Prepared in cooperation with the Kansas Water Office

Linear Regression Model Documentation for Computing Water-Quality Constituent Concentrations using Continuous Real-Time Water-Quality Data for the Republican River, Clay Center, Kansas, July 2018 through March 2021

Scientific Investigations Report 2022–5016

U.S. Department of the Interior
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Cover. Photograph showing the Republican River at Clay Center, Kansas, at low flow on October 26, 2021, taken by Justin Abel, U.S. Geological Survey.

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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
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	
millimeter (mm)	0.03937	inch (in.)

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

$$°C = (°F – 32) / 1.8.$$

Datum

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

Supplemental Information

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L). Concentrations of nitrogen species in water are given in milligrams per liter (mg/L) as nitrogen. Concentrations of phosphorus species in water are given in milligrams per liter (mg/L) as phosphorus.

Total nitrogen is the sum of total Kjeldahl nitrogen (U.S. Geological Survey parameter code 00625, also known as ammonia plus organic nitrogen) and dissolved nitrate plus nitrite (U.S. Geological Survey parameter code 00631).

Turbidity values are given in formazin nephelometric units.

Abbreviations

BMP	best management practice
$\log_{10}$	logarithm base 10
MSE	model standard error
R^2_{adj}	adjusted coefficient of determination
RPD	relative percentage difference
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TP	total phosphorus
USGS	U.S. Geological Survey

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Abstract

The Republican River is the primary inflow to Milford Lake and drains areas of Kansas, Nebraska, and Colorado. Milford Lake has been listed as impaired and designated hypereutrophic by the Kansas Department of Health and Environment because of excessive nutrient loading. Milford Lake had confirmed harmful algal blooms every summer from 2011 through 2017 and in 2020 and 2021.

In the lower Republican River drainage basin, the Regional Conservation Partnership Program, administered by the Natural Resources Conservation Service, provides reimbursement to agricultural producers that implement best management practices intended to decrease sediment and nutrient runoff and loading into Milford Lake. Sediment and nutrient loads could potentially be driving factors in the development of harmful algal blooms in the reservoir.

Since July 2018, the U.S. Geological Survey, in cooperation with the Kansas Water Office, has collected continuous and discrete water-quality data at the Republican River at Clay Center, Kansas, streamgage (U.S. Geological Survey station 06856600), which is about 15 river miles upstream from Milford Lake. This report documents site-specific regression models for the computation of continuous concentrations of suspended sediment, total nitrogen, total phosphorus, and total carbon developed using continuous and discrete data collected from July 24, 2018, the date of continuous water-quality monitor installation, through March 31, 2021. The objective of this study is to characterize sediment and nutrient transport in the Milford Lake drainage basin before, during, and after best management practice implementation using the models described in this report.

The explanatory variable turbidity explained a high amount (72–96 percent) of the variance in suspended-sediment, total nitrogen, total phosphorus, and total carbon concentrations. Statistical plots for the four selected models showed the desired normality and homoscedasticity in residuals, and model standard error ratios indicated that recomputing each selected model after removing a randomly selected 10 percent of the data did not substantially change model coefficients.

Introduction

The Republican River is the primary inflow to Milford Lake and drains areas of Kansas, Nebraska, and Colorado. Milford Lake, the largest reservoir by surface area in Kansas, has been listed as impaired and designated hypereutrophic by the Kansas Department of Health and Environment because of excessive nutrient loading (Kansas Department of Health and Environment, 2014). Milford Lake had confirmed harmful algal blooms every summer from 2011 through 2017 and in 2020 and 2021 (Kansas Department of Health and Environment, 2020).

The lower Republican River drainage basin begins at Scandia, Kansas, (U.S. Geological Survey [USGS] station 06854500; fig. 1) and continues about 10 river miles downstream from Milford Lake to where the Republican River and the Smoky Hill River combine to form the Kansas River (fig. 1). The Kansas River provides drinking water for about 800,000 people in northeastern Kansas (J. Kenny, U.S. Geological Survey, written commun., March 27, 2011), about one-quarter of the Kansas population.

In the lower Republican River drainage basin, the Regional Conservation Partnership Program, administered by the Natural Resources Conservation Service, provides reimbursement to agricultural producers that implement best management practices (BMPs) intended to decrease sediment and nutrient runoff and loading into Milford Lake from August 2018 through August 2022 (Milford Watershed Regional Conservation Partnership Program, 2021). Sediment and nutrient loads could potentially be driving factors in the development of harmful algal blooms in the reservoir.

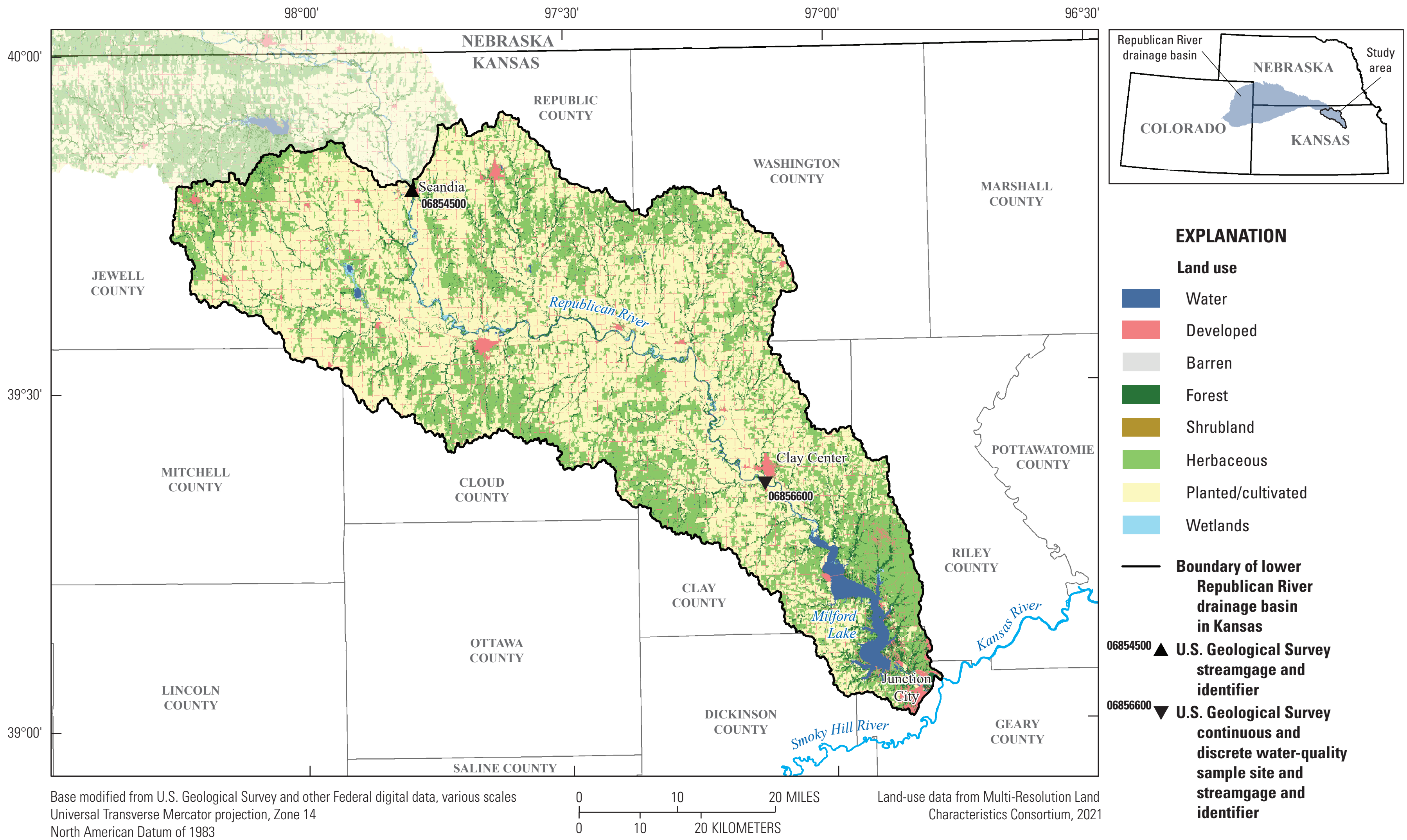

Figure 1. Land use in the Republican River drainage basin upstream from Milford Lake, Kansas.

Since July 2018, the USGS, in cooperation with the Kansas Water Office, has collected continuous and discrete water-quality data at the Republican River at Clay Center, Kans., streamgage (USGS station 06856600), hereafter referred to as “Clay Center.” The objective of this study is to characterize sediment and nutrient transport in the Milford Lake drainage basin before, during, and after BMP implementation using the models described in this report.

Purpose and Scope

The purpose of this report is to document site-specific regression models that continuously compute water-quality constituent concentrations using statistical relations between continuous and discrete water-quality data collected from Clay Center. These regression models characterize water-quality conditions of the Republican River about 15 river miles upstream from Milford Lake, Kans. Specifically, this report documents site-specific regression models for the computation of continuous concentrations of suspended sediment, total nitrogen (TN), total phosphorus (TP), and total carbon developed using continuous and discrete water-quality data collected from July 24, 2018, the date of continuous water-quality monitor installation, through March 31, 2021. The real-time, model-estimated computations of water-quality concentrations and loads are available at https://nrtwq.usgs.gov/.

Description of Study Area

The Republican River drains areas of Kansas, Nebraska, and Colorado (fig. 1). The total drainage area for the Republican River upstream from Clay Center is 17,042 square miles. The drainage area for the lower Republican River between Scandia and Clay Center is 982 square miles. Land use in the lower Republican River drainage basin is predominantly agricultural: 56 percent is planted/cultivated and 31 percent is herbaceous (according to the National Land Cover Database 2019; Multi-Resolution Land Characteristics Consortium, 2021). Mean annual precipitation at Clay Center is 30.9 inches; most (22.6 inches, 73 percent) precipitation typically falls during the spring and summer (April 1 through September 30; for years 1981–2010; PRISM Climate Group, 2021). Daily mean temperature ranges from 29.1 degrees Fahrenheit in January to 79.7 degrees Fahrenheit in July (for years 1981–2010; PRISM Climate Group, 2021).

Methods

Continuous and discrete water-quality data were collected at Clay Center from July 2018 through March 2021. Streamflow, water temperature, specific conductance, pH, dissolved oxygen, and turbidity were measured continuously in stream. Discrete water-quality samples collected over a range of hydrologic conditions (fig. 2) were used with continuous data to develop site-specific linear regression models for water-quality constituents.

Continuous Streamflow and Water-Quality Monitoring

Streamflow data have been collected at Clay Center since June 1917 (U.S. Geological Survey, 2021). Continuously measured (15-minute) streamflow data from July 2018 through March 2021 were collected according to standard USGS methods (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010; Painter and Loving, 2015). Continuously measured (15-minute) water-quality data collection at Clay Center began on July 24, 2018. During July 2018 through March 2021 a YSI, Inc., EXO3 multiparameter sonde measured water temperature, specific conductance, pH, dissolved oxygen, and turbidity (YSI, Inc., 2017). The water-quality monitor was suspended from the downstream side of the bridge deck of Kansas Highway 18 (not shown) in the deepest and fastest flowing water. The continuous water-quality monitor was operated and maintained according to standard USGS methods (Wagner and others, 2006; Bennett and others, 2014). All streamflow and continuous water-quality data at Clay Center are available in near-real time (updated hourly) from the USGS National Water Information System database (U.S. Geological Survey, 2021) using the station number 06856600.

Discrete Water-Quality Sampling

Equal-width-increment samples (as described in U.S. Geological Survey, 2006) were collected from the downstream side of the bridge using a Federal Interagency Sedimentation Project US DH–95 depth-integrated sampler with a Teflon bottle, cap, and nozzle and a manually operated reel. Subsamples from 10 equally spaced verticals were composited. Samples were collected during stable and runoff conditions so that water-quality samples were collected over a range of hydrologic conditions (fig. 2). Sample collection generally was completed in 1 hour or less, and sample time was assigned as the next 10-minute time interval (for example, 10:00, 10:10, 10:20, and so on) after the final subsample was collected. Instantaneous water-quality data were collected near the water surface during discrete sampling, regardless of water depth. Over the study period, the mean depth of water across the river cross section during discrete sampling was between 1.3 and 12 feet, and the median value was 3.3 feet. During July 2018 through June 2020, discrete water-quality samples were collected at Clay Center biweekly during May through October and monthly during November through April. During July 2020 through March 2021, discrete water-quality samples were collected about monthly. During the study period, 42 water-quality samples were collected.

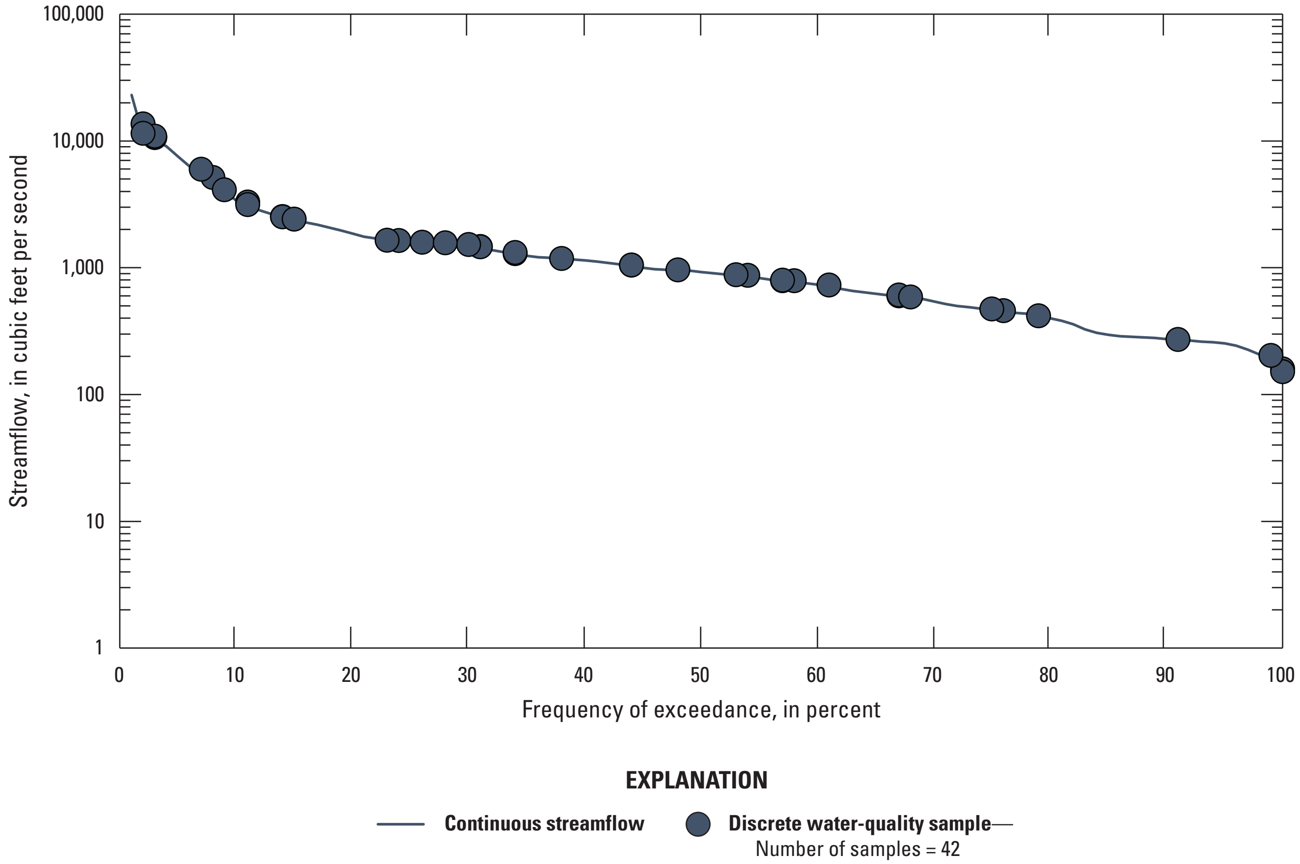

Figure 2. Streamflow duration curve and discrete water-quality samples collected at the Republican River at Clay Center, Kansas, streamgage (U.S. Geological Survey station 06856600) during July 2018 through March 2021.

Water-quality samples were analyzed for total and particulate nitrogen and phosphorus species and for total carbon at the USGS National Water Quality Laboratory in Lakewood, Colorado, according to standard methods (Patton and Truitt, 1992, 2000; Fishman, 1993; U.S. Environmental Protection Agency, 1997; Patton and Kryskalla, 2003, 2011). The suspended-sediment concentration and percentage of fines (percentage of sediment particles less than 0.0625 millimeter in diameter; useful for quality assurance) were analyzed at the USGS Iowa Sediment Laboratory in Iowa City, Iowa, using methods described by Guy (1969).

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

Continuous and discrete water-quality data were reviewed and approved on a quarterly basis during the study period in accordance with USGS policies and guidance (U.S. Geological Survey, 2016, 2017) and USGS Kansas Water Science Center quality-assurance plans (Rasmussen and others, 2014). Continuous water-quality data occasionally were corrected because of fouling and sensor calibration drift (Wagner and others, 2006; Bennett and others, 2014). Data values may be missing from the continuous record because of equipment malfunction, ice, or other factors. Between July 24, 2018, and March 31, 2021, about 7 percent of the water temperature record, 9 percent of the specific conductance record, 8 percent of the dissolved oxygen record, 10 percent of the pH record, and 10 percent of the turbidity record were missing or deleted. Missing water-quality data were not estimated.

About 10 percent of all discrete samples collected were quality-control samples: concurrent replicate samples and field-blank samples. During the study period, three concurrent replicate samples (one per year) were collected to assess bias and variability introduced by sample collection, processing, and analytical methods. The relative percentage difference (RPD) was used to evaluate differences for each replicate pair of constituents. The RPD was calculated by dividing the absolute difference between the replicate values by the mean of the replicate values and multiplying by 100. The RPDs for dissolved nitrate plus nitrite, total Kjeldahl nitrogen (TKN), and TP were 2 percent or less, and the RPDs for total carbon were 27 percent or less. The RPDs for suspended sediment were 10 percent or less for two of the replicate sets; the RPD for the third replicate set was not available because sand particles included in the sediment sample affected the data quality of one of the replicate pairs and the affected results were rejected.

Two field-blank samples were collected between July 2018 and March 2021 to assess bias caused by sampling, field processing, and analytical methods (Mueller and others, 2015). The blank samples were analyzed for nitrogen, phosphorus, and carbon; blank samples were not analyzed for suspended sediment. Generally, field-blank-sample concentrations were less than or equal to laboratory reporting levels for all constituents except total carbon. Total carbon was detected at concentrations greater than the reporting limit of 0.05 milligram per liter (mg/L) in both blank samples. For both blank-sample detections, total carbon was 5 percent or less of the concentration of the corresponding environmental sample (blank sample concentration 0.49 mg/L with corresponding environmental sample concentration 9.37 mg/L and blank sample concentration 0.08 mg/L with corresponding environmental sample concentration 2.19 mg/L). Neither blank-sample detection of total carbon exceeded 0.62 mg/L, the lowest environmental sample concentration measured between July 2018 and March 2021.

Development of Regression Models

Ordinary least squares linear regression analysis was used to develop surrogate regression models that relate continuous water-quality sensor measurements to discretely sampled constituent concentrations. Models for suspended sediment, TN, TP, and total carbon were developed to compute continuous estimates of constituent concentration. Model archive summaries containing exploratory, statistical, and cross-validation plots and the model-calibration datasets and definitions are provided in appendixes 1–4. No censored (less than laboratory reporting limit) results were in the suspended sediment, TN, TP, and total carbon datasets.

TN is the sum of TKN (USGS parameter code 00625, also known as ammonia plus organic nitrogen) and dissolved nitrate plus nitrite (USGS parameter code 00631). In the TN dataset, seven samples had censored nitrate plus nitrite results (less than 0.01 mg/L as nitrogen; data available in appendix 2). No samples had censored TKN results. For all seven of the samples with censored nitrate plus nitrate results, the corresponding TKN result was greater than 1.0 mg/L as nitrogen and had only one decimal place; therefore, the sum of TKN and dissolved nitrate plus nitrite was limited to one decimal place, and the censored nitrate plus nitrite result did not affect the sum calculation of TN. Thus, no censored results were in the TN dataset.

All regression models were developed using R software environment (R Core Team, 2021). Potential explanatory variables evaluated individually and in combination were continuous streamflow, water temperature, specific conductance, dissolved oxygen, pH, and turbidity. Explanatory and response variables were transformed by logarithm base 10 ($\log_{10}$), if necessary, to develop a linear relation. The potential explanatory variables were interpolated within the 15-minute continuous record based on discrete sample collection time. The maximum time span between two continuous data points used for interpolation was 5 hours. Seasonal components (sine and cosine variables) also were evaluated as potential explanatory variables.

Potential regression models were evaluated based on normality and homoscedasticity in residual values. Residual values are the difference between the measured and predicted values. Homoscedastic plots are those in which the magnitude of residual values does not change substantially over the range of predicted values; that is, the magnitude of residual values neither increases nor decreases over the range of predicted values and the variance is constant. The best performing models were selected based on the appearance of the residual plots, fairly high adjusted coefficient of determination (R^2_{adj}) values compared to other models considered, and fairly low model standard percentage error compared to other models considered (Rasmussen and others, 2009; Helsel and others, 2020). Sensitivity of the selected model to outliers was checked using the ratio of the mean model standard error (MSE) of folds to the MSE of the selected model, called the MSE ratio. The residual plots and aforementioned statistics and metrics are included in each constituent's model archive summary (appendixes 1–4). Relevant sample data and more indepth statistical information also are available in appendixes 1–4. The linear regression models and selected statistics are listed in table 1.

Table 1. Linear regression models and summary statistics for computation of continuous water-quality constituent concentrations for the Republican River at Clay Center, Kansas (U.S. Geological Survey station 06856600), using data collected during July 2018 through March 2021.

[R^2_{adj}, adjusted coefficient of determination; MSPE, model standard percentage error; MSE ratio, ratio of mean model standard error of folds to model standard error of selected regression model; *n*, number of discrete samples used in model development; $\log_{10}$, logarithm base 10; *SSC*, suspended-sediment concentration, in milligrams per liter; *TBY*, continuous turbidity value, in formazin nephelometric units; App., appendix; *TN*, total nitrogen, in milligrams per liter as nitrogen; *TP*, total phosphorus, in milligrams per liter as phosphorus; --, not applicable; *totC*, total carbon, in milligrams per liter]

Regression model	Model archive summary	R^2_{adj}	Mean MSPE	MSE ratio	Duan's bias correction factor[1]	Discrete data used in model development dataset				
						n	Percent censored	Range of values in variable measurements	Mean	Median
$\log_{10}SSC=+0.934\times\log_{10}TBY+0.608$	App. 1	0.963	25.4	1.11000	1.03	42	0	*SSC*: 14–2,350 *TBY*: 5.47–810	449 155	184 56
$\log_{10}TN=+0.344\times\log_{10}TBY-0.258$	App. 2	0.719	29.7	1.06000	1.04	42	0	*TN*: 1.00–7.8 *TBY*: 5.47–810	2.8 155	2.0 56
$TP=+0.00254\times TBY+0.3$	App. 3	0.916	21.3	0.995000	--	42	0	*TP*: 0.20–2.4 *TBY*: 5.47–810	0.70 155	0.50 56
$totC=+0.0566\times TBY+2.39$	App. 4	0.888	34.6	1.05	--	42	0	*totC*: 0.62–44.3 *TBY*: 5.47–810	10.5 155	7.08 56

[1]Duan (1983); Helsel and others (2020).

Regression Models Used for Computing Constituents of Interest

Linear regression models that compute concentrations of suspended sediment, TN, TP, and total carbon were developed using data from 42 discrete samples collected during the study period, July 2018 through March 2021 (U.S. Geological Survey, 2021).

Suspended-Sediment Concentration

The single explanatory variable used in the suspended-sediment model was turbidity, which explained about 96 percent of the variance (R^2_{adj} value; table 1; Helsel and others, 2020) in suspended-sediment concentration (appendix 1). Turbidity is an indicator of sediment and other suspended material transported in a stream, and turbidity is therefore a logical explanatory variable for suspended-sediment concentration. Statistical plots for the $\log_{10}$-transformed model (appendix 1) showed the desired normality and homoscedasticity in residuals. The cross-validation plot for the model (appendix 1) had an MSE ratio of 1.11000 (table 1; appendix 1), which was close to the ideal value of 1.0. The MSE ratio near 1.0 indicated that recomputing the model after removing a randomly selected 10 percent of the data did not substantially change the model coefficients.

The $\log_{10}$-transformed model provided in appendix 1 may be retransformed to the original units so that the suspended-sediment concentration can be calculated directly. The retransformation introduces a negative bias in the retransformed calculated constituent (Helsel and others, 2020). The bias may be corrected using Duan's bias correction factor (Duan, 1983; Helsel and others, 2020), which is provided in table 1 and appendix 1.

Total Nitrogen, Total Phosphorus, and Total Carbon

The single explanatory variable used for TN, TP, and total carbon was turbidity. Turbidity explained about 72 percent of the variance (R^2_{adj} value; table 1; Helsel and others, 2020) in the TN concentration (appendix 2), about 92 percent of the variance in the TP concentration (appendix 3), and about 89 percent of the variance in the total carbon concentration (appendix 4). Turbidity is an indicator of sediment and other suspended material (including some with attached nutrients, like nitrogen, phosphorus, and carbon) transported in a stream, and turbidity is therefore a logical explanatory variable for TN, TP, and total carbon concentrations.

Statistical plots for the $\log_{10}$-transformed TN model (appendix 2), untransformed TP model (appendix 3), and untransformed total carbon model (appendix 4) showed the desired normality and homoscedasticity in residuals. The cross-validation plot for the TN model (appendix 2) had an MSE ratio of 1.06000 (table 1; appendix 2), which was close to the ideal value of 1.0. This ratio was 0.995000 for the TP model (table 1; appendix 3) and 1.05 for the total carbon model (table 1; appendix 4). Each MSE ratio near 1.0 indicated that recomputing the model after removing a randomly selected 10 percent of the data did not substantially change the model coefficients.

The $\log_{10}$-transformed TN model provided in appendix 2 may be retransformed to the original units so that the TN concentration can be calculated directly. The retransformation introduces a negative bias in the retransformed calculated constituent (Helsel and others, 2020). The bias may be corrected using Duan's bias correction factor (Duan, 1983; Helsel and others, 2020), which is provided in table 1 and appendix 2.

Summary

The Republican River is the primary inflow to Milford Lake and drains areas of Kansas, Nebraska, and Colorado. Milford Lake has been listed as impaired and designated hypereutrophic by the Kansas Department of Health and Environment because of excessive nutrient loading. Milford Lake had confirmed harmful algal blooms every summer from 2011 through 2017 and in 2020 and 2021.

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The explanatory variable turbidity explained a high amount (72–96 percent) of the variance in suspended-sediment, total nitrogen, total phosphorus, and total carbon concentrations. Statistical plots for the four selected models showed the desired normality and homoscedasticity in residuals, and model standard error ratios indicated that recomputing each selected model after removing a randomly selected 10 percent of the data did not substantially change model coefficients.

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Appendix 1. Model Archive Summary for Suspended Sediment at U.S. Geological Survey Station 06856600, Republican River at Clay Center, Kansas, during July 2018 through March 2021

The model archive summary for suspended sediment is available for download at https://doi.org/10.3133/sir20225016. The model archive summary documents model-specific information including, but not limited to, exploratory, statistical, and cross-validation plots and the model-calibration datasets and definitions.

Appendix 2. Model Archive Summary for Total Nitrogen at U.S. Geological Survey Station 06856600, Republican River at Clay Center, Kansas, during July 2018 through March 2021

The model archive summary for total nitrogen is available for download at https://doi.org/10.3133/sir20225016. The model archive summary documents model-specific information including, but not limited to, exploratory, statistical, and cross-validation plots and the model-calibration datasets and definitions.

Appendix 3. Model Archive Summary for Total Phosphorus at U.S. Geological Survey Station 06856600, Republican River at Clay Center, Kansas, during July 2018 through March 2021

The model archive summary for total phosphorus is available for download at https://doi.org/10.3133/sir20225016. The model archive summary documents model-specific information including, but not limited to, exploratory, statistical, and cross-validation plots and the model-calibration datasets and definitions.

Appendix 4. Model Archive Summary for Total Carbon at U.S. Geological Survey Station 06856600, Republican River at Clay Center, Kansas, during July 2018 through March 2021

The model archive summary for total carbon is available for download at https://doi.org/10.3133/sir20225016. The model archive summary documents model-specific information including, but not limited to, exploratory, statistical, and cross-validation plots and the model-calibration datasets and definitions.

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