamber during a deployment at the Indian Creek at Indian Creek Parkway, Overland Park, Kansas site. Photograph by L.R. King.

circumference of the chamber. Hourly measurements allowed documentation of changes in chamber depth throughout the deployment because of filling or scouring around the chamber, and also provided an early warning of a possible breach in the seal of the chamber. All depth measurements were averaged and used to calculate the volume of water isolated inside the chambers.

After completion of deployments, streambed-sediment samples were collected from the area underneath the A and B chambers generally following guidelines in Shelton and Capel (1994). Sediment samples were scooped into sample containers and composited, and represented approximately 6 inches of sediment depth. Streambed-sediment samples were analyzed by the USGS Iowa Sediment Laboratory in Iowa City, Iowa, for grain-size distribution and loss on ignition (LOI), a measure of organic content, according to methods described in Guy (1969). A higher LOI value corresponds to greater organic content. All streambed-sediment data are available from NWIS (http://dx.doi.org/10.5066/F7P55KJN).

Calculation of Sediment Oxygen Demand

The SOD rates were calculated using methods described in Heckathorn and Gibs (2010), Utley and others (2008), Doyle and Lynch (2005), Ziadat and Berdanier (2004), Doyle and Rounds (2003), and Rounds and Doyle (1997). Dissolved-oxygen concentrations were plotted as a function of elapsed time, resulting in a dissolved oxygen depletion curve (fig. 4*A*). Typically, the first 10 to 120 minutes of a deployment are affected by resuspended streambed sediments. These suspended sediments can cause computed SOD rates to be anomalously high (Doyle and Rounds, 2003). Thus, only data collected after sediments had resettled (based on turbidity) were used to calculate the slope of dissolved oxygen depletion; initially disturbed sediments took between 8 and 140 minutes to settle. The slope of the linear part of the oxygen-depletion curve was determined through linear regression (Helsel and Hirsch, 2002) (fig. 4*B*) and used to calculate the SOD rate:

$$SOD_T = 1.44\left(\frac{V}{A}\right)\times b$$

where

SOD_T is the sediment oxygen demand rate, in grams per square meter per day ($g/m^2/d$), at water temperature T, in degrees Celsius (°C);

V is the volume of water in the chamber, in liters;

A is the area of the streambed covered by the chamber, in square meters (0.2 square meters);

b is the slope of the oxygen-depletion curve, in milligrams per liter per minute; and 1.44 is a unit conversion constant.

Water temperature is a primary factor controlling the biological and chemical processes that affect DO uptake (Allan, 1995). Sediment oxygen demand deployments were done over a range of water temperatures. To facilitate some comparisons, SOD rates were normalized to 20 °C using a standard van 't Hoff equation (Thomann and Mueller, 1987):

$$SOD_{20} = SOD_T \ / \ 1.065^{(T-20)}$$

where

SOD_{20} is the sediment oxygen demand rate, in $g/m^2/d$, at 20 °C,

T is the average water temperature in the chamber during deployments, in °C, and 1.065 is an accepted, empirically determined constant (Ziadat and Berdanier, 2004).

Oxygen depletion rates also were calculated for the control chamber, and are representative of water column oxygen demand in the SOD chambers. Sediment oxygen demand rates were corrected for water column oxygen depletion by subtracting oxygen depletion in the control chamber from SOD rates in chamber A and B (Rounds and Doyle, 1997). When the control chamber oxygen depletion rate was greater than the SOD rate in the primary or replicate chambers, SOD was considered to be zero. When seals were properly maintained throughout the course of a deployment, the final SOD rate assigned to the site was based on the mean of the two independent chamber results. The seal between the SOD chamber and the stream bottom was broken during late fall deployments at Pottawatomie (likely because of course bed-sediment grain sizes), invalidating results.

Data Analysis and Interpretation

Median sediment grain size (D_{50}) was calculated using methods described in Bunte and Abt (2001). Nonparametric Spearman rank-correlation analysis was used to test for monotonic relations between SOD_T rates, land use, and streambed sediment characteristics (LOI, grain size, and D_{50}). Spearman rank-correlation coefficients (rho values) were considered significant when probability values (p-values) were less than 0.05 (Helsel and Hirsch, 2002). To develop relations with land use, SOD_T rates were averaged by site. Relations with land use were developed for each season (summer and late fall). Because LOI, grain size, and D_{50} data were available for each SOD chamber, all data were included in rank-correlation analysis (for example, two data points per site per season). Relations with streambed sediment characteristics were developed seasonally (summer and late fall) using the overall combined dataset.

Quality Assurance and Control

Stream stage was measured and streamflow was computed using standard USGS methods (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). For sites without nearby USGS streamgages, discharge was measured during SOD chamber deployment using a SonTek Flowtracker acoustic Doppler velocimeter (ADV) as described in Turnipseed and Sauer (2010). Two-point calibration checks of the DO sensors were completed in accordance with Rounds and others (2013) and the manufacturer's guidelines (Yellow Springs Instruments, 2014). Checks were done at 100 and zero percent oxygen saturation before each SOD chamber deployment. Turbidity sensors used to assess within-chamber sediment re-suspension were checked and calibrated in accordance with Anderson (2005) and the manufacturer's guidelines (Yellow Springs Instruments, 2014). Thermistors used on the water-quality monitors receive annual calibration checks against National Institute of Standards and Technology (NIST) certified laboratory thermometers as per Wilde (2006). The pH, specific conductance, and total algae sensors (for the determination of total chlorophyll-*a* and phycocyanin concentrations) were calibrated before each deployment in accordance with USGS protocols (U.S. Geological Survey, variously dated) and manufacturer's guidelines (Yellow Springs Instruments, 2014).

Sediment Oxygen Demand In Eastern Kansas Streams

Final mean SOD_{20} rates in eastern Kansas streams ranged from 0.03 to 4.00 $g/m^2/d$ (table 2). Few data are available for comparison, but SOD_{20} rates in Kansas streams were generally lower than measured using similar methods in streams elsewhere. Maximum SOD_{20} rates in Oregon streams (range: 0.2–10.9 $g/m^2/d$) were about 2.7-times larger than the maximum SOD_{20} rates measured in Kansas streams (Rounds and Doyle, 1997; Doyle and Rounds, 2003; Doyle and Lynch, 2005). Similarly, maximum SOD_{20} rates in New Jersey streams were about 1.8-times larger (range: 0.3–7.1 $g/m^2/d$) than in Kansas streams (Heckathorn and Gibs, 2010; Wilson, 2014).

Table 2. Ambient water temperature, in-chamber sediment oxygen demand, and final sediment oxygen demand, in each chamber during each deployment.

[L, liter; ºC, Celsius; mg/L, milligram per liter, SOD, sediment oxygen demand; SOD_T, sediment oxygen demand at the water temperature in the chamber; g/m²d, gram per square meter per day; SOD_{20}, sediment oxygen demand normalized to a water temperature of 20 °C]

Short site name	Date month/day/year	Chamber	Chamber volume (L)	Water temperature (ºC)	Start time	End time	Duration (minutes)	Beginning dissolved oxygen concentration (mg/L)	Ending dissolved oxygen concentration (mg/L)	Slope determined by simple linear regression[1]
De Soto	8/20/2014	A	50.4	31.94	12:12	16:31	259	10.46	7.82	-0.0057
		B	52.9	31.54	12:26	16:26	240	10.48	8.54	-0.0028
	11/20/2014	A	45.9	0.77	9:52	14:44	291	14.31	13.98	-0.0005
		B	30.6	0.97	9:36	14:41	305	14.92	14.79	-0.0003
Wamego	8/11/2015	A	50.5	28.11	11:48	13:47	119	6.80	6.36	-0.0017
		B	51.8	27.98	11:01	16:34	333	6.18	3.30	-0.0048
	12/7/2015	A	47.8	5.21	8:53	14:38	345	11.02	10.95	0.0000
		B	48.5	5.22	9:19	14:44	266	11.22	10.91	-0.0003
Indian Creek	9/1/2015	A	53.2	25.72	11:13	13:44	150	3.34	1.10	-0.0074
		B	53.0	25.71	11:13	13:44	150	3.17	0.71	-0.0084
	12/3/2015	A	41.8	8.53	10:47	13:10	143	8.71	6.46	-0.0089
		B	35.6	8.49	12:29	13:45	75	7.36	6.66	-0.0049
Pottawat-omie	8/22/2014	A	56.9	26.33	12:11	13:22	71	2.69	1.00	-0.0135
		B	56.1	26.46	11:47	12:45	58	2.38	1.67	-0.0058
	11/19/2014	A	--	--	--	--	--	--	--	--
		B	--	--	--	--	--	--	--	--
Marmaton	8/21/2014	A	51.6	28.14	12:20	15:49	209	4.32	3.59	-0.0014
		B	52.6	28.14	12:08	15:50	222	4.26	3.36	-0.0029
	11/24/2014	A	52.5	5.90	10:36	12:58	142	7.05	6.57	-0.0017
		B	52.8	5.86	10:23	15:07	284	7.09	5.61	-0.0029
Little Ar-kansas	8/19/2014	A	45.8	27.63	12:49	13:46	56	6.87	6.65	-0.0019
		B	45.5	27.59	11:54	13:53	118	7.03	5.87	-0.0047
	11/18/2014	A	51.2	1.52	11:06	12:06	60	13.91	13.66	0
		B	41.6	1.29	10:47	12:13	86	14.14	13.99	-0.0009
Walnut	9/4/2015	A	54.2	25.89	12:01	12:59	58	6.12	5.66	-0.0031
		B	54.1	25.96	9:12	9:56	44	5.87	5.41	-0.0026
	12/9/2015	A	52.0	5.49	9:47	14:05	258	10.79	9.75	-0.0014
		B	53.6	5.49	9:30	12:41	191	10.97	10.83	0.0000
Grouse	9/3/2015	A	52.2	26.56	10:15	14:00	225	5.85	2.62	-0.0072
		B	52.3	26.55	11:20	13:16	115	3.54	2.65	0
	12/8/2015	A	47.3	6.21	8:48	12:48	240	11.39	11.31	0
		B	46.0	6.23	10:15	11:02	46	10.71	10.42	-0.0022

In-chamber SOD rates						Final SOD rates (corrected by control chamber SOD rates)					
SOD_T (g/m^{2}d)	**Mean SOD_T (g/m^{2}d)**	**SOD_T (g/m^{2}d) variance**	**SOD_{20} (g/m^{2}d)**	**Mean SOD_{20} (g/m^{2}d)**	**SOD_{20} (g/m^{2}d) variance**	**SOD_T (g/m^{2}d)**	**Mean SOD_T (g/m^{2}d)**	**SOD_T (g/m^{2}d) variance**	**SOD_{20} (g/m^{2}d)**	**Mean SOD_{20} (g/m^{2}d)**	**SOD_{20} (g/m^{2}d) variance**
2.07 1.07	1.57	0.50	0.98 0.52	0.75	0.11	1.09 0.09	0.59	0.50	0.51 0.05	0.28	0.11
0.17 0.07	0.12	0.01	0.55 0.22	0.39	0.05	0.08 0.00	0.04	0	0.28 0	0.14	0.04
0.62 1.78	1.20	0.67	0.37 1.08	0.73	0.25	0.50 1.66	1.08	0.67	0.30 1.00	0.65	0.25
0.00 0.10	0.05	0.01	0 0.27	0.13	0.04	0.00 0.02	0.01	0	0.00 0.06	0.03	0
2.82 3.19	3.01	0.07	1.97 2.23	2.10	0.03	2.66 3.03	2.85	0.07	1.85 2.12	1.99	0.04
2.68 1.26	1.97	1.01	5.51 2.60	4.06	4.23	2.65 1.23	1.94	1.01	5.45 2.54	4.00	4.23
5.51 2.34	3.93	5.02	3.70 1.56	2.63	2.29	4.74 1.56	3.15	5.06	3.18 1.04	2.11	2.29
-- --	--	--	-- --	--	--	-- --	--	--	-- --	--	--
0.52 1.10	0.81	0.17	0.31 0.66	0.49	0.06	0.28 0.85	0.56	0.17	0.16 0.51	0.34	0.06
0.64 1.10	0.87	0.11	1.56 2.68	2.12	0.63	0.56 1.02	0.79	0.11	1.36 2.48	1.92	0.63
0.62 1.53	1.08	0.41	0.39 0.95	0.67	0.16	0.09 1.00	0.55	0.41	0.06 0.63	0.35	0.16
0.00 0.27	0.14	0.04	0.00 0.87	0.44	0.38	0.00 0.19	0.10	0.02	0.00 0.61	0.31	0.19
1.21 1.01	1.11	0.02	0.83 0.69	0.76	0.01	0.96 0.77	0.87	0.02	0.66 0.52	0.59	0.01
0.52 0.00	0.26	0.14	1.30 0.00	0.65	0.85	0.44 0	0.22	0.10	1.10 0	0.55	0.61
2.70 0.00	1.35	3.65	1.79 0	0.90	1.60	2.66 0	1.33	3.54	1.76 0	0.88	1.55
0.00 0.73	0.37	0.27	0 1.73	0.87	1.50	0 0.12	0.06	0.01	0 0.27	0.14	0.04

[1] Slopes determined by simple linear regression are not equilavent to those computed by simply determining difference in beginning and ending dissolved oxygen concentrations divided by time. Simple linear regression takes into account the full dataset instead of just the beginning and ending data points.

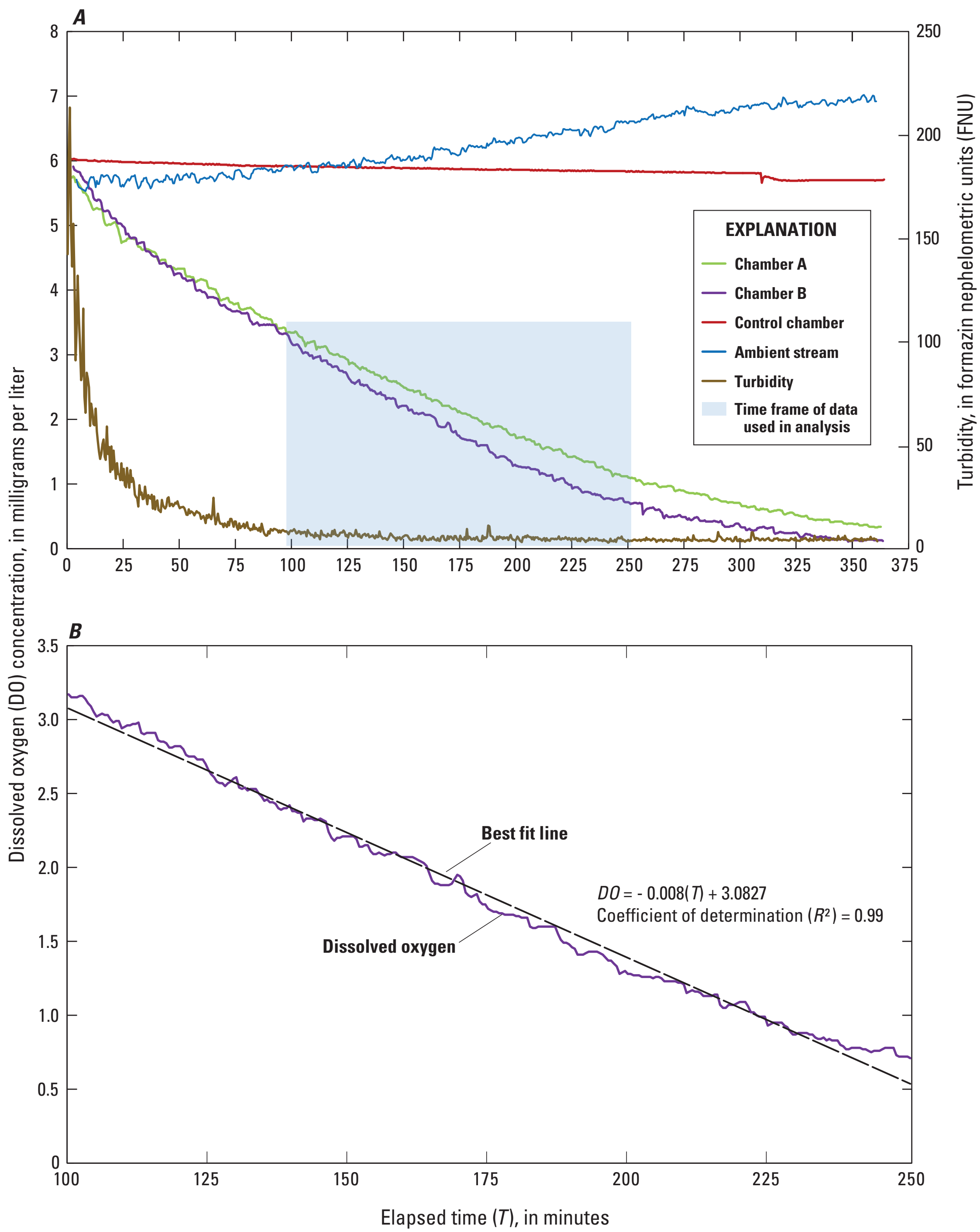

Figure 4. Sediment oxygen demand deployment results and depletion analysis at Indian Creek at Indian Creek Parkway, Overland Park, Kansas during summer 2015. *A*, typical changes in oxygen concentration, including data from replicates, control, and ambient sample locations; and *B*, example of sediment oxygen demand depletion analysis.

Although SOD_{20} values are useful for among-site and among-study comparisons, in this analysis SOD_T rates are a better measure of seasonal differences in actual measurements of sediment oxygen demand. Final mean SOD_T rates in eastern Kansas streams ranged from 0.01 to 3.15 $g/m^2/d$ (table 2). Summer mean SOD_T (1.37 $g/m^2/d$) was 3.0-times larger than late fall mean SOD_T (0.45 $g/m^2/d$) (figs. 5 and 6), likely because of increased biological activity at warm water temperatures (Allan, 1995). With the exception of the Marmaton site, summer SOD_T rates were larger than late fall rates. The late fall mean SOD_T rate (0.79 $g/m^2/d$) at the Marmaton site was 0.23 $g/m^2/d$ higher than the summer mean SOD_T rate (0.56 $g/m^2/d$) (table 2; fig. 6). Pottawatomie and Indian Creek had the largest mean SOD_T rates during summer (3.15 and 2.85 $g/m^2/d$, respectively). During late fall, the mean SOD_T rate in Indian Creek (1.94 $g/m^2/d$) was 2 to 169-times larger than at the other study sites (table 2). Indian Creek was the only stream in this study located in an urban area, and wastewater effluent has a substantial influence on its ecology (Graham and others, 2014). Little Arkansas (0.55 $g/m^2/d$) and Marmaton (0.56 $g/m^2/d$) had the smallest mean SOD_T during summer and Wamego (0.01 $g/m^2/d$) and De Soto (0.04 $g/m^2/d$) had the smallest mean SOD_T during late fall (table 2). The largest seasonal differences were observed at Grouse and Wamego; summer mean SOD_T rates were 22 and 108-times larger, respectively, in summer than late fall (table 2; fig. 6).

During each deployment, chambers were not necessarily placed on the same substrate types. As with final SOD_T rates, within site variance was larger during summer (range: 0.02–5.06 $g/m^2/d$; mean: 1.30 $g/m^2/d$) than late fall (range: 0.00–1.01 $g/m^2/d$; mean: 0.18 $g/m^2/d$), which may reflect more biological activity at the sediment-water interface during summer months. Within-site variance during summer was largest at the Pottawatomie (5.06 $g/m^2/d$) and Grouse (3.54 $g/m^2/d$) sites. Given the substantial amount of variability possible within sites, heterogeneity of substrate type is an important consideration when designing SOD studies and interpreting the results, particularly when oxygen budgets are required.

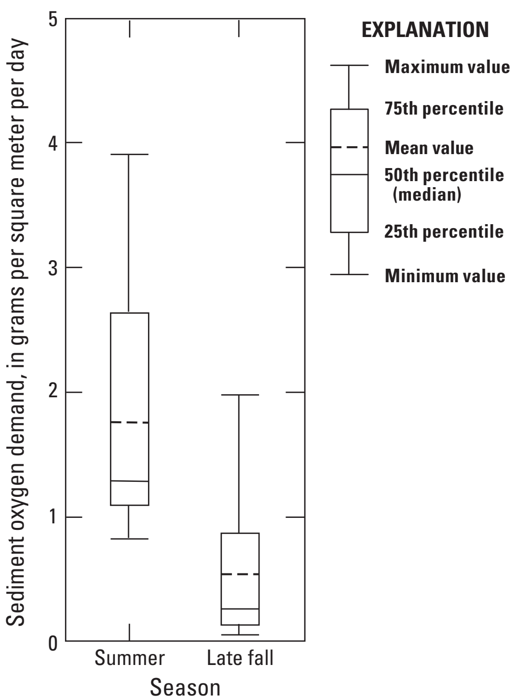

Figure 5. Box plots of summer and late fall sediment oxygen demand (SOD_T) rates.

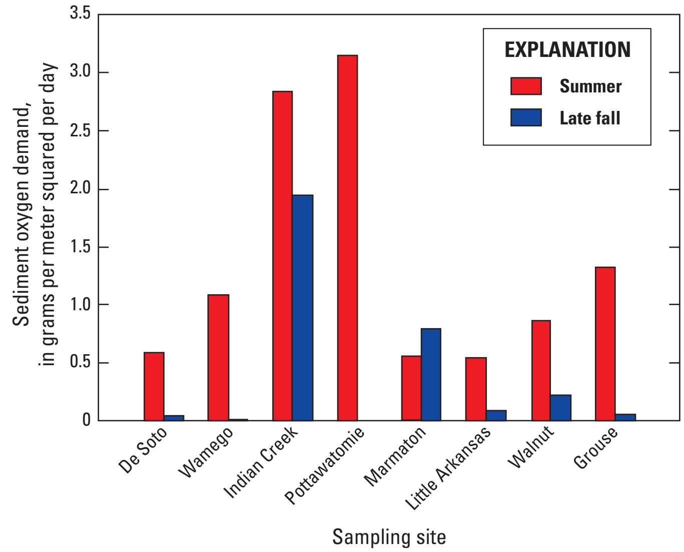

Figure 6. Mean summer and late fall sediment oxygen demand (SOD_T) rates for each site.

There were no seasonally consistent relations between final SOD_T rates and land use. Sediment oxygen demand (SOD_T) rates were negatively related to the percentage of grassland and cropland [Spearman rank-correlation coefficient (rho) = -0.94, p-value < 0.01, number of samples, n = 7)] and the combination of grassland, cropland, and pasture (rho = -1.00, p-value < 0.01, n = 7) during late fall. Relations between SOD_T and land use during summer were not statistically significant (all p-values ≥ 0.35, all n = 8), though the association with the combination of grassland and cropland indicated a similar negative pattern (fig. 7). A similar analysis using final SOD_{20} rates indicated similar results. Indian Creek, the only urban stream included in this study, had the largest measured SOD_T rates during summer and late fall; however, removing this data point from the analyses did not change the overall seasonal relations between SOD_T and land use (late fall grassland and cropland rho = -0.90, p = 0.02, n = 6; late fall grassland, cropland, and pasture rho = -1.00, p < 0.01, n = 6; summer all p-values > 0.44, all n = 7).

Loss on ignition, an indicator of the amount of organic material in sediment, ranged from a mean of 3,750 milligrams per kilogram (mg/kg) at De Soto (2014 summer assessment) to 190,000 mg/kg at Indian Creek (2015 late fall assessment) (table 3). There were no clear seasonal patterns in LOI among sites. Observed differences between summer and late fall at

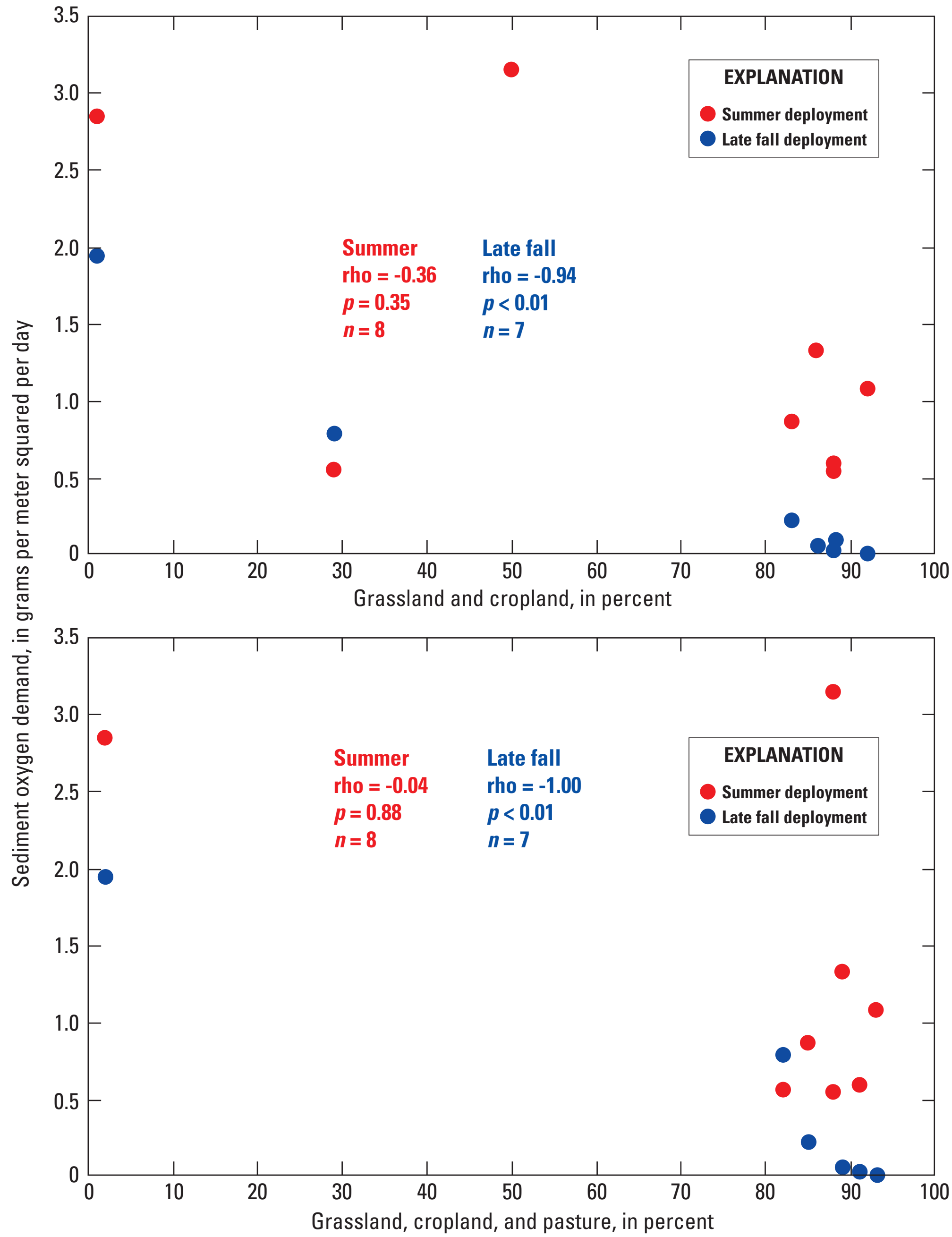

Figure 7. Relations between seasonal final mean sediment oxygen demand (SOD_T) rates and dominant basin land use.

Table 3. Grain size and loss on ignition results for bottom sediment samples taken beneath sediment oxygen demand chambers.

[<, less than; mm, millimeter; --, not available; D_{50}, median sediment grain size, in millimeters; mg/kg; millgram per kilogram]

Grain size	2014 Sediment oxygen demand sites (summer deployment)			
	Little Arkansas	De Soto	Maramaton	Pottawatomie
Chamber A				
<0.002 mm	2	21	6	2
<0.004 mm	2	25	7	2
<0.008 mm	2	35	7	2
<0.016 mm	3	47	9	3
<0.031 mm	4	65	12	4
<0.0625 mm	5	73	18	4
<0.125 mm	--	--	--	--
<0.25 mm	--	--	--	--
<0.5 mm	--	--	--	--
<1 mm	82	91	100	7
<2 mm	96	95	--	8
<4 mm	--	--	--	--
<8 mm	--	--	--	--
<16 mm	--	--	--	--
<31.5 mm	--	--	--	--
<63 mm	--	--	--	--
D_{50}	0.75	0.02	0.66	>63
Loss on ignition (mg/kg)	6,810	51,000	6,860	33,400
Chamber B				
<0.002 mm	6	--	24	3
<0.004 mm	7	--	29	4
<0.008 mm	7	--	38	5
<0.016 mm	9	--	52	6
<0.031 mm	13	1	71	8
<0.0625 mm	19	1	79	9
<0.125 mm	--	--	--	--
<0.25 mm	--	--	--	--
<0.5 mm	--	--	--	--
<1 mm	79	75	94	12
<2 mm	95	92	97	14
<4 mm	--	--	--	--
<8 mm	--	--	--	--
<16 mm	--	--	--	--
<31.5 mm	--	--	--	--
<63 mm	--	--	--	--
D_{50}	0.72	0.79	0.01	>63
Loss on ignition (mg/kg)	10,900	3,750	47,300	27,000

Table 3. Grain size and loss on ignition results for bottom sediment samples taken beneath sediment oxygen demand chambers.—Continued

[<, less than; mm, millimeter; --, not available; D_{50}, median sediment grain size, in millimeters; mg/kg; millgram per kilogram]

Grain size	2015 Sediment oxygen demand sites (summer deployment)			
	Wamego	Indian Creek	Grouse	Walnut
	Chamber A			
<0.002 mm	--	--	--	--
<0.004 mm	--	--	--	--
<0.008 mm	--	1	--	--
<0.016 mm	1	1	--	1
<0.031 mm	1	2	--	1
<0.0625 mm	2	2	--	1
<0.125 mm	3	5	--	2
<0.25 mm	7	19	--	2
<0.5 mm	28	32	2	3
<1 mm	58	47	7	4
<2 mm	73	66	19	7
<4 mm	80	80	50	12
<8 mm	87	90	87	21
<16 mm	100	100	100	37
<31.5 mm	--	--	--	54
<63 mm	--	--	--	100
D_{50}	0.83	1.12	4.00	26.9
Loss on ignition (mg/kg)	48,700	58,900	55,400	44,500
	Chamber B			
<0.002 mm	--	1	--	1
<0.004 mm	--	1	--	1
<0.008 mm	--	1	--	1
<0.016 mm	--	2	--	2
<0.031 mm	1	4	--	3
<0.0625 mm	2	6	--	4
<0.125 mm	3	12	--	6
<0.25 mm	7	36	--	8
<0.5 mm	21	50	1	9
<1 mm	49	61	3	11
<2 mm	61	72	12	14
<4 mm	68	84	33	18
<8 mm	78	100	69	34
<16 mm	100	--	100	100
<31.5 mm	--	--	--	--
<63 mm	--	--	--	--
D_{50}	1.06	0.50	5.55	9.46
Loss on ignition (mg/kg)	38,100	57,700	69,400	48,400

Table 3. Grain size and loss on ignition results for bottom sediment samples taken beneath sediment oxygen demand chambers.—Continued

[<, less than; mm, millimeter; --, not available; D_{50}, median sediment grain size, in millimeters; mg/kg; millgram per kilogram]

Grain size	2015 Sediment oxygen demand sites (late fall deployment)			
	Wamego	Indian Creek	Grouse	Walnut
	Chamber A			
<0.002 mm	--	--	--	9
<0.004 mm	--	--	--	13
<0.008 mm	--	--	--	13
<0.016 mm	--	--	--	17
<0.031 mm	--	--	--	35
<0.0625 mm	1	--	--	53
<0.125 mm	2	1	--	65
<0.25 mm	8	5	--	74
<0.5 mm	44	24	1	82
<1 mm	89	39	4	90
<2 mm	98	50	15	94
<4 mm	100	63	39	96
<8 mm	--	80	78	96
<16 mm	--	100	100	100
<31.5 mm	--	--	--	--
<63 mm	--	--	--	--
D_{50}	0.55	2.00	4.86	0.06
Loss on ignition (mg/kg)	24,100	190,000	51,700	39,000
	Chamber B			
<0.002 mm	--	1	--	10
<0.004 mm	--	1	--	11
<0.008 mm	--	1	--	13
<0.016 mm	1	1	--	16
<0.031 mm	1	2	--	31
<0.0625 mm	3	3	--	45
<0.125 mm	9	6	--	55
<0.25 mm	33	28	--	63
<0.5 mm	69	49	--	73
<1 mm	91	59	2	84
<2 mm	97	65	9	94
<4 mm	99	70	33	98
<8 mm	100	76	78	100
<16 mm	--	84	100	--
<31.5 mm	--	100	--	--
<63 mm	--	--	--	--
D_{50}	0.35	0.54	5.20	0.09
Loss on ignition (mg/kg)	35,500	92,100	78,500	32,900

each site may have been because of variation in the organic content of the streambed sediment or site selection during deployment. Sediment oxygen demand (SOD_T) rates generally increased with increased LOI (table 3; fig. 8). In late fall, SOD_T rates were positively, and relatively strongly, correlated with LOI (rho = 0.80, p-value < 0.01, n = 9). Removal of the high late fall (Indian Creek) data point, which is larger than all other LOI values by almost 100,000 mg/kg, still results in a strong positive association (rho = 0.70, p-value = 0.05, n = 7) (table 3; fig. 8). The positive association between SOD_T rates and LOI was weaker, and not statistically significant, during summer (rho = 0.30, p-value = 0.26, n = 16) and in the overall dataset (rho = 0.31, p-value = 0.14, n = 24). There were no statistically significant relations between sediment grain sizes, percentage of sediment greater than or less than 63 micrometer (the sand-fine sediment break at 0.0625 millimeters in table 3), or D_{50} and SOD_T rates (all p-values > 0.14).

Land use likely plays a role in determining the types and amount of detritus contributed to streams. The relations between SOD and LOI suggest that the organic content of streambed sediment may be an important factor influencing SOD rates. Though results from this study may be indicative of connections between SOD, land use, and streambed sediment characteristics, the small number of study sites precludes a more detailed analysis. The influence of basin land use and streambed sediment characteristics on SOD is currently (2016) not well understood, and there may be many contributing factors including basin influences on water quality that affect biogeochemical cycles and the biological communities supported by the stream (Bowie and others, 1985; Allan, 1995; Rounds and Doyle, 1997).

Summary

Dissolved oxygen (DO) is an important factor for the survival of aquatic organisms. In 2014, 175 Kansas streams were listed as impaired because of low DO levels. Sediment oxygen demand (SOD), the rate of water column DO depletion at the sediment-water interface, may contribute to low dissolved oxygen concentrations in Kansas streams. The U.S. Geological Survey (USGS), in cooperation with the Kansas Department of Health and Environment, measured SOD in eastern Kansas streams to quantify SOD rates and variability with respect to season, land use, and bottom-sediment characteristics.

Study sites were selected based on drainage basin size, land use, and DO impairment, and generally represent the range of environmental conditions found in eastern Kansas streams. The SOD data were collected mostly during below-normal streamflow conditions in late summer and late fall

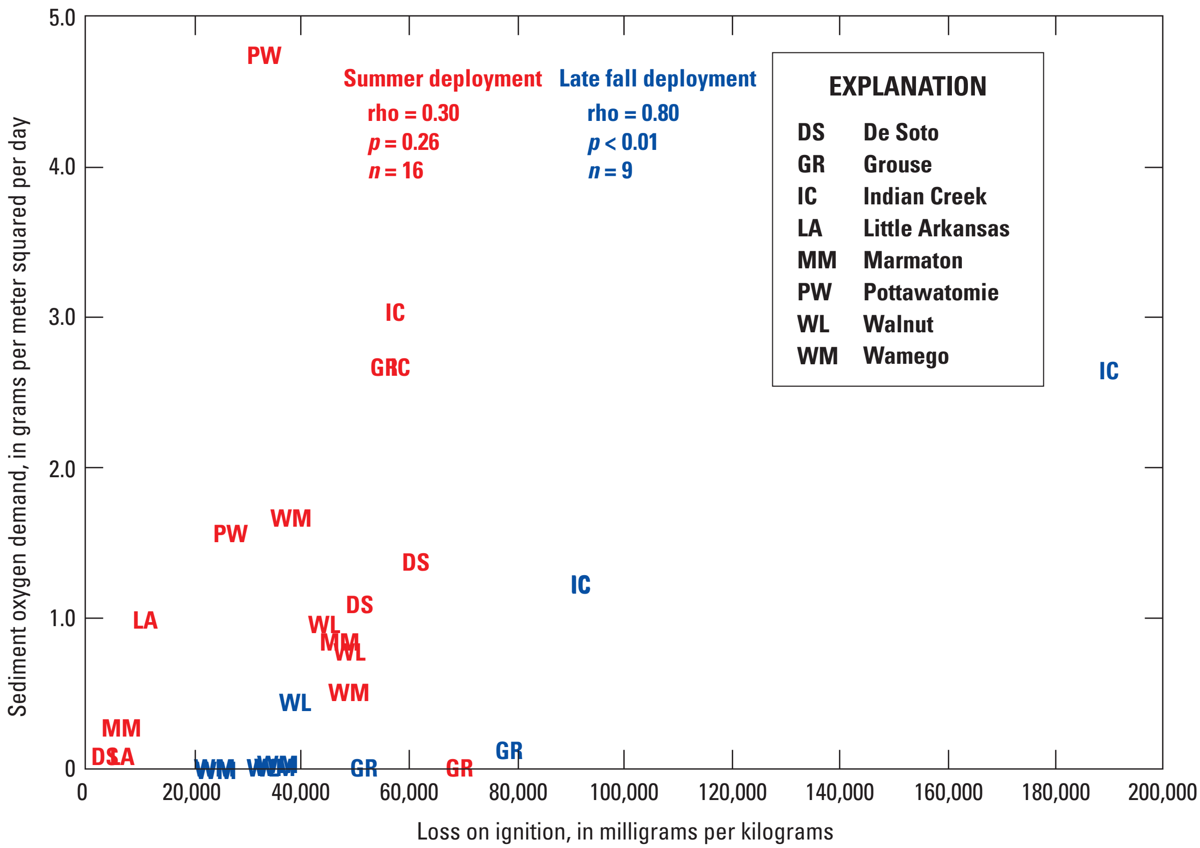

Figure 8. Relations between final sediment oxygen demand (SOD_T) rates and loss on ignition.

2014 and 2015. At each site, two replicate SOD chambers, a control chamber, and an ambient stream location were equipped with multiparameter water-quality monitors during deployments. Deployments typically lasted for 5 to 6 hours and were repeated until DO was depleted by 2 milligrams per liter (mg/L) in the chambers or a consistent minimum DO was achieved. After completion of deployments, streambed-sediment samples for analysis of grain-size distribution and loss on ignition (LOI) were collected from the area underneath the replicate SOD chambers. Sediment oxygen demand rate (SOD_T), in grams per square meter per day ($g/m^2/d$), was calculated and normalized to 20 degrees Celsius (SOD_{20}) to facilitate among-study comparisons.

Few data are available for comparison, but mean SOD_{20} rates in eastern Kansas streams (0.03–4.00 $g/m^2/d$) were generally lower than SOD_{20} rates measured using similar methods in other states. Although mean SOD_{20} values are useful for among-study comparisons, mean SOD_T rates are a better measure of seasonal differences in actual SOD demand. The mean SOD_T rates in eastern Kansas streams ranged from 0.01 to 3.15 $g/m^2/d$. Summer mean SOD_T was 3.0-times larger than late fall mean SOD_T, likely because of increased biological activity at warm water temperatures. During each deployment, chambers were not necessarily placed on the same substrate types to account for within-site variability. As with mean SOD_T rates, within-site variance was larger during summer than late fall, which may reflect more biological activity at the sediment-water interface during summer months. Given the substantial amount of variability possible within sites, heterogeneity of substrate type is an important consideration when designing SOD studies and interpreting results, particularly when oxygen budgets are required.

Sediment oxygen demand in eastern Kansas streams was negatively associated with the percentage of grassland and cropland and the combination of grassland, cropland, and pasture in the basin and positively associated with LOI, though the strength of relations varied seasonally. Land use likely plays a role in determining the types and amount of detritus contributed to streams. The relations between SOD and LOI suggest that the organic content of streambed sediment may be an important factor influencing SOD rates. Though results from this study may be indicative of connections between SOD, land use, and streambed sediment characteristics, the small number of study sites precludes a more detailed analysis. The influence of basin land use and streambed sediment characteristics on SOD is currently (2016) not well understood, and there may be many contributing factors including basin influences on water quality that affect biogeochemical cycles and the biological communities supported by the stream.

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