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DISSOLVED OXYGEN CONCENTRATION IN THE BIG SIOUX RIVER DOWNSTREAM FROM SIOUX FALLS, SOUTH DAKOTA, DURING WINTER CONDITIONS

BY

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A thesis submitted in
partial fulfillment of the requirements for
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in Civil Engineering, South
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1970

DISSOLVED OXYGEN CONCENTRATION IN
THE BIG SIOUX RIVER DOWNSTREAM
FROM SIOUX FALLS, SOUTH DAKOTA,
DURING WINTER CONDITIONS

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser Date

Head, Civil Engineering Department Date

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INTRODUCTION

Water quality standards were adopted by the South Dakota Committee on Water Pollution on February 16, 1967. The adoption of these standards was a partial fulfillment of the requirements of the Water Quality Act of 1965. This Act, Public Law 234, required each state to prepare water quality standards for all interstate streams within its boundaries, formulate a plan for implementation and enforcement of these standards, and after holding public hearings, adopt such standards and plan before June 30, 1967 (1).

The Federal Water Pollution Control Administration (FWPCA) reviewed the standards adopted by the South Dakota Committee on Water Pollution and suggested some alterations. The State Committee concurred with the suggested changes by a letter which was attached to the original water quality standards as an addendum. On August 7, 1967, the Secretary of the Interior sent a letter informing the Governor of South Dakota that the standards were officially approved.

Sioux Falls, the largest center of population and industry in South Dakota, is located on the Big Sioux River and discharges its wastewater into this interstate stream. The pending adoption of the water quality standards, served as the prime factor for initiating a study to determine the impact of imposing water quality standards on the reach of the Big Sioux River affected by wastewater discharged in the Sioux Falls' vicinity.

The first phase of the study, conducted by Herreid (2), compared past water quality of the Big Sioux River downstream from Sioux Falls with the recommended limits as proposed in the quality standards. Herried's report showed that the quality of the river water, except for total coliform count, at the Brandon sampling station would have been within the limits as established in the standards nearly all of the time.

Herried's conclusions regarding the minimum dissolved oxygen requirement of the river were perhaps premature as his appraisal was completed before the addendum was attached to the standards. Among other things, the addendum concurred with the suggestion that the minimum dissolved oxygen requirement of the river be raised from 2.0 to 4.0 milligrams per liter (mg/l). However, the upgrading of the dissolved oxygen standard was contingent upon the availability of supplemental dilution flow in the river (3).

According to the water quality standards, if the wastewater flow comprises 50 percent or more of the total flow of a river, the river is considered to be classified in the intermittent stream category. In the intermittent stream category, the quality requirements are substantially different from those listed for the other beneficial uses of the river. Herried showed that the Big Sioux River would have been classified in the intermittent stream category for a significant portion of the time in the past years and that the frequency of the occurrence of this classification would probably increase in the future. Although the intermittent stream classification would have been applicable during different seasons of the year, it would have been more predominate during the winter months (2-53).

The prime objective of the second phase of the study was to determine the relationship between dissolved oxygen concentrations and various river conditions. In the second phase, Naughton (4) found a high degree of correlation between minimum dissolved oxygen concentrations in the river and the variables of the river temperature (above 0° C), BOD, and the reciprocal of flow. He concluded that when the river temperature is 0° C, the minimum dissolved oxygen concentration of the water in the river is very unpredictable because of possible ice cover (4-50).

The third phase of the study was conducted by Rakness (5) to determine the flow variation of the Big Sioux River throughout the year, and to estimate the probable effect of increased water resources development on this flow. Rakness concluded that the Big Sioux River downstream from Sioux Falls would be in the intermittent stream use category for an increasing amount of time in the future, especially during the late fall and winter months. The increase in frequency of occurrence of the intermittent stream use category was attributed to greater wastewater discharges, greater water supply demands for the city of Sioux Falls, and increased irrigational development upstream from Sioux Falls. Rakness also concluded that by the year 2010, the intermittent stream use category would be expected to be applicable to the Big Sioux River below Sioux Falls every winter of each year.

The fourth phase of the study of the Big Sioux River downstream from Sioux Falls, South Dakota, is reported herein. The objectives of the fourth phase were to (a) evaluate the data on water quality presently available for the winter months and determine if a relationship exists between the flow in the river and the minimum dissolved oxygen concentration; (b) determine if treatment provided by the Sioux Falls wastewater treatment plant varies significantly during the winter and if the discharge grossly influences the water quality downstream; and (c) establish the river flow and/or sewage treatment requirements to maintain four milligrams per liter of dissolved oxygen in the Big Sioux River downstream from Sioux Falls during winter conditions.

DESCRIPTION OF AREA

General

The Big Sioux River originates in northeastern South Dakota and in general flows southward to Sioux City, Iowa, where it joins the Missouri River. A major portion, 69 percent, of the Big Sioux River Basin is located in South Dakota. The remaining 31 percent of the basin's 9,570 square miles is distributed almost equally between the states of Iowa and Minnesota (6-2).

The climate of the Big Sioux River Basin is described as mid-continental, subhumid, and with rapid fluctuation of temperature. Temperatures of over 100° F are not uncommon during summer months and temperatures frequently fall below 0° F during the winter months. Average temperatures at Sioux Falls, South Dakota, for the months of January and July are 15.2° and 74.3° F, respectively (6-7).

This study is concerned with that reach of the Big Sioux River located between the Sioux Falls wastewater treatment plant and the Klondike Bridge (See Figure 1). The reach measures 32.0 river miles and has an average gradient of about 2.0 feet per mile. From 18.4 river miles below the treatment plant to its concurrence with the Missouri River, the Big Sioux forms the border between South Dakota and Iowa, and thus is classified as an interstate stream (4-4).

The Sioux Falls wastewater treatment plant is located 1.0 miles downstream from the Falls of the Big Sioux and immediately downstream

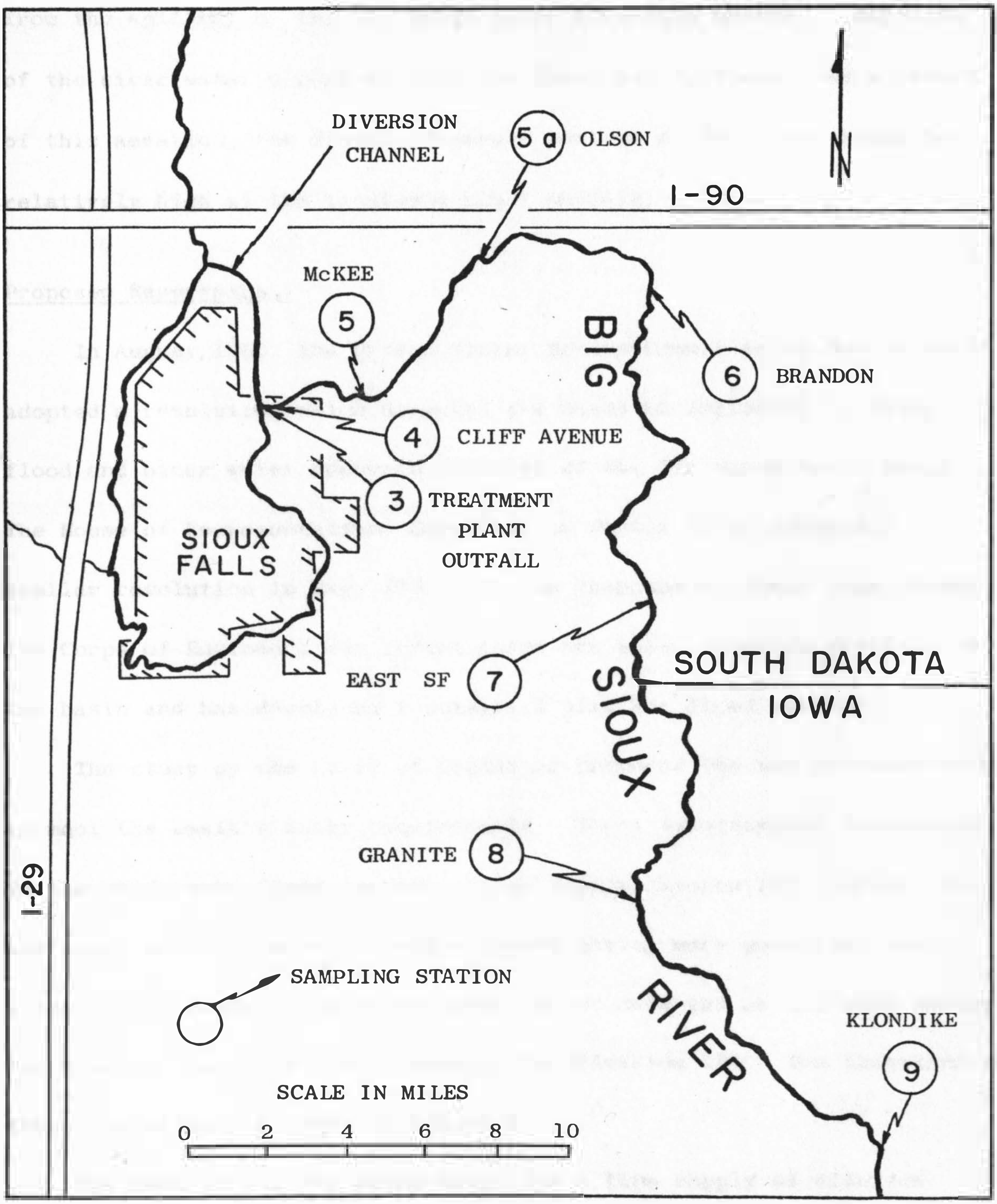

Figure 1. Big Sioux River in vicinity of Sioux Falls, South Dakota.

from the spillway of the Big Sioux River diversion channel. Aeration of the river water occurs at both the falls and spillway. As a result of this aeration, the dissolved oxygen content of the river would be relatively high at the treatment plant outfall.

Proposed Reservoirs

In August,1963, the United States Senate Committee on Public Works adopted a resolution which directed the Corps of Engineers to study flood and other water resource problems of the Big Sioux River Basin. The House of Representatives Committee on Public Works adopted a similar resolution in May, 1964 (7). In response to these resolutions, the Corps of Engineers has investigated the water resource problems in the basin and has developed a potential plan for flood control.

The study by the Corps of Engineers proposed the use of reservoirs to meet the basin's water requirements. Those requirements considered in the study were flood control, water supply, recreation, irrigation, and water quality control. After investigating many potential dam sites in the basin, five sites were finally selected as the ones having the greatest potential for economic justification (8). The locations of these dam sites are shown in Figure 2.

The need in the Big Sioux Basin for a firm supply of dilution water for quality control will become increasingly critical. An overall basin requirement of 79 million gallons a day for water quality

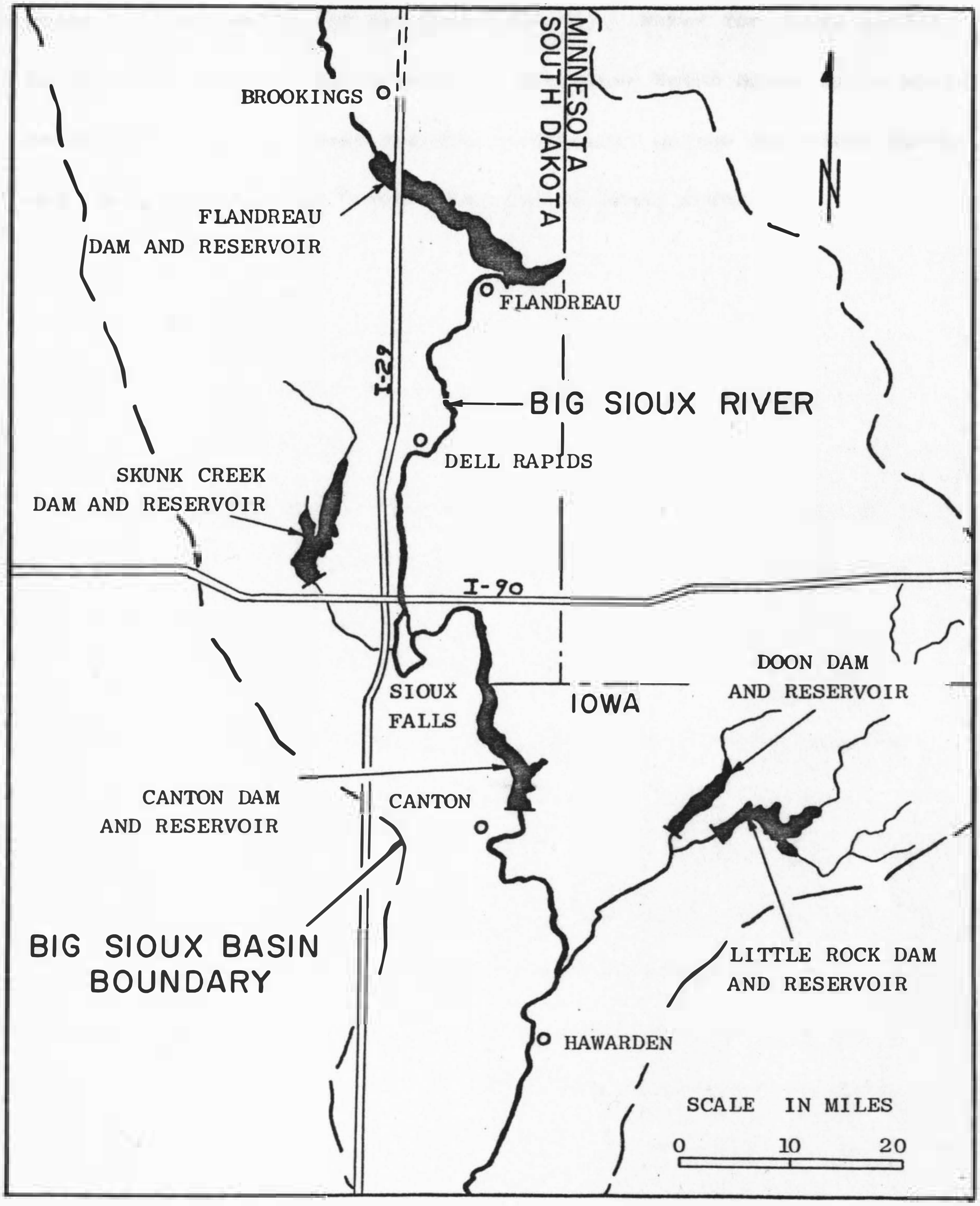

Figure 2. Locations of proposed dams and reservoirs in the Big Sioux River Basin.

control is projected for the year 2020 (8). Water for water quality control for the critical stretch of the river below Sioux Falls would be stored in the proposed Flandreau reservoir on the Big Sioux River and the proposed Skunk Creek reservoir on Skunk Creek.

DATA EVALUATION AND RESULTS

Source of Data

Data collected by the United States Geological Survey (9)(10)(11) and the Sioux Falls wastewater treatment plant personnel (12) were reviewed and evaluated during this study.

The United States Geological Survey has operated a stream gaging station northwest of Brandon since July, 1959. River flows recorded by the United States Geological Survey at this gaging station, located 6.55 miles downstream from the Sioux Falls wastewater treatment plant, were used in the evaluation. Records of flow for the winter months are considered to be poor as compared to the records for the rest of the year because of the effect of ice (9)(10).

Personnel of the Sioux Falls wastewater treatment plant have collected and analyzed samples from several sampling stations at about weekly intervals since February, 1964. Data from those stations downstream from the treatment plant provided the major portion of the information for this evaluation. The locations of these stations and their distance in river miles downstream from the treatment plant outfall are presented in Table 1. The numbers assigned to the sampling stations are the same as used by Naughton (4-11). Figure 1 shows the locations of the sampling stations.

The treatment plant records contained information on the temperature, dissolved oxygen (DO), and the biochemical oxygen demand

Table 1. Locations of the Big Sioux River Sampling Stations Downstream from Sioux Falls Wastewater Treatment Plant

Number	Designation	Distance* (miles)	Bridge Location
3	Plant Outfall	0.0	River at treatment plant outfall (no bridge).
4	Cliff Avenue	0.4	North Cliff Avenue.
5	McKee	1.8	First township road east of I-29, north from Minnehaha County Highway No. 140.
5a	Olson	5.0	Minnehaha County Highway No. 121.
6	Brandon	9.1	Minnehaha County Highway No. 140.
7	East Sioux Falls	16.1	South Dakota Highway 38 east of East Sioux Falls.
8	Granite	24.0	Lincoln County Highway No. 135 Spur.
9	Klondike	32.0	Lincoln County Highway No. 116.

* Distance from Sioux Falls Wastewater Treatment Plant Outfall (13).

(BOD) of the river at the sampling stations. Prior to November 1, 1967, samples were collected at seven stations from the wastewater treatment plant outfall to the Klondike Bridge. Naughton (4) suggested the addition of another sampling station at the Minnehaha County Highway 121 (Olson) Bridge to better define the river conditions at low flows. Samples have been collected at the Olson Bridge since November 1, 1967. Samples have also been collected at points upstream from the wastewater treatment plant outfall.

River Temperature

The Big Sioux River is located in a region that experiences great seasonal variations in temperature. At Sioux Falls, South Dakota, air temperature extremes have ranged from 115° F to -42° F with the average annual air temperature being about 46° F. A frost-free period occurs on the average for about 130 days in the northern part of the Big Sioux River basin and for about 160 days in the southern part of the basin (14).

River temperature measurements have been made by the Sioux Falls wastewater treatment plant personnel at about weekly intervals at the sampling stations on the Big Sioux River. For the time period of June, 1961 to July, 1969, a total of 346 river temperatures were recorded at the Brandon sampling station. These river temperature data were used in constructing the curve in Figure 3 which shows

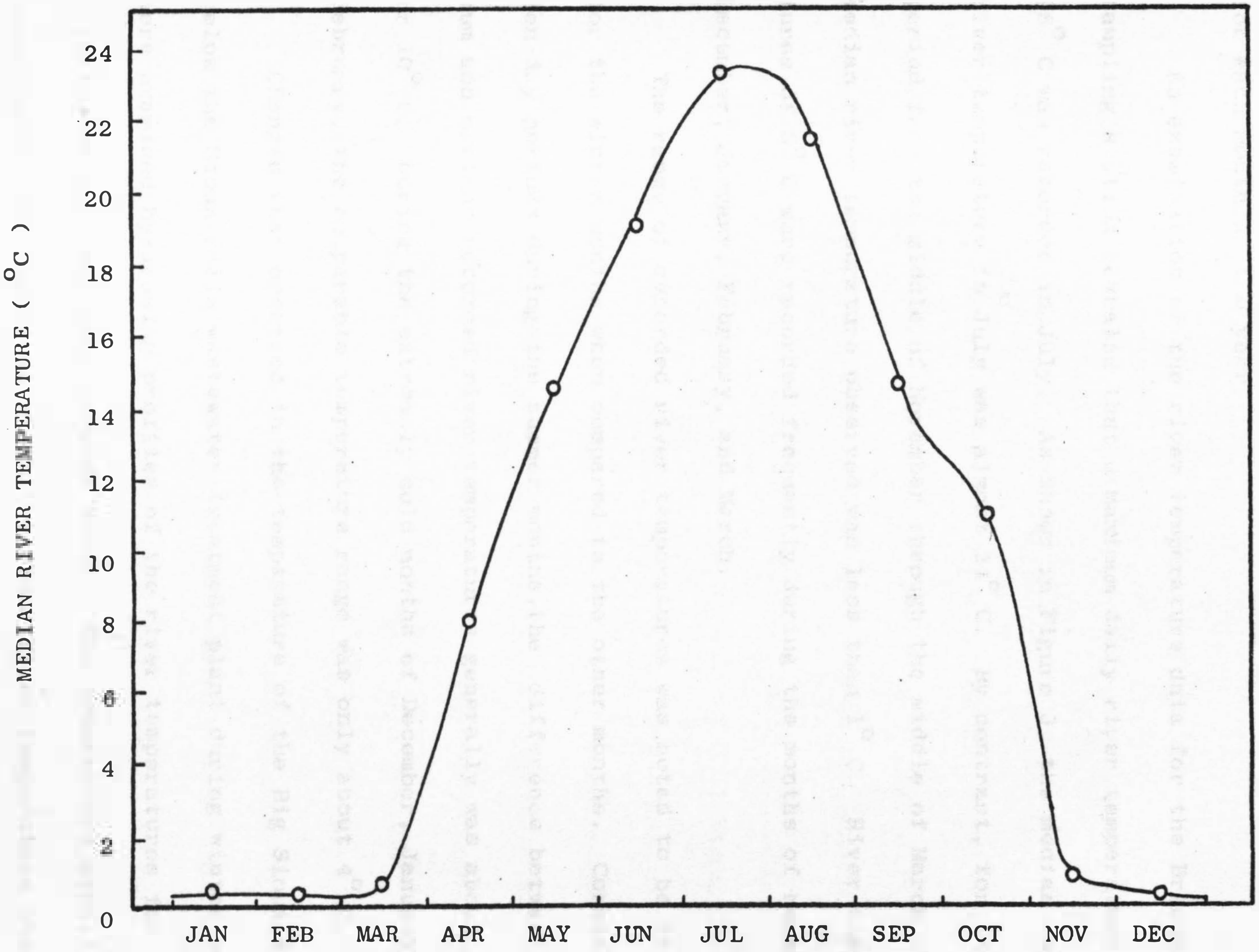

Figure 3. Median temperature of samples collected from the Big Sioux River at Brandon for the months of the year (1961-1969).

the median temperature of the samples collected at the Brandon station for each month of the year.

An examination of the river temperature data for the Brandon sampling station revealed that a maximum daily river temperature of 28° C was recorded in July. As shown in Figure 3, the median recorded river temperature in July was almost 24° C. By contrast, for the time period from the middle of November through the middle of March the median river temperature observed was less than 1° C. River temperatures of 0° C were recorded frequently during the months of November, December, January, February, and March.

The range of recorded river temperatures was noted to be less for the winter months when compared to the other months. Considering ten day periods during the summer months, the difference between maximum and minimum recorded river temperatures generally was about 9° or 10° C. During the extremely cold months of December, January, and February, the comparable temperature range was only about 4° C.

Changes that occurred in the temperature of the Big Sioux River below the Sioux Falls wastewater treatment plant during winter months were examined by drawing profiles of the river temperatures for the sampling days in November through March. The temperature profiles demonstrated the manner in which the Sioux River temperature changed as the water progressed downstream. It was concluded from the temperature profiles that the water temperature was increased substantially, often 5° C or more, below the wastewater treatment plant outfall during the winter months. However, the water temperature decreased rapidly as the flow progressed downstream and had generally reached 0° C at the Brandon sampling station.

Wastewater Treatment Provided by the City of Sioux Falls

The Sioux Falls municipal wastewater treatment plant treats both the domestic sewage and industrial wastewater of the city of Sioux Falls. Although the population of Sioux Falls is approximately 75,000 people, the combined domestic and industrial waste entering the plant has a BOD population equivalent of almost 500,000. This high BOD load is largely due to wastes discharged to the treatment plant from the John Morrell and Company meat packing plant. The 4.0 million gallons per day of wastes entering the municipal treatment plant from the Morrell packing plant have a BOD of about 2,000 milligrams per liter and a population equivalent of approximately 390,000 (14).

Treatment in the Sioux Falls plant is provided by an activated sludge process and a trickling filter operation. Wastes from the Morrell packing house are treated by trickling filters after which they are combined with the domestic sewage for further treatment by the activated sludge process (15-23). Generally, reduction of BOD in the plant has been very good with removals of more than 97 percent (12).

One of the objectives of this study was to determine if the treatment provided by the Sioux Falls wastewater treatment plant was less effective during the winter. Figure 4 shows frequency distribution of the BOD concentrations of the plant effluent during the winter months of January and February and the summer months of July, August, and September. Daily BOD concentrations of the treatment plant effluent were used in the evaluation.

It can be seen from Figure 4 that low effluent BOD concentrations have been achieved by the Sioux Falls wastewater treatment plant during the summer. Figure 4 also shows that the BOD concentration of the treatment plant effluent was substantially higher during the winter months than it was during the summer months. An effluent BOD of 30 mg/l, considered the maximum permissible concentration for discharge to an intermittent stream[1], was exceeded about 45 percent of the time during January and February as compared to only about 8 percent of the time during the summer months. The higher BOD concentration in the treatment plant effluent during the winter can probably be related to lower air temperatures, because trickling filtration and activated sludge are both biological treatment processes which are temperature dependent.

A statistical test (<u>t</u> test) was also conducted on the summer and winter BOD concentrations of the treatment plant effluent. This test showed that in January and February the BOD concentration was

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[1] Letter to Dr. James N. Dornbush from Charles E. Carl, Secretary and Executive Officer, South Dakota Committee on Water Pollution, State Department of Health, Pierre, South Dakota (May 13, 1969).

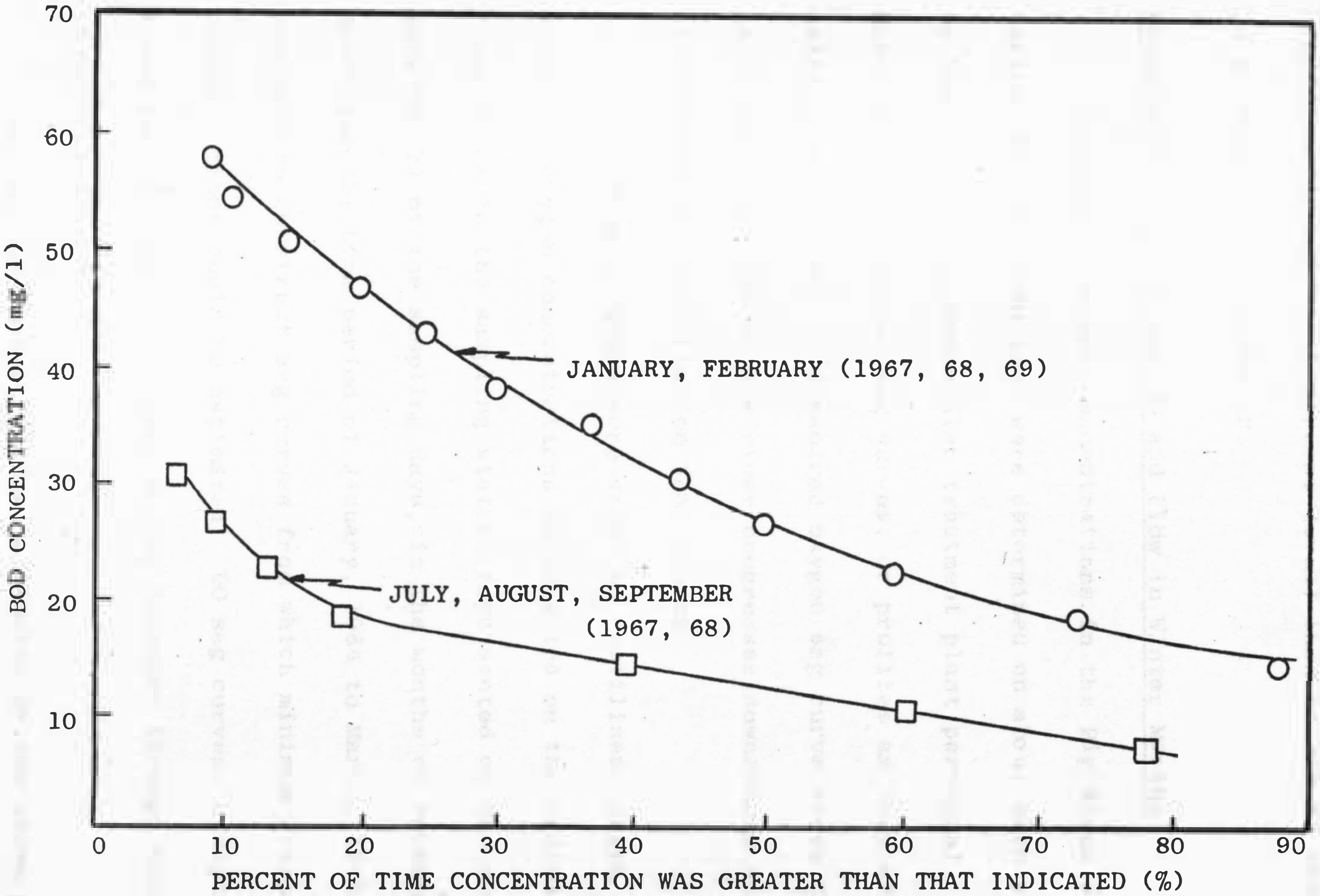

Figure 4. Frequency distribution of BOD concentrations discharged by Sioux Falls wastewater treatment plant during the summer (1967, 68) and winter (1967, 68, 69) months.

significantly higher (5 percent level) than it was in the months of July, August, and September.

Relationship of Minimum DO and Flow in Winter Months

Dissolved oxygen concentrations in the Big Sioux River at the various sampling stations were determined on about weekly intervals by the Sioux Falls wastewater treatment plant personnel. Using these data, dissolved oxygen sag curves, or profiles as they are sometimes called, were drawn. A dissolved oxygen sag curve shows the change in DO concentration as the river progresses downstream and indicates the minimum DO concentration that occurs.

The DO sag curves were drawn on rectilinear graph paper with dissolved oxygen concentrations represented on the ordinate and river miles to the sampling station represented on the abscissa. Data for 71 of the sampling days, in the months of November through March for the time period of January, 1964 to March, 1969, were adequate to construct sag curves from which minimum dissolved oxygen concentrations could be estimated. DO sag curves, examples of those found for the Big Sioux River during November through March, are shown in Figure 5.

Minimum DO concentrations, estimated by the above procedure, were used in evaluating the relationship of river flow with dissolved oxygen concentration during winter conditions. Median and mean values

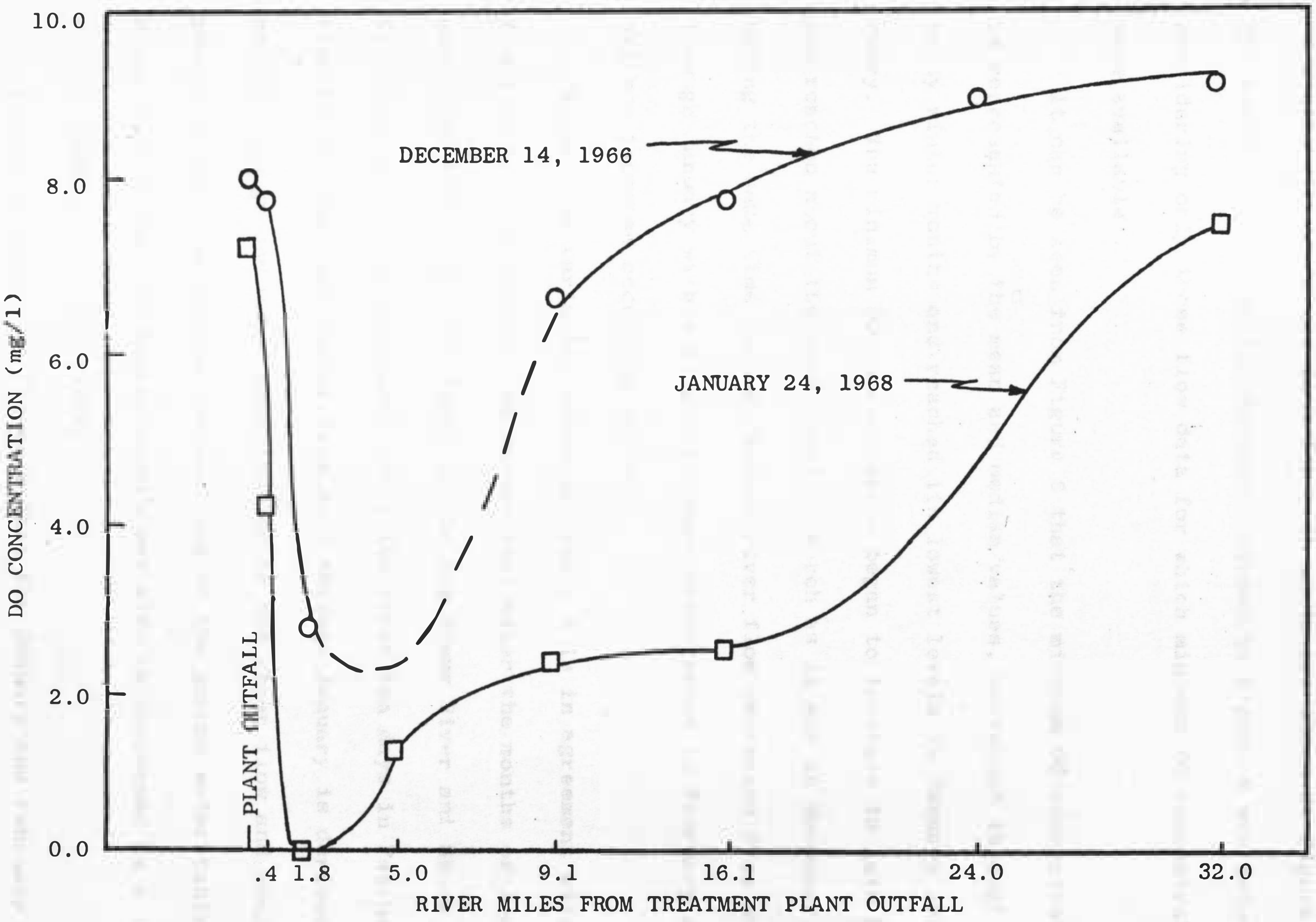

Figure 5. Examples of DO sag curves for the Big Sioux River below Sioux Falls, South Dakota, during winter months.

of minimum DO concentrations for each month are shown in Figure 6. The median river flow for Brandon included in Figure 6 was determined considering only those flow data for which minimum DO concentrations were available.

It can be seen from Figure 6 that the minimum DO concentration, as represented by the mean and median values, decreased through the early winter months and reached its lowest levels in January and February. The minimum DO concentration began to increase in late February and reached about the same level in March as it was in November. During the same time period, median river flow decreased from November through January with a slight increase experienced in February and an extreme increase occurring in March.

River flow variation shown in Figure 6 is in agreement with that found by Rakness (5-13). He showed that after the months of June, the one-third-months average flows in the Big Sioux River and Skunk Creek tributary generally decreased until the first ten days in February. Flow in the Big Sioux River from July through January is derived mainly from ground water contribution to the river flow and would generally decrease due to the lowering of the ground water table. River flow during the winter months may also be decreased as a result of ice formation on the river.

It can be seen from Figure 6 that for January and February both the mean and median minimum dissolved oxygen concentrations were less

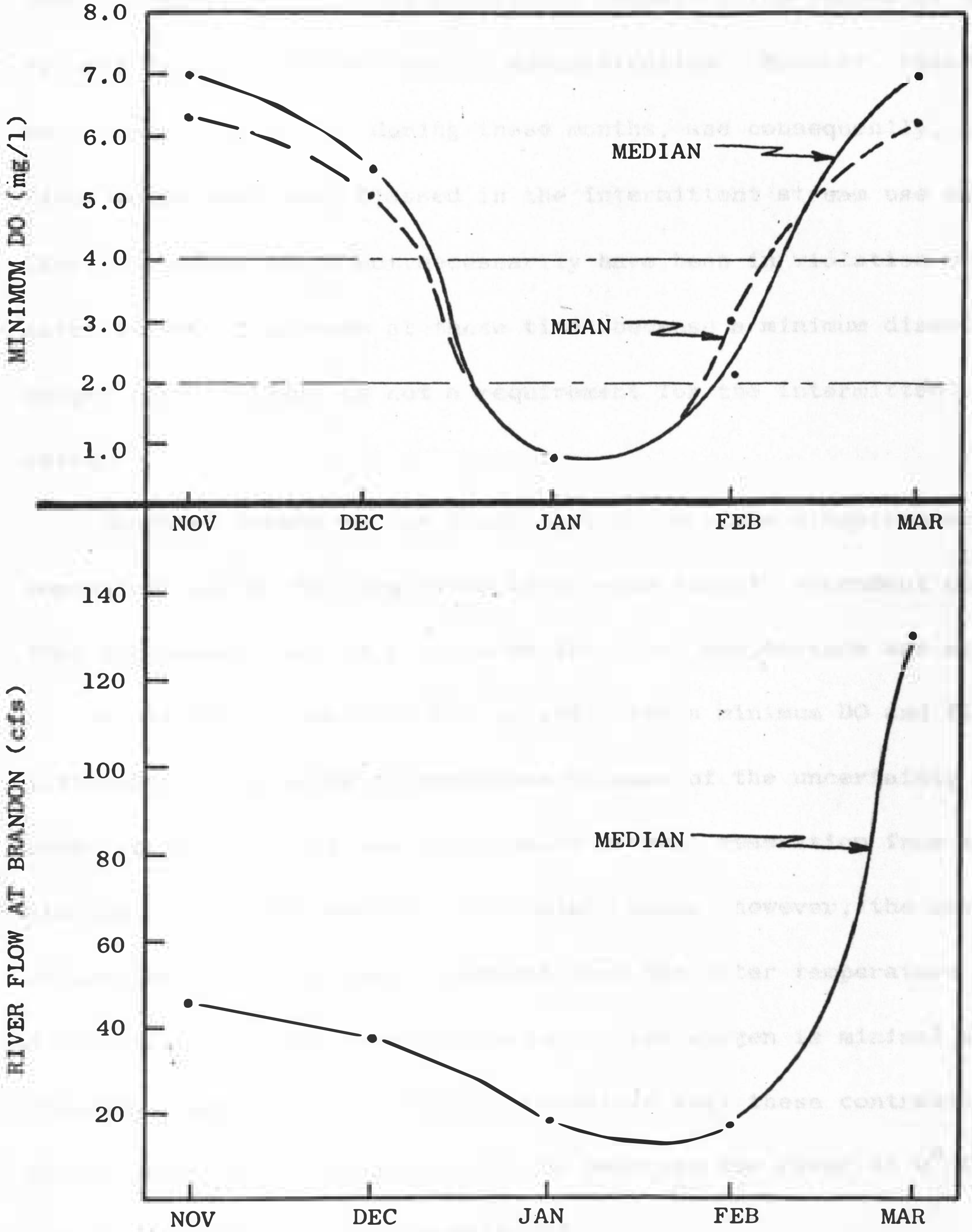

Figure 6. Big Sioux River flow and minimum dissolved oxygen concentration on sampling days during November through March (January, 1964 - March, 1969).

than 4.0 mg/l, the minimum acceptable concentration requested by the Federal Water Pollution Control Administration. However, river flows were nearly always low during these months, and consequently, the river would have been classed in the intermittent stream use category. Thus, the river would not necessarily have been in violation of the water quality standards at these times because a minimum dissolved oxygen concentration is not a requirement for the intermittent stream category.

Naughton showed in his study that the minimum dissolved oxygen concentrations of the Big Sioux River were largely dependent on river flow and temperature at times when the river temperature was above 0^o C. No attempt was made by him to establish a minimum DO and flow relationship at freezing temperatures because of the uncertainty of ice cover conditions. If ice cover would prevent reaeration from the atmosphere, low DO concentrations might occur; however, the oxygen concentration at saturation is highest when the water temperature is 0^o C, and bacterial action which tends to utilize oxygen is minimal at freezing temperatures. Naughton explained that these contrasting conditions make it nearly impossible to describe the river at 0^o C unless ice cover conditions are known(4-37).

Ice cover conditions at the various sampling stations on the Big Sioux River were recorded during the winter of 1968 by the Sioux Falls wastewater treatment plant personnel. These data, however, were insufficient to correlate ice cover with minimum DO because they represented only a single year's record. An examination of the river flow data for winter months from 1964 through 1969 revealed that generally the flows were very low, with the exception of the occurrence of a few unusually high flows. These high flows occurred in late winter and were probably the result of spring thaws. At various times throughout the winter months, abrupt increases in river flow were noted to occur from one week to the next. Usually, by the following week, the flow had decreased to approximately the discharge it was before the abrupt increase had occurred. Melting snow on the river banks and in the city of Sioux Falls could have been responsible for these abrupt increases in river flow.

The river water was probably not completely under an ice cover when flows were exceptionally high or after rapid increases in flow had occurred. If there was not a continuous ice cover, reaeration of the river from the atmosphere would have taken place and the river conditions would be comparable to those considered in the evaluation by Naughton.

In order to evaluate the river under winter conditions, the maximum river flow which would likely have been under continuous ice cover was estimated as being 75 cfs. River flows of greater than 75 cfs occurred most frequently in November and March. At other times when the flow was greater than 75 cfs, melt conditions appeared possible and the existence of an ice cover over the flow was questionable. The frequency of occurrence of minimum dissolved oxygen concentrations in various dissolved oxygen ranges at various river flows, for sampling days when the river temperature was 0^{o} C and the river flow was less than 75 cfs, is shown in Table 2.

It can be seen from Table 2 that during times of ice cover minimum DO concentrations of less than 4.0 mg/l were never observed when the river flow exceeded 40 cfs. From Table 2 it can be observed that the minimum DO was generally in a higher range when river flows were higher. The totals on the bottom of Table 2 reveal that minimum DO concentrations of less than 2.0 mg/l occurred most frequently in the months of January and February and minimum DO concentrations of greater than 4.0 mg/l were most predominate in the months of November and December.

Multiple Linear Regression to Describe Stream Conditions

In attempting to find the best way to describe the dissolved oxygen profile of the Big Sioux River below Sioux Falls, Naughton (4) subjected the available treatment plant and river flow data to a number of different evaluations. Methods used by him included those described by LeBosquet and Tsivoglou (16), Smith, Layell, and Gray (17), and Churchill and Buckingham (18). He did not attempt to use the classical Streeter-Phelps approach and its modifications because the

Table 2. Frequency of Occurrence of Minimum Dissolved Oxygen Concentrations at Various Minimum Dissolved Oxygen and River Flow Ranges in the Big Sioux River Downstream from Sioux Falls, South Dakota, During Winter Months with Ice Cover Conditions[*]

Range of River Flow at Brandon (cfs)	Range of Minimum DO Concentration (mg/l)		
	0.0 - 1.9	2.0 - 3.9	≥4.0
11 - 15	1 - Jan 3 - Feb	1 - Feb	1 - Feb
16 - 20	1 - Jan 1 - Feb 1 - Mar		
21 - 25	1 - Jan	1 - Feb 1 - Mar	
26 - 30			1 - Nov 1 - Dec
31 - 35	2 - Jan	1 - Dec	1 - Nov 1 - Dec
36 - 40		1 - Dec	1 - Nov
41 - 75			2 - Nov 4 - Dec
Total	5 - Jan 4 - Feb 1 - Mar	2 - Dec 2 - Feb 1 - Mar	5 - Nov 6 - Dec 1 - Feb

[*] Ice cover conditions were considered to occur when river temperature was 0^{o} C and river flow did not exceed 75 cfs.

data were inadequate for determining the deoxygenation and reaeration coefficients, k_1 and k_2, and the river flow time. Naughton considered the results obtained using the LeBosquet and Tsivoglou approach (16) to be insufficiently accurate because the method was recommended for rivers much larger than the Big Sioux. The method of Smith, Layell and Grey (17), which is a graphical approach, was abandoned by Naughton because he felt the inaccuracies that are inherent in a graphical solution were magnified in his case due to the small scale that was required to fit available data on a reasonably sized sheet of paper. The most successful approach attempted by Naughton was the statistical technique of multiple linear regression. This method was first used by Churchill and Buckingham (18) in a study of a river in the Tennessee Valley.

Churchill and Buckingham used the technique of multiple linear regression to relate the dissolved oxygen drop in a river to several factors which were considered to be most responsible for the drop. They related DO drop in a river polluted from a single source to river flow, temperature and BOD. The decrease in dissolved oxygen was considered to vary linearly with BOD, temperature, and a stream discharge factor. Churchill and Buckingham acknowledged that DO drop does not vary in an exact linear manner with BOD and temperature, but the deviation is so slight that the assumption of a linear relationship was felt justified. A linear relationship between DO and the reciprocal of flow was accepted because such a relationship was shown to exist by LeBosquet and Tsivoglous (16).

The basic form of the linear equation proposed by Churchill and Buckingham was as follows (18):

$$Y = a + b_1(BOD) + b_2(T) + b_3(10{,}000/Q)$$

in which

Y = dissolved oxygen drop in mg/l,

a = a constant,

b_1, b_2, b_3 = partial regression coefficients,

BOD = the biochemical oxygen demand in mg/l,

T = the temperature in ^{o}C, and

Q = the flow in cubic feet per second.

Using the available field data, the partial regression coefficients were determined by the method of least squares. The least squares method yields an equation such that the sum of the squares of the deviations of the observed values from the values computed by the equation is a minimum. The number, 10,000, was used with the flow factor to obtain numbers which would be of a convenient size to use in the analysis.

The significance of multiple linear regression equations can be determined by computing the multiple correlation coefficient. Values for the multiple correlation coefficient, denoted by _r_, may vary from 0 to 1.0 depending on the degree of linear relationship that exists between the variables. The nearer the value is to 1.0, the greater the correlation between the observed values of Y and those determined by the regression equation. The proportion of the dependent variable (Y) that is explained by the variation in the independent variables (BOD, T, Q) is given by the coefficient of determination. The coefficient of determination equals the square of the correlation coefficient and is denoted by $\underline{r}^2$. Therefore, 100 times $\underline{r}^2$ yields the percent of the total variability in Y that is attributable to variation in the independent variables (19-287).

A correlation coefficient of 0.869 was reported by Churchill and Buckingham when correlating DO drop with the independent variables of the flow, temperature, and BOD at the sampling station nearest to the bottom of the oxygen sag. This gave a value of 75.5 for 100 $\underline{r}^2$, therefore 75.5 percent of the variation in the DO drop was accounted for by the independent variables (18).

In applying the technique of multiple linear regression, Naughton (4) utilized many different parameters in an attempt to find the equation that would best define the critical dissolved oxygen conditions in the Big Sioux River below Sioux Falls. Rather than correlate the river conditions with DO drop, and then use the DO drop to determine the minimum dissolved oxygen in the river, Naughton correlated the river conditions directly with minimum DO. The highest correlation coefficient achieved (0.908) was obtained by correlating minimum dissolved oxygen concentration with BOD at the Cliff Avenue station, water temperature above 0^{o} C, and a river flow factor. The correlation coefficient of 0.908 yielded a coefficient of determination ($\underline{r}^2$) equal to 0.824. Thus, 82.4 percent of the variability of the minimum dissolved oxygen concentration was accounted for by the independent variables of temperature, flow and BOD (4).

The relationship developed by Naughton (4) was as follows:

$$\text{Minimum DO in mg/l} = 9.83 - \frac{132}{Q} - 0.248\ T - 0.016\ \text{BOD}$$

in which

Q = river flow at Brandon (cfs),

T = river temperature at Brandon (^{o}C), and

BOD = the BOD at the Cliff Avenue sampling station (mg/l).

Naughton observed that the BOD values which occurred in the river did not exhibit as much of an effect as temperature on the computed minimum DO. The relationship determined by Naughton indicates that approximately 60 mg/l of BOD are required to account for a drop of one mg/l in the minimum DO, whereas a 4^{o} C rise in temperature would account for a one mg/l DO drop. He attributed the relatively minor effect of BOD in the equation to the uniform treatment provided by the Sioux Falls wastewater treatment plant.

The equation developed by Naughton to describe the dissolved oxygen concentration in the Big Sioux River is not applicable for winter conditions because all data for those days when the river temperature was 0^{o} C were excluded in the analysis. Ice cover, which probably was prevalent at times when the river temperature was 0^{o} C, would impose unique conditions on the river and as a result dissolved oxygen concentrations would be affected differently.

Evaluation of DO Conditions in the Big Sioux River During Winter

Researchers, who have worked on the problem of stream self-purification, have recognized the existence of two opposing forces which affect oxygen balance. These two forces are deoxygenation and reaeration. Deoxygenation results primarily from the utilization of oxygen by micro-organisms in breaking down organic matter to stable, relatively harmless and odorless end products. Reaeration occurs when oxygen is absorbed from the atmosphere or released into the river waters by green plants during photosynthesis. When temperatures are such that ice forms on a river, oxygen can no longer be absorbed into the water from the atmosphere and the resulting absence of reaeration would tend to cause the dissolved oxygen concentration of a river to be depressed further by a pollutional load.

The saturation concentration of oxygen in water and the rate of bacterial action is also affected by temperature changes. Under normal atmospheric conditions, the concentration of dissolved oxygen at which pure water is saturated at 0^{o} C is 14.6 mg/l, while at 25^{o} C, saturation occurs at 8.4 mg/l (20-147). Bacterial activity decreases with temperature and thus oxygen utilization also is decreased. An increase of 10° C in the temperature between 8° C and 35° C will approximately double the bacterial activity rate (17). The high saturation level of dissolved oxygen at 0° C and the low bacterial activity rate at 0° C would tend to offset the absence of reaeration from the atmosphere under ice cover conditions.

In attempting to define the oxygen sag in the Big Sioux River below Sioux Falls during winter conditions, the technique of multiple linear regression was utilized. Minimum dissolved oxygen, rather than DO drop as used by Churchill, was considered the dependent variable in the analysis because Naughton (4) had shown very successfully that the minimum DO could be used directly in the analysis. The minimum dissolved oxygen concentration was correlated with the independent variables of river flow at Brandon and BOD at the Cliff Avenue station. The analysis was limited to the data for the months of November through March because a review of the data had revealed that river temperature of 0° C had been recorded only during these months. It was felt that these were the months when ice cover conditions could generally be expected in the Big Sioux River.

Eight different regression analyses, using data available for the months of November through March, were attempted in order to correlate minimum dissolved oxygen with river flow and BOD. The IBM 360 computer, located on the campus at South Dakota State University, was used for the computation of the regression analyses. All data used for the various analyses are presented in the Appendix.

Analyses were tried using the data when water temperatures recorded at the Brandon sampling station were 0^{o} C, less than 1^{o} C, and less than 2^{o} C. Data collected when river temperatures at Brandon were greater than 0^{o} but less than 2^{o} C were used in some of the trials because it was discerned that ice cover conditions had possibly existed downstream from the Brandon station at these times. Data for consideration were also limited to those times when the river flow was less than 75 cfs because it had been estimated that Big Sioux River flows greater than 75 cfs probably did not occur under a continuous ice cover. Various analyses were also conducted using all the data available during the months of November through March, regardless of river temperature and flow.

The limiting conditions of flow and temperature, number of sampling days, correlation coefficients, and coefficients of determination for each of the various regression analysis are presented in Table 3. It can be seen from Table 3 that the correlation coefficients, which indicate the degree of association between the dependent (minimum DO) and independent variables (flow and BOD), were greater than 0.75 for all but one trial. All of the resulting correlation coefficients were found to be statistically significant (5 percent level).

Table 3. Correlation Coefficients (r) and Coefficients of Determination (r^2) Obtained in Regression Analysis Trials for Various River Flow and Temperature Conditions (Data for January, 1964 - March, 1969)

Limiting Conditions for the Regression Analyses (November-March)		Number of Sampling Days (n)	Correlation Coefficient (r)	Coefficient of Determination (r^2)
Flow (cfs)	Temperature (°C)			
<75	0	25	.8294	.6879
all data	0	35	.8333	.6944
<75	≤ 1	36	.7842	.6150
all data	≤ 1	50	.7915	.6265
<75	≤ 2	40	.7940	.6304
all data	≤ 2	55	.8006	.6410
<75	all data	46	.7298	.5326
all data	all data	64	.8041	.6465

As can be seen from Table 3, the highest correlation coefficient (0.8333) was obtained from the regression analysis utilizing all the November through March data when the river temperature was 0^{o} C, and the second highest correlation coefficient (0.8294) was obtained using only those data when river temperature was 0^{o} C and the river flow was less than 75 cfs. Because the regression analysis giving the highest correlation had been performed using several pieces of data when flows were exceptionally high due to spring runoff and therefore may not have been indicative of winter flows occurring under an ice cover, the regression analysis giving the second highest correlation (0.8294) was used to describe the minimum DO.

The coefficient of determination $\underline{(r^2)}$ for the regression analysis selected to describe winter conditions was found to be 0.6879. Therefore, 68.79 percent of the variability of the minimum dissolved oxygen was accounted for by the independent variables of flow and BOD. Although 0.6879 is less than the coefficient of determination found by Naughton (4-43), it was considered adequate because considerably less information concerning downstream conditions was available for the winter and exact ice cover conditions were unknown. Flow records for the winter are also less reliable than those for other months (9)(10).

The mathematical expression determined by the use of multiple linear regression to describe the minimum DO concentration in the

Big Sioux River during the winter in terms of the variables of flow and BOD was as follows:

$$\text{Minimum DO in mg/l} = 8.82 - \frac{84}{Q} - .0861\ \text{BOD}$$

in which

Q = river flow at Brandon (cfs), and

BOD = the BOD at Cliff Avenue sampling station (mg/l).

The expression was applicable for those times when the river temperature was 0° C and the river flow was less than 75 cfs.

By comparing the above equation with the equation derived by Naughton (4-43), it can be seen that during ice cover conditions the BOD apparently accounts for more of the variability in the minimum dissolved oxygen concentration than when ice cover is not present. The relationship for winter conditions indicates that approximately 12 mg/l of BOD account for a depression of the minimum DO by one mg/l while Naughton's (4) equation indicated that approximately 60 mg/l of BOD are required to account for a drop of one mg/l in the minimum DO. The greater influence of BOD on the dissolved oxygen during the winter may be related to the greater variability of the treatment provided by the Sioux Falls wastewater treatment plant.

River Flow Requirements for Winter Months

Using the equation presented in the preceding section, it was possible to calculate flow which would be required to maintain specific minimum dissolved oxygen levels in the Big Sioux River for various BOD concentrations during winter conditions. The results of such calculations are shown graphically in Figure 7. Using this figure, the flows can be determined that would be required to maintain 2.0, 3.0, 4.0, and 5.0 mg/l of dissolved oxygen in the river when the BOD at the Cliff Avenue station is within the range of 10 to 60 mg/l.

It can be seen from Figure 7 that a flow of about 38 cfs would be needed at Brandon to maintain a minimum dissolved oxygen concentration of 4.0 mg/l in the Big Sioux River below Sioux Falls when the BOD at the Cliff Avenue station is 30 mg/l. The wastewater flow from the municipal treatment plant and the condenser water from John Morrell and Company the past five years has averaged approximately 19 cfs (12). Twice this flow, or about 38 cfs, would be the flow required in the Big Sioux River below Sioux Falls for the intermittent stream category not to apply. Therefore, it appears that if flows were maintained in the river such that it would not be classed in the intermittent stream category, the Federal Water Pollution Control Administration request of 4.0 mg/l of dissolved oxygen could be met during the winter months, provided the BOD concentration at the Cliff Avenue station does not exceed 30 mg/l.

The Federal Water Pollution Control Administration (FWPCA) has computed the necessary flow to maintain the desired 4.0 mg/l of dissolved oxygen concentration below Sioux Falls. A river basin model

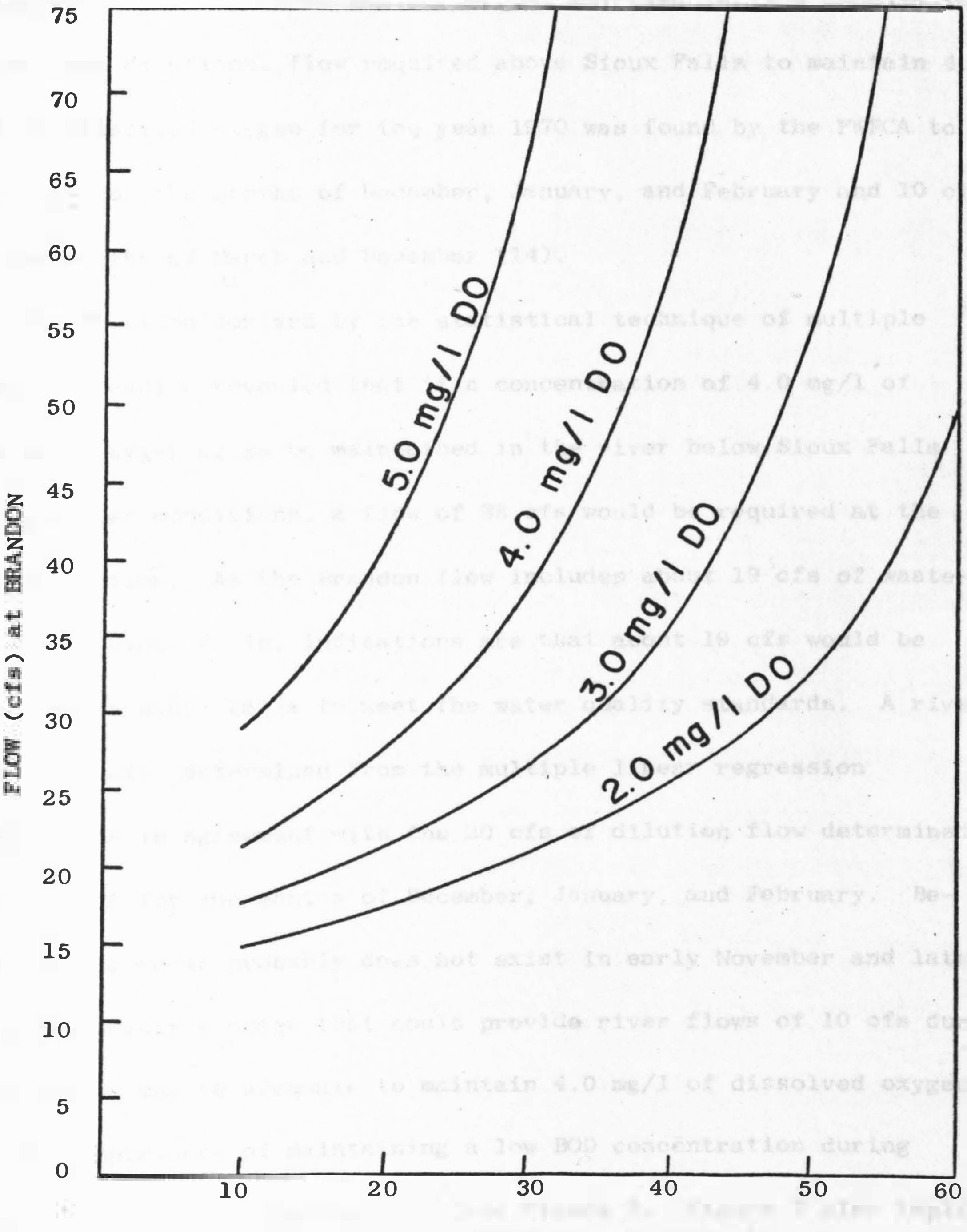

Figure 7. Flow required to maintain minimum DO concentrations of 2.0, 3.0, 4.0, and 5.0 mg/l in the Big Sioux River below Sioux Falls for various BOD concentrations at the Cliff Avenue station during winter conditions.

developed by the Northwest Region, FWPCA, was used for the computation. The minimum dilutional flow required above Sioux Falls to maintain 4.0 mg/l of dissolved oxygen for the year 1970 was found by the FWPCA to be 20 cfs for the months of December, January, and February and 10 cfs for the months of March and November (14).

The equation derived by the statistical technique of multiple linear regression revealed that if a concentration of 4.0 mg/l of dissolved oxygen is to be maintained in the river below Sioux Falls during winter conditions, a flow of 38 cfs would be required at the Brandon station. As the Brandon flow includes about 19 cfs of wastewater from Sioux Falls, indications are that about 19 cfs would be needed above Sioux Falls to meet the water quality standards. A river flow of 19 cfs, determined from the multiple linear regression equation, is in agreement with the 20 cfs of dilution flow determined by the FWPCA for the months of December, January, and February. Because an ice cover probably does not exist in early November and late March, reservoir-storage that could provide river flows of 10 cfs during these months may be adequate to maintain 4.0 mg/l of dissolved oxygen.

The importance of maintaining a low BOD concentration during winter conditions becomes obvious from Figure 7. Figure 7 also implies that the maintenance of a dissolved oxygen concentration greater than 4.0 mg/l would require exceptionally high winter flows even when low BOD is maintained. The winter flows required at Sioux Falls to maintain 5.0 mg/l of DO would be more than 65 cfs if the Cliff BOD was 30 mg/l. Thus, considerably greater volumes of storage would be required in the reservoirs for water quality control purposes.

SUMMARY AND CONCLUSIONS

The objective of this study was to examine the water quality of the Big Sioux River downstream from Sioux Falls, South Dakota, during winter conditions. Particular emphasis was given to evaluating the effect that river flow and BOD had on dissolved oxygen concentrations when conditions of ice cover were prevalent.

Water quality data collected for the Big Sioux River downstream from Sioux Falls were subjected to the statistical technique of multiple linear regression. This technique of analysis was chosen because it had given good results in an earlier study by Naughton which evaluated the river during conditions other than winter. The regression analysis revealed that almost 70 percent of the variability of the minimum dissolved oxygen concentrations in the river during the winter was accounted for by the variations of river flow and BOD.

The mathematical expression that resulted from the regression analysis was applicable for those conditions when the river temperature was 0^{o} C and the flow was less than 75 cfs as recorded at Brandon. The expression determined was as follows:

$$\text{Minimum DO in mg/l} = 8.82 - \frac{84}{Q} - .0861\ \text{BOD}$$

in which

Q = river flow at Brandon (cfs), and

BOD = the biochemical oxygen demand at the Cliff station (mg/l).

Based upon the above relationship and other results of this investigation, the following conclusions seem to be justified:

1. River temperatures of 0^{o} C have frequently been recorded at the Brandon station during the months of November, December, January, and February. The median temperature of the river at Brandon was less than 1^{o} C from the later part of November through the middle of March for those occasions for which samples were collected during the period from June, 1961, to July, 1969.

2. Low effluent BOD concentrations have been achieved by the Sioux Falls wastewater treatment plant during the summer, whereas, substantially high BOD concentrations have occurred in the winter months. In recent years, the BOD limit of 30 mg/l, considered the maximum concentration for discharge to an intermittent stream, was exceeded 8 percent of the time during summer months and 45 percent of the time during winter months.

3. The minimum dissolved oxygen concentration downstream from Sioux Falls during the months of January and February has generally been less than 4.0 mg/l, the minimum acceptable concentration that the Federal Water Pollution Control Administration has requested. However; flows were nearly always low during this period and consequently the river would have been classed in the intermittent stream category. At these times, the minimum dissolved oxygen concentrations of the river would not necessarily have violated the water quality standards

because a minimum dissolved oxygen concentration is not a requirement for the intermittent stream category.

4. During winter months, the Big Sioux River in the Brandon area has probably been influenced by surface runoff at times when flows exceeded 75 cfs and as a result complete ice cover conditions may not have occurred.

5. Using multiple linear regression, the variation in the minimum dissolved oxygen concentration was shown to be largely accounted for by the variables of river flow and BOD when the river at Brandon had a temperature of 0° C and a flow of less than 75 cfs.

6. If dilution water would be made available from the proposed Flandreau and Skunk Creek reservoirs in quantities as suggested by the Federal Water Pollution Control Administration (14), the requested 4.0 mg/l of DO could be maintained in the river during ice cover conditions, providing wastewater treatment could maintain BOD concentrations below 30 mg/l.

RECOMMENDATIONS

Based on this investigation of the water quality of the Big Sioux River downstream from Sioux Falls, South Dakota, during winter conditions, the following recommendations are made:

1. Ice cover conditions should be recorded throughout the winter at all of the sampling stations to facilitate a more complete evaluation of the quality data collected for the river during winter conditions.
2. A study should be conducted to examine the influence which wastewater discharged at Sioux Falls has on the temperature of the Big Sioux River during those months when there is no ice cover.
3. An investigation should be made to determine how the Sioux Falls wastewater treatment plant might economically upgrade its treatment during the winter months.

LITERATURE CITED

1. Federal Water Pollution Act (Public Law 84-660, As Amended, 1961, 1965, 1966), United States Department of the Interior, Federal Water Pollution Control Administration, United States Government Printing Office, 0-243-126 (1967).

2. Herreid, John M., Appraisal of Water Quality Standards for the Big Sioux River Downstream from Sioux Falls, South Dakota, Master of Science Thesis, South Dakota State University, Brookings, South Dakota (1968).

3. Water Quality Standards for the Surface Waters of South Dakota, South Dakota Committee on Water Pollution, Pierre, South Dakota, Addendum No. 1 (1967).

4. Naughton, Daniel J., Relationship of Dissolved Oxygen Concentration with Flow, Temperature, and BOD for the Big Sioux River Downstream from Sioux Falls, South Dakota, Master of Science Thesis, South Dakota State University, Brookings, South Dakota (1968).

5. Rakness, Kerwin L., Analysis of the Flow Variation of the Big Sioux River, Master of Science Thesis, South Dakota State University, Brookings, South Dakota (1970).

6. Report on Big Sioux Basin and Missouri Terrace Area, United States Department of the Interior, Bureau of Reclamation. Region 6, Huron, South Dakota (1968).

7. Big Sioux River Basin Study Information Bulletin, United States Army Corps of Engineers, Omaha, Nebraska, Bulletin distributed at the Corps of Engineers hearing, Sioux Falls, South Dakota (May 28, 1969).

8. McKenzie III, Colonel William H., Water Resources Development in Eastern South Dakota, United States Army Corps of Engineers, Omaha, Nebraska, Paper presented to the Northeastern Chapter of the South Dakota Engineering Society (April 22, 1969).

9. Water Resources Data for North Dakota and South Dakota, United States Geological Survey, United States Department of the Interior (1964-65).

10. Water Resources Data for South Dakota, United States Geological Survey, United States Department of the Interior (1966-68).

11. Unpublished Water Supply Data, United States Geological Survey, United States Department of Interior (1968-69).

12. Unpublished Annual Operating Data of Sioux Falls Wastewater Treatment Plant, City of Sioux Falls, South Dakota (1964-69).

13. Hydrologic Atlas of East Dakota Conservancy Sub-District, East Dakota Conservancy Sub-District, Brookings, South Dakota, Appendix A (1969).

14. Water Quality Control Study Big Sioux River Basin Iowa, Minnesota, and South Dakota, United States Department of Interior, Federal Water Pollution Control Administration, Missouri Basin Region, Kansas City, Missouri (1969).

15. Sioux Falls, South Dakota, Report on Sewerage and Waste Treatment, Greeley and Hansen, Engineers, Chicago, Illinois (1965).

16. LeBosquet, M., and Tsivoglou, E. C., "Simplified Dissolved Oxygen Computation," Sewage and Industrial Wastes, 22 No. 8, 1054-1061 (1950)

17. Smith, Arthur, Layel, Joe, and Grey, John, "How to Predict Downstream DO Drop," Wastes Engineering, 33, No. 9, 456-458 (1962).

18. Churchill, M. A., and Buckingham, R. A., "Statistical Method for Analysis of Stream Purification Capacity," Sewage and Industrial Wastes, 28, No. 4, 517-537 (1956).

19. Steel, Robert G. D., and Torrie, James H., Principles and Procedures of Statistics, McGray-Hill Book Company, Inc., New York, New York (1960).

20. Phelps, Earle B., Stream Sanitation, John Wiley and Sons Inc., New York, New York (1954).

APPENDIX

APPENDIX

All Data Available for the Sampling Days During November Through March, Big Sioux River Below Sioux Falls, South Dakota

Data	River Temperature at Brandon Station °C	River Flow at Brandon Station cfs	BOD at Cliff Station mg/l	Minimum Dissolved Oxygen mg/l
2-05-64	0.9	28	20.5	2.3
2-19-64	0.2	31	30.4	4.8
2-26-64	0.2	29	19.0	4.4
3-04-64	0.3	33	7.2	4.7
3-11-64	3.9	52	15.0	5.5
3-25-64	4.5	130	18.4	9.3
1-20-65*	0.0	18	34.0	0.0
1-27-65*	0.0	14	38.0	0.7
2-17-65*	0.0	12	61.0	0.0
3-04-65*	0.0	18	33.0	0.4
3-10-65*	0.0	25	55.0	1.2
3-17-65	0.0	350	24.5	6.5
3-24-65	0.5	80	21.0	0.1
3-31-65	0.0	200	22.5	7.0
11-10-65	4.0	94	12.0	6.9
11-17-65*	0.0	67	19.5	8.4
11-24-65	2.0	102	10.5	7.5
12-01-65*	0.0	73	15.5	8.0
12-08-65*	0.0	71	14.0	8.5
12-15-65*	0.0	47	36.0	9.1
2-16-66	0.0	250	13.5	11.6
2-23-66	0.0	130	7.5	8.1
3-02-66	0.5	130	6.0	7.4
3-09-66	0.0	348	6.0	9.6
3-16-66	0.0	3,070	14.5	10.7
3-30-66	5.5	516	5.0	8.7
11-02-66*	0.0	63	11.2	8.5
11-09-66*	0.0	28	12.8	6.8
11-16-66	1.0	54	8.8	7.5
11-23-66	2.0	60	8.4	6.8
12-07-66*	0.0	33	19.2	5.6
12-14-66*	0.0	33	20.0	2.3
12-21-66*	0.0	40	21.0	3.1
12-28-66*	0.0	26	26.5	5.8

APPENDIX (continued)

Date	River Temperature at Brandon Station °C	River Flow at Brandon Station cfs	BOD at Cliff Station mg/l	Minimum Dissolved Oxygen mg/l
1-11-67*	0.0	34	29.0	1.1
1-25-67*	0.0	23	36.0	1.4
2-01-67*	0.0	23	33.0	2.1
2-08-67*	0.0	13	25.0	2.2
2-15-67*	0.0	15	30.0	4.2
2-22-67*	0.0	14	30.4	1.9
3-01-67	0.0	300	38.0	4.8
3-08-67	0.0	350	22.0	8.0
3-15-67	0.0	450	10.5	10.3
3-22-67	1.0	321	4.4	10.1
3-29-67	8.5	579	9.2	8.7
11-01-67	4.5	32	23.2	1.2
11-15-67	0.5	32	25.6	2.0
11-22-67	2.5	34	20.5	3.7
11-29-67	0.5	31	16.0	3.9
12-06-67	1.0	24	31.0	1.5
12-13-67	0.5	26	23.5	2.2
1-24-68	2.0	18	36.0	0.0
1-31-68	0.5	14	28.0	0.9
2-07-68	5.0	12	20.0	0.8
2-14-68	0.5	13	17.0	2.1
2-21-68	0.5	17	23.0	0.0
2-28-68*	0.0	12	44.0	0.3
3-13-68	1.5	36	20.0	6.9
3-27-68	9.5	70	17.0	4.1
11-13-68	0.0	102	6.4	10.0
11-20-68*	0.0	36	24.0	7.2
12-04-68	1.5	68	6.4	6.5
1-08-69*	0.0	34	20.0	0.7
2-12-69*	0.0	17	28.0	1.4

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* Data utilized in the regression analysis selected to describe minimum dissolved oxygen concentrations during winter conditions (occasions when the river temperature was 0° C and the river flow was less than 75 cfs).