Prepared in cooperation with the Kansas Water Office, the Kansas Department of Health and Environment, The Nature Conservancy, the City of Lawrence, the City of Manhattan, the City of Olathe, the City of Topeka, and Johnson County WaterOne

Linear Regression Model Documentation and Updates for Computing Water-Quality Constituent Concentrations or Densities using Continuous Real-Time Water-Quality Data for the Kansas River, Kansas, July 2012 through September 2019

Open-File Report 2021–1018

U.S. Department of the Interior
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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Volume	
milliliter (mL)	0.0338	ounce, fluid (fl. oz)
liter (L)	33.81402	ounce, fluid (fl. oz)
	Mass	
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
microgram (µg)	0.00000003527	ounce, avoirdupois (oz)

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

$$°F = (1.8 \times °C) + 32.$$

Datum

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

Supplemental Information

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 in either milligrams per liter (mg/L) or micrograms per liter (µg/L).

Densities of fecal indicator bacteria are given in colonies per 100 milliliters (colonies/100 mL).

Abbreviations

E. coli	*Escherichia coli*
KSWSC	Kansas Water Science Center
log	logarithm with base 10
MRL	minimum reporting limit
NO_x	nitrate plus nitrite
NWQL	National Water Quality Laboratory
p	probability
PRESS	prediction error sum of squares
QA/QC	quality-assurance and quality-control
R^2	coefficient of determination
RMSE	root mean square error
RPD	relative percentage difference
USGS	U.S. Geological Survey
VIF	variance inflation factor

Linear Regression Model Documentation and Updates for Computing Water-Quality Constituent Concentrations or Densities using Continuous Real-Time Water-Quality Data for the Kansas River, Kansas, July 2012 through September 2019

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Abstract

The Kansas River provides drinking water to about 800,000 people in northeastern Kansas. Water-treatment facilities that use the Kansas River as a water-supply source use chemical and physical processes during water treatment to remove contaminants before public distribution. Advanced notification of changing water-quality conditions near water-supply intakes allows water-treatment facilities to proactively adjust treatment. The U.S. Geological Survey (USGS), in cooperation with the Kansas Water Office (funded in part through the Kansas Water Plan), the Kansas Department of Health and Environment, The Nature Conservancy, the City of Lawrence, the City of Manhattan, the City of Olathe, the City of Topeka, and Johnson County WaterOne, collected water-quality data at the Kansas River at Wamego (USGS site 06887500; hereafter referred to as the “Wamego site”) and De Soto (USGS site 06892350; hereafter referred to as the “De Soto site”) monitoring sites to update previously published regression models relating continuous water-quality sensor measurements, streamflow, and seasonal components to discretely sampled water-quality constituent concentrations or densities. Linear regression analysis was used to update and develop models for total dissolved solids, major ions, hardness as calcium carbonate, nutrients (nitrogen and phosphorus species), chlorophyll *a*, total suspended solids, suspended sediment, and fecal indicator bacteria at the Wamego and De Soto monitoring sites using data collected during July 2012 through September 2019. The water-quality information documented in this report can be used as guidance for water-treatment processes and to characterize changes in water-quality conditions in the Kansas River over time that would not be otherwise possible.

Introduction

The Kansas River supplies drinking water to about 800,000 people in northeastern Kansas (Joan Kenny, U.S. Geological Survey, written commun., March 27, 2011). Additional uses of the Kansas River include recreation, aquatic-life support, food procurement, groundwater recharge, irrigation, and livestock water use (Kansas Department of Health and Environment, 2011). Water-treatment facilities that use the Kansas River as a drinking-water source use various chemical and physical processes to remove contaminants before distribution. Source-water quality affects treatment processes used to effectively remove contaminants. An advanced notification system of changing water-quality conditions, particularly those near water-supply intakes, provides water-treatment facilities the ability to proactively treat their water supply. Additionally, water-quality monitoring allows characterization of water-quality conditions in the Kansas River over time.

Concomitant Kansas River continuous water-quality monitoring and discrete water-quality sampling began during July 1999 (lasting through September 2005) with the primary goals of characterizing water-quality conditions and developing continuous regression-computed concentrations or densities of major ions, nutrients, sediment, fecal indicator bacteria, and trace elements using continuously measured water-quality properties as surrogates at sites near Wamego, Topeka, and De Soto, Kansas (Rasmussen and others, 2005). After water releases from Milford Lake (a reservoir that contributes streamflow to the Kansas River) during a toxic cyanobacterial bloom in August 2011, water-quality sampling resumed with the primary goal of characterizing cyanotoxin transport and associated taste-and-odor compounds from upstream reservoirs to the Kansas River (Graham and others, 2012). After this event, continuous and discrete water-quality monitoring continued at the Kansas River at Wamego (U.S. Geological Survey [USGS] site 06887500; hereafter referred to as the

“Wamego site”) and De Soto (USGS site 06892350; hereafter referred to as the “De Soto site”) to describe water-quality conditions with an emphasis on cyanobacteria and associated toxins and taste-and-odor compounds and to develop a real-time notification system for changing water-quality conditions that may affect drinking-water-treatment processes (Foster and Graham, 2016; Graham and others, 2018). Foster and Graham (2016) developed continuous linear regression models that established relations between continuous and discrete water-quality data and provided real-time computations of constituent concentrations or densities for major ions, nutrients, sediment, and fecal indicator bacteria. Additionally, logistic regression models were developed that continuously computed the probability of cyanobacteria, microcystin (a cyanotoxin), and geosmin (a taste-and-odor compound) exceeding selected thresholds of interest (Foster and Graham, 2016). Foster and Graham (2016) developed new regression models using data collected during July 2012 through June 2015 at the Kansas River at Wamego and De Soto because of updated analytical methods and sensor technology, potential changes in drainage basin practices, water-quality conditions, riverine processes, and elapsed time between previously published models by Rasmussen and others (2005). The USGS, in cooperation with the Kansas Water Office (funded in part through the Kansas Water Plan), the Kansas Department of Health and Environment, The Nature Conservancy, the City of Lawrence, the City of Manhattan, the City of Olathe, the City of Topeka, and Johnson County WaterOne, continued water-quality data collection at the Wamego and De Soto sites to update previously published regression models developed by Foster and Graham (2016) and provide advanced notification of changing water-quality conditions for constituents of interest in the Kansas River. Real-time computations of water-quality constituent concentrations or densities using the models documented in this report are available at the USGS National Real-Time Water-Quality website (https://nrtwq.usgs.gov).

Purpose and Scope

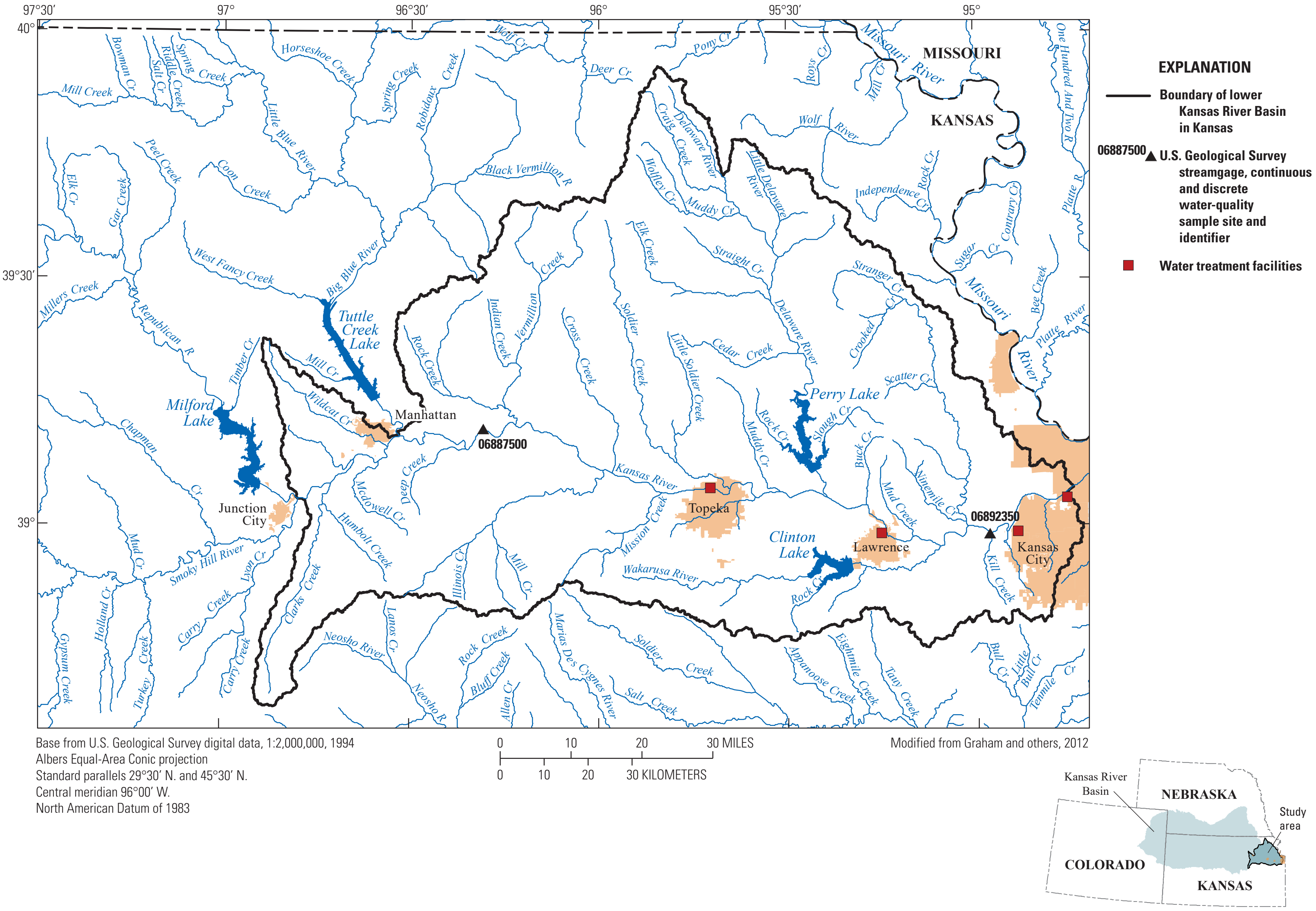
The purpose of this report is to update previously published linear regression models (Foster and Graham, 2016) that continuously compute water-quality constituent concentrations or densities that are not easily measured in near-real time. This includes model updates for major ions, nutrients, sediment, and fecal indicator bacteria at the Wamego and De Soto sites (Foster and Graham, 2016). Additional water-quality data collected during July 2012 through September 2019 were used to develop new linear regression models, including hardness as calcium carbonate ($CaCO_3$), chlorophyll *a*, and total suspended solids; nitrate plus nitrite (NO_x) and total phosphorus at the De Soto site; and *Escherichia coli* (*E. coli*), fecal coliform, and enterococci bacteria at the Wamego site. Linear regression models documented in this report characterize changes in water-quality conditions at the Wamego and De Soto sites, which may affect drinking-water-treatment processes. The regression-computed concentrations or densities from these models are useful for comparison to Federal and State water-quality criteria, for computation of loads and yields to evaluate constituent transport through the drainage basin, and for characterization of changes in water-quality conditions in the Kansas River through time.

Logistic regression models that continuously computed the probability of occurrence above selected thresholds for cyanobacteria, microcystin, and geosmin developed by Foster and Graham (2016) were evaluated by Graham and others (2018) and generally did not fulfill the model suitability criteria. Additional data collected during cyanobacteria, microcystin, and geosmin events are necessary for future model refinement (Graham and others, 2018). Further logistic regression model evaluation is beyond the scope of this report.

Description of Study Area

The Kansas River Basin includes most of the northern half of Kansas, as well as parts of Nebraska and Colorado, and has an area of about 60,097 square miles (mi^2; fig. 1). Formed by the confluence of the Smoky Hill and Republican Rivers near Junction City, Kans., the Kansas River flows about 174 miles east into the Missouri River at Kansas City, Kans. (fig. 1). The study area, commonly referred to as the lower Kansas River Basin, has an area of about 5,448 mi^2 and consists of the area downstream from the confluence of the Smoky Hill and Republican Rivers. Four large reservoirs regulate streamflow in the Kansas River: Milford Lake, Tuttle Creek Lake, Perry Lake, and Clinton Lake (fig. 1). These bottom-release reservoirs were constructed during the 1960s and 1970s for flood control, recreation, and public water supply (U.S. Army Corps of Engineers, 2017). Although most of the study area is used for agricultural purposes (about 77 percent), urban areas represent about 9 percent of study area land use (Fry and others, 2011). There are four major urban areas along the Kansas River: Manhattan, Topeka, Lawrence, and Kansas City metropolitan area, Kans. (fig. 1). These cities and numerous smaller municipalities withdraw water from the Kansas River and its alluvial aquifer for public water supply. Rasmussen and others (2005), Graham and others (2012, 2018), and Foster and Graham (2016) describe the study area in greater detail.

Linear regression models that continuously compute water-quality constituent concentrations or densities were updated or developed at two sites along the Kansas River: the Wamego site and the De Soto site (fig. 1). The Wamego site is upstream from the four major public water-treatment facilities in the cities of Topeka, Lawrence, and Olathe and Johnson County WaterOne (fig. 1). The De Soto site is about 98 river miles downstream from the Wamego site and is upstream from the Johnson County WaterOne public water-treatment facility (fig. 1).



Base from U.S. Geological Survey digital data, 1:2,000,000, 1994
Albers Equal-Area Conic projection
Standard parallels 29°30′ N. and 45°30′ N.
Central meridian 96°00′ W.
North American Datum of 1983

Modified from Graham and others, 2012

Figure 1. Location of the Kansas River at Wamego and Kansas River at De Soto streamgages and discrete water-quality sampling sites in the lower Kansas River Basin (U.S. Geological Survey sites 06887500 and 06892350, respectively), Kansas.

Methods

Continuous and discrete water-quality data were collected at the Wamego and De Soto sites during July 2012 through September 2019. Data collected by the USGS over the range of streamflows at these sites during the study period (fig. 2) were used to update previously published site-specific linear regression models developed by Foster and Graham (2016) and to develop new site-specific linear regression models for several additional constituents because of additional samples collected during the current study period.

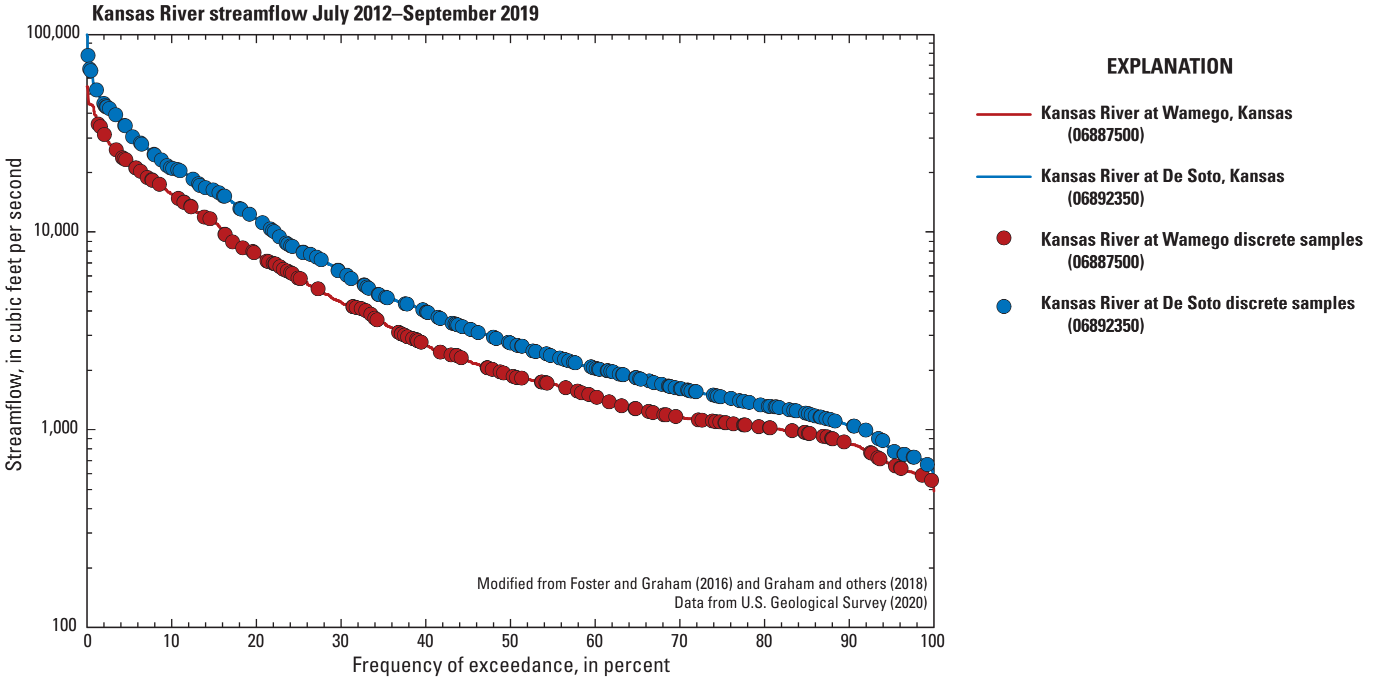
Continuous Streamflow and Water-Quality Monitoring

Streamflow data have been collected at the Wamego and De Soto sites since January 1919 and July 1917, respectively (U.S. Geological Survey, 2020). Continuous (15-minute interval) streamflow data during July 2012 through September 2019 were collected using standard USGS methods (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010) and are available in near-real time (hourly) from the USGS National Water Information System database at https://doi.org/10.5066/F7P55KJN.

Continuous (15-minute interval) water-quality data collection at the Wamego and De Soto sites began during July 1999 through September 2004 and resumed in August and July 2012, respectively. During July 2012 through September 2019, water-quality monitors were suspended from bridges near the centroid of flow, about 1 to 3 feet below the water surface. Continuous water-quality monitors were operated and maintained in accordance with standard USGS methods (Wagner and others, 2006; Bennett and others, 2014). All data are available in near-real time (hourly) from the USGS National Water Information System database at https://doi.org/10.5066/F7P55KJN.

During July 2012 through June 2014, YSI 6600 V2 water-quality monitors were installed at each site and measured water temperature, specific conductance, pH, dissolved oxygen, turbidity, and chlorophyll fluorescence. These monitors were replaced with YSI EXO2 water-quality monitors in June 2014 and measured the same properties as the YSI 6600 V2 in addition to phycocyanin fluorescence. All data recorded by the two monitor types were comparable during the study period (Foster and Graham, 2016) except for turbidity (YSI Incorporated, 2012) and chlorophyll fluorescence (Graham and others, 2018); because of this, the YSI 6600 V2 turbidity and chlorophyll fluorescence data were not included in model development for this report.

An optical NO_x sensor (Hach Nitratax plus sc, 5-millimeter pathlength) was installed at the De Soto site during June 2013 through September 2019 alongside the EXO2 continuous water-quality monitor and was operated and maintained in accordance with USGS methods (Pellerin and others, 2013).



Modified from Foster and Graham (2016) and Graham and others (2018)
Data from U.S. Geological Survey (2020)

Figure 2. Streamflow duration curves and discrete water-quality samples at the Kansas River at Wamego and Kansas River at De Soto, Kansas, streamgages (U.S. Geological Survey sites 06887500 and 06892350, respectively) during July 2012 through September 2019.

Discrete Water-Quality Sampling

During July 2012 through June 2017, water-quality samples at the Wamego and De Soto sites were collected biweekly during March through October, monthly during November through February, and during selected reservoir release and runoff events. During July 2017 through September 2019, water-quality samples at these sites were collected on a monthly to bimonthly basis, depending on flow conditions. Water-quality samples were collected over the range of flow conditions throughout the study period using this fixed-schedule sampling approach (fig. 2). Water-quality samples were collected using depth- and width-integrated sampling techniques (U.S. Geological Survey, 2006). Occasionally, water-quality samples were collected using a weighted-basket or grab-sample approach (U.S. Geological Survey, 2006) near the centroid of flow or safest possible near-shore location for safety purposes during ice or extreme cold conditions. All fecal indicator bacteria samples were collected at the centroid of flow using a weighted basket. Water-quality samples were analyzed for dissolved solids, major ions, hardness as calcium carbonate, nutrients (nitrogen and phosphorus species), chlorophyll *a* (indicator of algal biomass), suspended solids, suspended sediment, and fecal indicator bacteria (*E. coli*, fecal coliform, and enterococci). Because of a temporary project scope reduction, dissolved solids, major ions, hardness as calcium carbonate, suspended solids, and fecal indicator bacteria were not collected during August 2017 through September 2018.

Major ions (including dissolved solids and hardness as calcium carbonate), nutrients, turbidity, and suspended solids were analyzed at the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colorado, following methods described in Fishman and Friedman (1989). Fecal indicator bacteria were analyzed at the USGS Kansas Water Science Center (KSWSC) following standard methods (U.S. Geological Survey, 2008). Suspended-sediment concentration was analyzed at the USGS Iowa Sediment Laboratory in Iowa City, Iowa, following standard methods (Guy, 1969). During July 2012 through June 2018, chlorophyll *a* concentration was analyzed fluorometrically using U.S. Environmental Protection Agency Method 445.0 (Arar and Collins, 1997), modified for heated ethanol extraction (Sartory and Grobbelaar, 1984) using a fluorometer flow-through cell (Knowlton, 1984) at the USGS KSWSC. During June 2017 through September 2019, chlorophyll *a* was analyzed at the USGS NWQL in Lakewood, Colo., using U.S. Environmental Protection Agency Method 445.0 (Arar and Collins, 1997).

Water-quality samples also were analyzed for phytoplankton abundance and community composition, microcystin (a cyanotoxin), and geosmin and 2-methylisoborneol (taste-and-odor compounds). As previously discussed, results of these analytes will not be used in this report because additional data collected during cyanobacteria, microcystin, and taste-and-odor events are necessary for future model refinement (Graham and others, 2018). Foster and Graham (2016) and Graham and others (2018) describe discrete water-quality sampling and analytical methodology for these constituents in greater detail.

Quality Assurance and Quality Control of Continuous and Discrete Water-Quality Data

All continuous and discrete water-quality data were reviewed and approved on a quarterly basis during the study period following guidance and the policies described by the USGS (U.S. Geological Survey, 2016, 2017). Continuous water-quality data occasionally had to be corrected because of fouling and sensor calibration drift (Wagner and others, 2006; Pellerin and others, 2013; Bennett and others, 2014) during August 2012 through September 2019. Additionally, continuous water-quality data were occasionally deleted or missing because of excessive fouling, equipment malfunction, or temporary removal to prevent equipment damage or loss during icy conditions. At the Wamego site during July 2012 through September 2019, about 6 percent of the water temperature and dissolved oxygen records, 7 percent of the pH record, 8 percent of the chlorophyll fluorescence record, 9 percent of the turbidity record, 10 percent of the specific conductance record, and 18 percent of the phycocyanin fluorescence record were missing or deleted. At the De Soto site during July 2012 through September 2019, about 7 percent of the water temperature record, 8 percent of the pH record, 9 percent of the dissolved oxygen record, 13 percent of the turbidity and chlorophyll fluorescence records, 15 percent of the specific conductance record, 19 percent of the phycocyanin fluorescence record, and 21 percent of the optical NO_x record were missing or deleted. Missing continuous water-quality data were not estimated to fill in resultant data gaps.

Quality-assurance and quality-control (QA/QC) samples were collected during about 10 percent of all discrete water-quality sample collections. QA/QC samples collected throughout the study period included concurrent replicates and field and equipment blank samples. Concurrent replicate samples were collected to assess variability potentially introduced by sample collection and processing techniques, and by analytical method (Bennett and others, 2014; Mueller and others, 2015). Relative percentage difference (RPD) was used to quantify differences in noncensored constituent concentrations or densities among concurrent replicate pairs. The RPD was calculated by dividing the absolute difference of two replicate samples by their mean value and multiplying by 100 (Zar, 1999). Median RPDs among concurrent replicate pairs were considered acceptable if they were less than 5 percent for total dissolved solids, major ions, and hardness as calcium carbonate; less than 10 percent for nutrients (nitrogen and phosphorus species), chlorophyll *a*, total suspended solids, and suspended-sediment concentration; and less than 30 percent for fecal indicator bacteria. A total of 26 concurrent replicate pairs were collected at the Wamego and De Soto sites during July 2012 through September 2019. Median RPDs among concurrent replicate pairs for total dissolved solids, major ions, and hardness as calcium carbonate were 1.29, 0.67, and 0.73 percent, respectively. Median RPDs for nutrients (nitrogen and phosphorus species) and chlorophyll *a* were 2.29 and 6.55 percent, respectively. Median RPDs for total suspended solids and suspended-sediment concentration were 6.35 and 6.05 percent, respectively. Fecal indicator bacteria had greater variability among concurrent replicate pairs, having a median RPD of 22.9 percent. Insufficient sample mixing when processing fecal indicator bacteria samples can increase variability among replicate paired samples (Myers and others, 2014). Overall, concurrent replicate QA/QC objectives were met for all constituents used for model development as described in this report.

Split-replicate samples were collected to assess analytical variability among laboratories and methodology for chlorophyll *a* analysis by the USGS KSWSC (analyzed chlorophyll *a* during July 2012 through June 2018) and the USGS NWQL (analyzed chlorophyll *a* during June 2017 through September 2019). A total of 16 split-replicate samples were collected at the Wamego and De Soto sites during June 2017 through June 2018 and analyzed by both laboratories. All split-replicate results were considered comparable during the laboratory assessment period (median RPD=13.6 percent; coefficient of determination [R^2]=0.958).

Field and equipment blank samples were collected to assess bias caused by sampling procedures and analytical methods (Mueller and others, 2015). A total of 16 field or equipment blank samples were collected at the Wamego and De Soto sites during July 2012 through September 2019. Generally, field and equipment blank sample concentrations were less than or equal to reporting levels for most constituents sampled. Four constituents had detections greater than the laboratory minimum reporting limit (MRL) in blank samples. There were four chloride detections in blank samples; however, all detections were less than the greatest laboratory MRL (0.06 milligram per liter [mg/L]) during the study period. There were two NO_x detections in blank samples; however, all NO_x detections were less than the greatest laboratory MRL (0.04 mg/L) during the study period. There was one total dissolved nitrogen detection in blank samples; however, this detection exceeded the laboratory MRL (0.05 mg/L) by only 0.01 mg/L. Three total particulate nitrogen detections in blank samples (0.039, 0.055, and 0.168 mg/L) were greater than the laboratory MRL. The environmental sample concentration associated with the highest blank detection of 0.168 mg/L was 2.17 mg/L (percentile rank of 94.1). One other blank sample was collected that coincided with an environmental sample concentration that had a percentile rank greater than 90. The blank sample concentration associated with this fairly high environmental sample concentration (2.09 mg/L; percentile rank of 93.6) was less than the laboratory MRL of 0.03 mg/L. Therefore, the environmental sample associated with the blank sample detection of 0.168 mg/L may be biased high but was likely an isolated occurrence because no other blank sample detections were associated with fairly high environmental sample concentrations (percentile rank greater than 90). Equipment and procedure blank samples were collected for all fecal indicator bacteria samples during July 2012 through September 2019. There were no detections in any fecal indicator bacteria blank samples.

Development and Update of Regression Models

Linear regression analysis was used to develop models that relate continuous water-quality sensor measurements, streamflow, and seasonal components to discretely sampled water-quality constituent concentrations or densities. Ordinary least squares estimation was used to update or develop models for constituents without censored data (sample results less than the laboratory MRL) in the model calibration dataset. Tobit regression estimation was used to update or develop models for constituents with censored data in the model calibration dataset using the maximum likelihood estimation approach (total suspended solids; NO_x and *E. coli* bacteria at the De Soto site; Hald, 1949; Cohen, 1950; Tobin, 1958; Helsel and others, 2020). The regression estimation method and percentages of censored data for each modeled constituent are described in table 1 and appendixes 1–32. Regression models were not updated or developed if more than 50 percent of the data for a discretely sampled constituent were censored as less than the laboratory MRL, as was the case with ammonia at the Wamego and De Soto sites (54-percent censored at each site). High proportions of censored data can result in poor computations of response variable data using linear regression analysis (Helsel, 2012).

Censored data for total nitrogen were handled using an alternative approach. Total nitrogen data were compiled for regression model update by combining total particulate nitrogen and total dissolved nitrogen (Foster and Graham, 2016). There was one instance at both the Wamego and De Soto sites in which a total particulate nitrogen sample result was censored as less than the laboratory MRL, but the associated total dissolved nitrogen result was greater than the laboratory MRL. The associated combined total nitrogen result (total particulate nitrogen plus total dissolved nitrogen) could not be accurately censored as less than a laboratory MRL, which prevented the use of the Tobit regression estimation approach for censored data described previously. Therefore, ordinary least squares estimation was used by arbitrarily substituting one-half of the laboratory MRL for the censored total particulate nitrogen results (one at each site) described previously and then combining the substituted value with the associated total dissolved nitrogen result. This is described in additional detail in appendixes 17–18. This approach can result in poor computations of response variable data using ordinary least squares estimation (Helsel, 2012) but likely had a minor effect on the final selected regression models because of low percentages of data censored as less than the laboratory MRL for total nitrogen at the Wamego and De Soto sites (1.35 and 1.06 percent, respectively).

Table 1. Linear regression models and summary statistics for computations of continuous water-quality constituent concentrations or densities for the Kansas River at Wamego and Kansas River at De Soto, Kansas, streamgages (U.S. Geological Survey sites 06887500 and 06892350, respectively) using data collected during July 2012 through September 2019.

[Modified from Foster and Graham (2016). R^2, coefficient of determination; *MSE*, mean square error; *RMSE*, root mean square error; *RSE*, residual standard error; *MSPE*, model standard percentage error; BCF, bias correction factor; *n*, number of discrete samples used in model development dataset; mg/L, milligram per liter; log, common logarithm with base 10; *SC*, continuously measured specific conductance, in microsiemens per centimeter at 25 degrees Celsius; *OLS*, ordinary least squares; App., appendix; --, not applicable; $CaCO_3$, calcium carbonate; fCHL, chlorophyll fluorescence at wavelengths of 650 to 700 nanometers, in relative fluorescence units; sin, sine; *D*, date, in decimal years; cos, cosine; sNO_x, continuously measured nitrate plus nitrate, in milligrams per liter as nitrogen; *AMLE*, absolute maximum likelihood estimation; <, less than; *TBY*, turbidity, in formazin nephelometric units; µg/L, microgram per liter; colonies/100 mL, colonies per 100 milliliters]

Site	Regression model	Regression estimation method	Model archival summary	Adjusted R^2	[1]Pseudo-R^2	*MSE*	*RMSE*	Estimated *RSE* (unbiased)	Mean *MSPE*	BCF (Duan, 1983)	Discrete data used in model development dataset				
											n	Percent censored	Range of values in variable measurements	Mean	Median
						Total dissolved solids (TDS), mg/L									
Wamego	log(*TDS*)= 0.940log(*SC*) −0.0278	*OLS*	App. 1	0.970	--	0.000773	0.0278	0.0278	6.40	1.00	101	0	TDS: 156–810 SC: 262–1,280	480 762	474 749
De Soto	log(*TDS*)= 0.962log(*SC*) −0.102	*OLS*	App. 2	0.966	--	0.000841	0.0290	0.0290	6.69	1.00	132	0	TDS: 138–876 SC: 192–1,350	438 712	443 714
						Calcium (Ca), dissolved, mg/L									
Wamego	log(*Ca*)= 0.690log(*SC*) −0.131	*OLS*	App. 3	0.876	--	0.00189	0.0435	0.0435	10.0	1.00	101	0	Ca: 29.6–127 SC: 262–1,280	71.4 762	72.1 749
De Soto	log(*Ca*)= 0.658log(*SC*) −0.0415	*OLS*	App. 4	0.820	--	0.00247	0.0497	0.0497	11.5	1.01	132	0	Ca: 29.2–113 SC: 192–1,350	68.1 712	69.2 714
						Magnesium (Mg), dissolved, mg/L									
Wamego	log(*Mg*)= 0.808log(*SC*) −1.11	*OLS*	App. 5	0.889	--	0.00229	0.0479	0.0479	11.1	1.01	101	0	Mg: 5.90–26.5 SC: 262–1,280	16.5 762	16.7 749
De Soto	log(*Mg*)= 0.861log(*SC*) −1.26	*OLS*	App. 6	0.915	--	0.00179	0.0423	0.0423	9.75	1.00	132	0	Mg: 5.14–25.0 SC: 192–1,350	15.7 712	15.6 714
						Sodium (Na), dissolved, mg/L									
Wamego	log(*Na*)= 1.52log(*SC*) −2.57	*OLS*	App. 7	0.950	--	0.00338	0.0581	0.0581	13.4	1.01	101	0	Na: 9.79–134 SC: 262–1,280	66.7 762	63.8 749
De Soto	log(*Na*)= 1.70log(*SC*) −3.12	*OLS*	App. 8	0.939	--	0.00489	0.0699	0.0699	16.2	1.01	132	0	Na: 5.29–149 SC: 192–1,350	57.8 712	55.7 714

Table 1. Linear regression models and summary statistics for computations of continuous water-quality constituent concentrations or densities for the Kansas River at Wamego and Kansas River at De Soto, Kansas, streamgages (U.S. Geological Survey sites 06887500 and 06892350, respectively) using data collected during July 2012 through September 2019.—Continued

[Modified from Foster and Graham (2016). R^2, coefficient of determination; *MSE*, mean square error; *RMSE*, root mean square error; *RSE*, residual standard error; *MSPE*, model standard percentage error; BCF, bias correction factor; *n*, number of discrete samples used in model development dataset; mg/L, milligram per liter; log, common logarithm with base 10; *SC*, continuously measured specific conductance, in microsiemens per centimeter at 25 degrees Celsius; *OLS*, ordinary least squares; App., appendix; --, not applicable; $CaCO_3$, calcium carbonate; fCHL, chlorophyll fluorescence at wavelengths of 650 to 700 nanometers, in relative fluorescence units; sin, sine; *D*, date, in decimal years; cos, cosine; sNO_x, continuously measured nitrate plus nitrate, in milligrams per liter as nitrogen; *AMLE*, absolute maximum likelihood estimation; <, less than; *TBY*, turbidity, in formazin nephelometric units; µg/L, microgram per liter; colonies/100 mL, colonies per 100 milliliters]

Site	Regression model	Regression estimation method	Model archival summary	Adjusted R^2	[1]Pseudo-R^2	*MSE*	*RMSE*	Estimated *RSE* (unbiased)	Mean *MSPE*	BCF (Duan, 1983)	Discrete data used in model development dataset				
											n	Percent censored	Range of values in variable measurements	Mean	Median
Sulfate (SO_4), dissolved, mg/L															
Wamego	$\log(SO_4)= 1.10\log(SC) -1.18$	*OLS*	App. 9	0.901	--	0.00377	0.0614	0.0614	14.2	1.01	101	0	SO_4: 26.4–243 SC: 262–1,280	101 762	98.3 749
De Soto	$\log(SO_4)= 1.32\log(SC) -1.82$	*OLS*	App. 10	0.938	--	0.00299	0.0547	0.0547	12.6	1.01	132	0	SO_4: 12.7–246 SC: 192–1,350	91.8 712	92.5 714
Chloride (Cl), dissolved, mg/L															
Wamego	$\log(Cl)= 1.77\log(SC) -3.22$	*OLS*	App. 11	0.939	--	0.00570	0.0755	0.0755	17.5	1.01	101	0	Cl: 10.5–175 SC: 262–1,280	82.8 762	80.2 749
De Soto	$\log(Cl)= 1.92\log(SC) -3.67$	*OLS*	App. 12	0.936	--	0.00651	0.0807	0.0807	18.7	1.02	132	0	Cl: 4.93–200 SC: 192–1,350	69.6 712	64.5 714
Hardness ($CaCO_3$), mg/L															
Wamego	$\log(CaCO_3)= 0.723\log(SC) +0.314$	*OLS*	App. 13	0.899	--	0.00165	0.0406	0.0406	9.37	1.00	101	0	$CaCO_3$: 98.5–426 SC: 262–1,280	247 762	249 749
De Soto	$\log(CaCO_3)= 0.712\log(SC) +0.343$	*OLS*	App. 14	0.887	--	0.00167	0.0409	0.0409	9.43	1.00	132	0	$CaCO_3$: 94.5–380 SC: 192–1,350	235 712	240 714
Nitrate plus nitrite (NO_x), dissolved, mg/L															
Wamego	$NO_x= -0.00065(SC) -0.0995(fCHL) +0.163\sin(2\pi D) -0.0823\cos(2\pi D) +1.77$	*OLS*	App. 15	0.615	--	0.106	0.326	0.3330	33.0	--	73	0	NO_x: 0.030–2.66 SC: 277–1,340 fCHL: 0.44–9.80	0.988 737 3.06	0.960 728 1.77

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Site	Regression model	Regression estimation method	Model archival summary	Adjusted R^2	[1]Pseudo-R^2	*MSE*	*RMSE*	Estimated *RSE* (unbiased)	Mean *MSPE*	BCF (Duan, 1983)	Discrete data used in model development dataset				
											n	Percent censored	Range of values in variable measurements	Mean	Median
Nitrate plus nitrite (NO_x), dissolved, mg/L—Continued															
De Soto	$NO_x=$ $1.02(sNO_x)$| -0.325	*AMLE*	App. 16	--	0.898	--	--	0.221	--	--	84	23.8	NO_x: <0.01–2.20	0.667	0.776
													sNO_x: 0.0678–2.26	1.02	1.13
Nitrogen, total (TN), mg/L; total particulate nitrogen plus dissolved nitrogen															
Wamego	$\log(TN)=$ $0.281\log(TBY)$ $-0.184\log(fCHL)$ $+0.0716\sin(2\pi D)$ $+0.00669\cos(2\pi D)$ -0.154	*OLS*	App. 17	0.814	--	0.00704	0.0839	0.0857	19.4	1.02	74	1.35	TN: 0.735–4.35	2.11	1.90
													TBY: 7.42–557	116	58.8
													fCHL: 0.44–9.80	3.09	1.77
De Soto	$\log(TN)=$ $0.327\log(TBY)$ $-0.0994\log(fCHL)$ $+0.0758\sin(2\pi D)$ $+0.0306\cos(2\pi D)$ -0.275	*OLS*	App. 18	0.845	--	0.00740	0.086	0.0874	19.9	1.02	94	1.06	TN: 0.763–8.94	2.12	1.83
													TBY: 6.06–1,110	147	59.0
													fCHL: 0.30–36.9	6.32	2.76
Phosphorus, total (TP), mg/L															
Wamego	$\log(TP)=$ $0.329\log(TBY)$ -0.909	*OLS*	App. 19	0.788	--	0.00697	0.0835	0.0835	19.3	1.02	85	0	TP: 0.210–1.38	0.508	0.440
													TBY: 7.42–557	105	50.2
De Soto	$\log(TP)=$ $0.390\log(TBY)$ -1.05	*OLS*	App. 20	0.793	--	0.0119	0.109	0.109	25.4	1.03	109	0	TP: 0.200–2.85	0.537	0.39
													TBY: 6.06–1,530	149	52.0

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[Modified from Foster and Graham (2016). R^2, coefficient of determination; *MSE*, mean square error; *RMSE*, root mean square error; *RSE*, residual standard error; *MSPE*, model standard percentage error; BCF, bias correction factor; *n*, number of discrete samples used in model development dataset; mg/L, milligram per liter; log, common logarithm with base 10; *SC*, continuously measured specific conductance, in microsiemens per centimeter at 25 degrees Celsius; *OLS*, ordinary least squares; App., appendix; --, not applicable; $CaCO_3$, calcium carbonate; fCHL, chlorophyll fluorescence at wavelengths of 650 to 700 nanometers, in relative fluorescence units; sin, sine; *D*, date, in decimal years; cos, cosine; sNO_x, continuously measured nitrate plus nitrate, in milligrams per liter as nitrogen; *AMLE*, absolute maximum likelihood estimation; <, less than; *TBY*, turbidity, in formazin nephelometric units; µg/L, microgram per liter; colonies/100 mL, colonies per 100 milliliters]

Site	Regression model	Regression estimation method	Model archival summary	Adjusted R^2	[1]Pseudo-R^2	*MSE*	*RMSE*	Estimated *RSE* (unbiased)	Mean *MSPE*	BCF (Duan, 1983)	Discrete data used in model development dataset				
											n	Percent censored	Range of values in variable measurements	Mean	Median
Chlorophyll *a*, (Chla), µg/L															
Wamego	log(*Chla*)= 1.28log(*fCHL*) +0.699	*OLS*	App. 21	0.852	--	0.0357	0.189	0.189	44.9	1.09	74	0	Chla: 1.20–88.3 fCHL: 0.44–9.80	24.2 3.09	14.3 1.77
De Soto	log(*Chla*)= 1.08log(*fCHL*) +0.751	*OLS*	App. 22	0.902	--	0.0292	0.171	0.171	40.4	1.08	78	0	Chla: 1.42–187 fCHL: 0.30–36.9	40.9 6.21	24.3 2.76
Total suspended solids, (TSS), mg/L															
Wamego	log(*TSS*)= 1.05log(*TBY*) +0.167	*AMLE*	App. 23	--	0.893	--	--	0.178	--	1.08	78	6.41	TSS: <15.0–1,830 TBY: 7.42–557	200 101	84.0 50.2
De Soto	log(*TSS*)= 1.03log(*TBY*) +0.226	*AMLE*	App. 24	--	0.966	--	--	0.110	--	1.03	79	5.06	TSS: <15.0–2,920 TBY: 6.1–1,530	340 166	96.0 58.0
Suspended-sediment concentration (SSC), mg/L															
Wamego	log(S*SC*)= 0.998log(*TBY*) +0.425	*OLS*	App. 25	0.876	--	0.0357	0.189	0.189	45.0	1.12	84	0	SSC: 16–2,990 TBY: 7.42–907	323 116	162 51.9
De Soto	log(S*SC*)= 1.05log(*TBY*) +0.275	*OLS*	App. 26	0.933	--	0.0243	0.156	0.156	36.6	1.07	105	0	SSC: 8–3,730 TBY: 6.06–1,530	437 165	131 58.1
Escherichia coli bacteria (ECB), colonies/100 mL															
Wamego	log(*ECB*)= 1.27log(*TBY*) −0.304	*OLS*	App. 27	0.598	--	0.263	0.513	0.513	148	1.90	78	0	ECB: 3.00–18,000 TBY: 7.42–557	734 107	58.0 51.1

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Site	Regression model	Regression estimation method	Model archival summary	Adjusted R^2	[1]Pseudo-R^2	*MSE*	*RMSE*	Estimated *RSE* (unbiased)	Mean *MSPE*	BCF (Duan, 1983)	Discrete data used in model development dataset				
											n	Percent censored	Range of values in variable measurements	Mean	Median
Escherichia coli bacteria (ECB), colonies/100 mL—Continued															
De Soto	$\log(ECB)=1.68\log(TBY)-1.02$	*AMLE*	App. 28	--	0.822	--	--	0.439	--	1.60	77	1.30	ECB: <1.0–22,000	1,590	77.0
													TBY: 6.1–1,530	162	58.0
Fecal coliform bacteria (FCB), colonies/100 mL															
Wamego	$\log(FCB)=0.968\log(TBY)-0.286\times\sin(2\pi D)-0.339\cos(2\pi D)+0.442$	*OLS*	App. 29	0.658	--	0.227	0.476	0.482	133	1.78	77	0	FCB: 7.00–14,000	921	140
													TBY: 7.42–557	108	52.0
De Soto	$\log(FCB)=1.28\log(TBY)-0.438\times\sin(2\pi D)-0.296\cos(2\pi D)-0.0872$	*OLS*	App. 30	0.806	--	0.188	0.434	0.440	117	1.60	75	0	FCB: 1.00–19,000	1,640	220
													TBY: 6.1–1,530	158	59.0
Enterococci bacteria (ENT), colonies/100 mL															
Wamego	$\log(ENT)=1.03\log(TBY)+0.578$	*OLS*	App. 31	0.530	--	0.218	0.467	0.467	129	1.73	77	0	ENT: 15.0–17,000	1,030	190
													TBY: 7.42–557	101	50.2
De Soto	$\log(ENT)=1.38\log(TBY)-0.295$	*OLS*	App. 32	0.754	--	0.187	0.433	0.433	117	1.62	76	0	ENT: 4.00–18,000	1,350	158
													TBY: 6.1–1,530	153	56.2

[1] Pseudo-R^2 is computed using the McKelvey and Zavoina (1975) method. For uncensored data, it is equal to the R^2 for ordinary least squares.

Occasionally, discrete water-quality sample results were qualified as “estimated” for analytical purposes. Results were qualified as “estimated” for chlorophyll *a* and *E. coli*, fecal coliform, and enterococci bacteria at the Wamego and De Soto sites. Estimated results were included in the model calibration dataset and then investigated as potential outliers. There was no evidence to remove any results qualified as “estimated” based on outlier identification methods described by Rasmussen and others (2009). The number of estimated results included in each model calibration dataset is provided in appendixes 21–22 and 27–32.

Several regression models were updated from previously published versions documented in Foster and Graham (2016), including models computing concentrations of total dissolved solids, calcium, magnesium, sodium, sulfate, chloride, NO_x (Wamego site only), total nitrogen (total particulate nitrogen plus total dissolved nitrogen; Foster and Graham, 2016), total phosphorus (Wamego site only), suspended sediment, and *E. coli*, fecal coliform, and enterococci bacteria (De Soto site only). Additional water-quality data collected during the current study period were used to develop new models that compute concentrations or densities of hardness as calcium carbonate, chlorophyll *a*, and total suspended solids; NO_x and total phosphorus at the De Soto site; and *E. coli*, fecal coliform, and enterococci bacteria at the Wamego site. All linear regression models were developed using R programming language (R Core Team, 2020).

Potential explanatory variables were evaluated individually and in combination including continuous streamflow, water temperature, specific conductance, dissolved oxygen, pH, turbidity, chlorophyll and phycocyanin fluorescence, and optical NO_x (at the De Soto site only) data. These potential explanatory variables were interpolated within the 15-minute continuous record based on discrete sample time. The maximum time span between two continuous data points used for interpolation was 2 hours. Occasionally, there were gaps in the continuous record that exceeded 2 hours because of excessive fouling, equipment malfunction, or temporary removal. In these cases, cross-sectional means collected from field water-quality monitors during each discrete water-quality sample were used. Seasonal components (sine and cosine variables) also were evaluated as potential explanatory variables (if the sine or cosine variable was an explanatory variable, both variables were included, regardless of statistical significance).

Potential linear regression models were evaluated based on patterns in residual plots, range and distribution of continuous and discrete data, and the following diagnostic statistics: adjusted R^2, pseudo-R^2 (computed for Tobit regression models; McKelvey and Zavoina, 1975), Mallows’ C_p, root mean square error (*RMSE*), and prediction error sum of squares (*PRESS*; Rasmussen and others, 2009; Helsel and others, 2020). Linear regression models were selected when variance in the response variable(s) explained by the model was maximized (as indicated by adjusted R^2 or pseudo-R^2), model precision was high with low bias (as indicated by Mallows’ C_p), uncertainty associated with computed values was minimized (as indicated by *RMSE* and *PRESS*), and heteroscedasticity (irregular scatter) was minimized (as observed in residual plots; Rasmussen and others, 2009; Helsel and others, 2020). Potential explanatory variables were only considered if they had a probability (*p*-value) less than 0.05. Potential outliers were identified using methods described in Rasmussen and others (2009). Additionally, computations of studentized residuals, leverage, and Cook’s distance were used to estimate potential outlier effect on the final selected regression model (Cook, 1977; Helsel and others, 2020). All outliers removed from linear regression analyses are identified, and justification for removal is included, in appendixes 1–32.

In addition to model selection criteria, model simplicity and previously published explanatory variables (Rasmussen and others, 2005; Foster and Graham, 2016) were considered during the selection process. Additional explanatory variables were considered for linear regression models if they increased the variance explained by the model by 5 percent or more, had a *p*-value less than 0.05, decreased Mallows’ C_p, minimized *RMSE* and *PRESS*, and minimized heteroscedasticity in residual plots. Multiple explanatory variables were only selected if the associated variance inflation factor (VIF; Marquardt, 1970) for each explanatory variable was less than 4, indicating minimal multicollinearity (O’brien, 2007; Vatcheva and others, 2016; Helsel and others, 2020). Models were considered suitable to continuously compute water-quality constituent concentrations or densities only if the variance explained by the model (as indicated by adjusted R^2 or pseudo-R^2) was greater than or equal to 0.50.

Common logarithmic transformations (logarithm with base 10; log transformations) of the response and explanatory variables were considered when heteroscedasticity was present in plots of residuals compared to computed values (included in appendixes 1–32). If the final selected linear regression model contained log transformations, a bias correction factor was computed for the retransformation of computed results back into their original units (Duan, 1983). This reduced the inherent negative bias caused by log transformations (Helsel and others, 2020). Methods used for model development are described in more detail in Foster and Graham (2016) and Rasmussen and others (2009) and appendixes 1–32.

Developed and Updated Regression Models

Linear regression models that continuously compute water-quality constituent concentrations or densities were updated or developed for 16 water-quality constituents at the Wamego and De Soto sites. Constituents that were modeled were total dissolved solids and major ions (calcium, magnesium, sodium, sulfate, and chloride), hardness as calcium carbonate, nutrients (NO_x, total nitrogen, and total phosphorus), chlorophyll *a*, total suspended solids, suspended sediment, and fecal indicator bacteria (*E. coli*, fecal coliform, and enterococci). A single model was selected for each constituent at the Wamego and De Soto sites. Models, model selection criteria results, and summary statistics are provided in table 1. Model archive summaries containing model development information, statistical model output (R Core Team, 2020), and model datasets for each model are provided in appendixes 1–32.

Total Dissolved Solids, Major Ions, and Hardness

The singular explanatory variable for total dissolved solids, major ions, and hardness (as calcium carbonate) models was specific conductance at the Wamego and De Soto sites (table 1; appendixes 1–14) because of its positive correlation with total dissolved solids and other charged ionic species (Hem, 1992). Specific conductance explained about 82–97 percent of the variance (as indicated by adjusted R^2) in total dissolved solids, major ions, and hardness concentrations (table 1; appendixes 1–14). Specific conductance also was used as the singular explanatory variable for total dissolved solids and major ions models previously published by Foster and Graham (2016). There were no previously published hardness models at these sites.

Nitrate Plus Nitrite, Total Nitrogen, Total Phosphorus, and Chlorophyll *a*

Explanatory variables for NO_x varied by site. At the Wamego site, explanatory variables were specific conductance, chlorophyll fluorescence, and seasonal components (sine and cosine variables), which explained about 62 percent of the variance in NO_x concentration (table 1; appendix 15). The addition of chlorophyll fluorescence as an explanatory variable increased the amount of variance explained by the Wamego NO_x model by about 14 percent, compared to using only specific conductance as an explanatory variable. Further, the addition of seasonal components as explanatory variables increased the amount of variance explained by the model by 5 percent, compared to using only specific conductance and chlorophyll fluorescence as explanatory variables. The VIFs for specific conductance, chlorophyll fluorescence, and seasonal components were less than 2 at the Wamego site, indicating minimal multicollinearity. Specific conductance and chlorophyll fluorescence also were used as explanatory variables in the Wamego model previously published by Foster and Graham (2016). Seasonality is likely related to NO_x because increases have historically been associated with seasonal precipitation runoff events in the Kansas River (Rasmussen and others, 2005; Graham and others, 2018). At the De Soto site, the single explanatory variable for NO_x was an optical NO_x sensor (deployed at the De Soto site only), which explained about 90 percent of the variance in NO_x concentration (as indicated by pseudo-R^2; table 1; appendix 16). There was not a previously published NO_x model at the De Soto site (Foster and Graham, 2016). The difference in explanatory variables for NO_x models at each site was mainly due to the additional continuous monitoring equipment (optical NO_x sensor) available at the De Soto site.

Explanatory variables for total nitrogen (total particulate nitrogen plus total dissolved nitrogen) models were turbidity, chlorophyll fluorescence, and seasonal components, which explained about 81 and 85 percent of the variance in total nitrogen concentration at the Wamego and De Soto sites, respectively (table 1; appendixes 17–18). The addition of chlorophyll fluorescence as an explanatory variable increased the amount of variance explained by the total nitrogen models by about 15 and 13 percent at the Wamego and De Soto sites, respectively, compared to using turbidity as a single explanatory variable. Further, the addition of seasonal components as explanatory variables increased the amount of variance explained by the total nitrogen models by about 6 percent at the Wamego and De Soto sites compared to using only turbidity and chlorophyll fluorescence as explanatory variables. The VIFs for turbidity, chlorophyll fluorescence, and seasonal components were less than 2 at both sites, indicating minimal multicollinearity. Turbidity and seasonal components are likely related to total nitrogen concentration because increases in total nitrogen can be associated with seasonal runoff events that increase turbidity. The optical NO_x sensor (deployed at the De Soto site only) was not selected as an explanatory variable for total nitrogen at the De Soto site because particulate nitrogen represented 50 percent or more of total nitrogen in about 40 percent of the samples collected during the study. Additionally, use of the optical NO_x sensor as an explanatory variable for total nitrogen at the De Soto site truncated the model calibration dataset from 94 to 66 observations. Total nitrogen models previously published by Foster and Graham (2016) used turbidity, chlorophyll fluorescence, and water temperature as explanatory variables.

The singular explanatory variable for total phosphorus models was turbidity, which explained about 79 percent of variance in total phosphorus concentration at both study sites, respectively (table 1; appendixes 19–20). Phosphorus can physically bind to suspended sediment, which makes turbidity a logical explanatory variable for total phosphorus concentrations. In addition to turbidity, the Wamego total phosphorus model previously published by Foster and Graham (2016) used seasonality as an explanatory variable. Foster and Graham (2016) did not publish a total phosphorus model for the De Soto site.

The singular explanatory variable for chlorophyll *a* was chlorophyll fluorescence, which explained about 85 and 90 percent of variance in chlorophyll *a* concentration at the Wamego and De Soto sites, respectively (table 1; appendixes 21–22). Chlorophyll *a* pigments fluoresce when irradiated by certain wavelengths of light, which makes chlorophyll fluorescence an appropriate explanatory variable for chlorophyll *a* concentration. There were no previously published chlorophyll *a* models at these sites (Foster and Graham, 2016).

Total Suspended Solids and Suspended Sediment

The singular explanatory variable for the total suspended solids and suspended-sediment models was turbidity, which explained about 89 and 97 percent of the variance in total suspended solids concentration, and about 88 and 93 percent of the variance in suspended-sediment concentration, at the Wamego and De Soto sites, respectively (table 1; appendixes 23–26). Turbidity is positively related to suspended material and is a logical explanatory variable for total suspended solids and suspended-sediment concentration. Foster and Graham (2016) did not publish total suspended solids models at either site. Suspended-sediment concentration models previously published by Foster and Graham (2016) also used turbidity as the single explanatory variable.

Fecal Indicator Bacteria

The singular explanatory variable for *E. coli* and enterococci bacteria was turbidity, which explained about 60 and 82 percent of the variance in *E. coli* bacteria density and about 53 and 75 percent of the variance in enterococci bacteria density at the Wamego and De Soto sites, respectively (table 1; appendixes 27–28 and 31–32). Turbidity and seasonal components were selected as explanatory variables for fecal coliform bacteria, which explained about 66 and 81 percent of the variance in fecal coliform bacteria at the Wamego and De Soto sites, respectively (table 1; appendixes 29–30). The addition of seasonal components as explanatory variables increased the amount of variance explained by the fecal coliform models by about 11 and 12 percent at the Wamego and De Soto sites, respectively, compared to using turbidity as a single explanatory variable. The VIFs for turbidity and seasonal components were less than 2 at both sites, indicating minimal multicollinearity. Fecal indicator bacteria can physically bind to suspended sediment, which makes turbidity a logical explanatory variable for *E. coli*, fecal coliform, and enterococci bacteria. Increases in turbidity during seasonal precipitation runoff events also makes seasonality a logical explanatory variable for fecal coliform bacteria.

Summary

The Kansas River supplies drinking water to about 800,000 people in northeastern Kansas. Water-treatment facilities that use the Kansas River as a source use various chemical and physical processes to remove contaminants before distribution. An advanced notification system of changing water-quality conditions near water-supply intakes provides water-treatment facilities the ability to proactively treat their water supply. The U.S. Geological Survey (USGS), in cooperation with the Kansas Water Office (funded in part through the Kansas Water Plan), the Kansas Department of Health and Environment, The Nature Conservancy, the City of Lawrence, the City of Manhattan, the City of Olathe, the City of Topeka, and Johnson County WaterOne, collected water-quality data at the Kansas River at Wamego (USGS site 06887500; hereafter referred to as the “Wamego site”) and De Soto (USGS site 06892350; hereafter referred to as the “De Soto site”) monitoring sites to update previously published regression models relating continuous water-quality sensor measurements, streamflow, and seasonal components to discretely sampled water-quality constituent concentrations or densities. These regression models continuously compute water-quality constituent concentrations or densities that are not easily measured in near-real time.

Continuous and discrete water-quality monitoring data collected during July 2012 through September 2019 were used to update previously published regression models at the Wamego and De Soto sites with the primary intent to provide advanced notification of changing water-quality conditions for constituents of interest in the Kansas River. This report updates regression models for total dissolved solids and major ions, nutrients (nitrogen and phosphorus species), suspended sediment, and fecal indicator bacteria at the Wamego and De Soto sites. Additional samples collected during July 2012 through September 2019 were used to develop new linear regression models, including hardness as calcium carbonate, chlorophyll *a*, and total suspended solids; nitrate plus nitrite and total phosphorus at the De Soto site; and *Escherichia coli*, fecal coliform, and enterococci bacteria at the Wamego site. This report documents regression model updates and development. Continuous and discrete water-quality monitoring data used in regression model updates and development are available in appendixes 1–32 and from the USGS National Water Information System database. Real-time computations of water-quality constituent concentrations or densities using the models documented in this report are available at the USGS National Real-Time Water Quality website (https://nrtwq.usgs.gov). The water-quality information in this report can be used by water-treatment facilities to aid in treatment decisions. Additionally, the regression-computed concentrations from the models documented in this report are useful for comparison to Federal and State water-quality criteria, for computation of loads and yields to evaluate constituent transport through the drainage basin, and for characterization of changes in water-quality conditions in the Kansas River through time.

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Appendixes 1–32

Appendixes 1–32 contain the model archive summaries for the regression models that were updated or developed at the Kansas River at Wamego (U.S. Geological Survey site 06887500) and De Soto (U.S. Geological Survey site 06892350) sites in this report. Each model archive summary documents model-specific information including, but not limited to, site location, methodology, regression-estimation method, percentage of censored data, data identified as outliers, model form, previously published regression models, model diagnostic statistics and plots, and the model calibration dataset. Appendixes 1–14 contain model information for total dissolved solids, major ions, and hardness; appendixes 15–22 contain model information for nutrients (including nitrate plus nitrite, total nitrogen, and total phosphorus) and chlorophyll *a*; appendixes 23–26 contain model information for total suspended solids and suspended-sediment concentrations; and appendixes 27–32 contain model information for fecal indicator bacteria, including *Escherichia coli*, fecal coliform, and enterococci bacteria. All appendixes are available for download at https://doi.org/10.3133/ofr20211018. A list of the appendix titles is included for the convenience of the reader:

- Appendix 1. Model Archival Summary for Total Dissolved Solids Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 2. Model Archival Summary for Total Dissolved Solids Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 3. Model Archival Summary for Calcium Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 4. Model Archival Summary for Calcium Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 5. Model Archival Summary for Magnesium Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 6. Model Archival Summary for Magnesium Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 7. Model Archival Summary for Sodium Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 8. Model Archival Summary for Sodium Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 9. Model Archival Summary for Sulfate Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 10. Model Archival Summary for Sulfate Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 11. Model Archival Summary for Chloride Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 12. Model Archival Summary for Chloride Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 13. Model Archival Summary for Hardness Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during July 2012 through September 2019
- Appendix 14. Model Archival Summary for Hardness Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during July 2012 through September 2019
- Appendix 15. Model Archival Summary for Nitrate plus Nitrite Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during June 2014 through September 2019
- Appendix 16. Model Archival Summary for Nitrate plus Nitrite Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during June 2013 through September 2019
- Appendix 17. Model Archival Summary for Total Nitrogen Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during June 2014 through September 2019

- Appendix 18. Model Archival Summary for Total Nitrogen Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during June 2014 through September 2019
- Appendix 19. Model Archival Summary for Total Phosphorus Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during September 2013 through September 2019
- Appendix 20. Model Archival Summary for Total Phosphorus Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during September 2013 through September 2019
- Appendix 21. Model Archival Summary for Chlorophyll *a* Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during June 2014 through September 2019
- Appendix 22. Model Archival Summary for Chlorophyll *a* Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during June 2014 through September 2019
- Appendix 23. Model Archival Summary for Total Suspended Solids Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during September 2013 through September 2019
- Appendix 24. Model Archival Summary for Total Suspended Solids Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during September 2013 through September 2019
- Appendix 25. Model Archival Summary for Suspended-Sediment Concentration at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during September 2013 through September 2019
- Appendix 26. Model Archival Summary for Suspended-Sediment Concentration at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during September 2013 through September 2019
- Appendix 27. Model Archival Summary for *Escherichia coli* Bacteria Density at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during September 2013 through September 2019
- Appendix 28. Model Archival Summary for *Escherichia coli* Bacteria Density at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during September 2013 through September 2019
- Appendix 29. Model Archival Summary for Fecal Coliform Bacteria Density at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during October 2013 through September 2019
- Appendix 30. Model Archival Summary for Fecal Coliform Bacteria Density at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during October 2013 through September 2019
- Appendix 31. Model Archival Summary for Enterococci Bacteria Density at U.S. Geological Survey Site 06887500, Kansas River at Wamego, Kansas, during September 2013 through September 2019
- Appendix 32. Model Archival Summary for Enterococci Bacteria Density at U.S. Geological Survey Site 06892350, Kansas River at De Soto, Kansas, during September 2013 through September 2019

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