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A rapid expansion of population and industrialization in recent years has created new and difficult problems in water resources management. Prudent management of water quality will require that more efficient methods be developed for evaluating large volumes of data on complex river systems, and tabulating the results in a form readily usable by the persons responsible for decisions. The digital computer is the most promising tool for rapid analysis of these complex water problems. The objective of this thesis is the development of a digital computer program which will investigate the dissolved oxygen relationships in flowing streams and provide for automatic adjustment of flows to maintain minimum dissolved oxygen requirements.

The computer program herein developed was applied to the Willamette River Basin in Northwestern Oregon to illustrate its use, but it is general in character so that it may be applied to any drainage basin. Three orders of streams including not more than sixty lengths of river (reaches) may be considered in any given study by a computer with sixty thousand digits of core storage. Limitations on the size of the river system which may be considered are imposed by computer

storage capacity above the forty thousand digits needed for program use.

The results of this study indicate that:

1. A digital computer using the program developed can, in a few minutes, complete an analysis which would require many man hours of manual computation time.

2. The digital computer program developed is a useful tool for investigating the oxygen relationships existing in a river system under present loadings and flows and for predicting the conditions that will be encountered under future loadings.

3. A computer program of this type could be adapted to nearly any of the quality parameters normally considered or possibly a combination of several parameters at such time as mathematical formulations describing their behavior in streams are available.

A SYSTEM ANALYSIS METHOD FOR WATER QUALITY MANAGEMENT BY FLOW AUGMENTATION

by

JOHN LARRY WORLEY

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INTRODUCTION

The rapid expansion of population and industrialization since World War II has resulted in increasingly difficult problems of water resources management. The most critical of these is the protection of our water resources from the ravages of pollution by the discharge of wastes which are increasing both in volume and complexity. Concomitant with the water pollution problem is the rapid development in demand for fresh water. Authorities (16) estimate that the rate of use of fresh water will exceed the estimated dependable supply by the year 1970. While an average of 4,300 billion gallons of rain falls each day on the United States, only a small portion of this is available for use after evaporation and transpiration losses take place. It has been estimated (16) that as increasing amounts of flood waters are stored by the creation of impoundments, the supply can be increased to an average of 515 billion gallons per day if present growth rates of water demand continue. Table 1 gives the use rate of fresh water versus the estimated dependable supply for the years 1900 through 1980 in billions of gallons per day. The availability of dependable supply is based upon present water use practices.

TABLE 1

Year	1900	1920	1940	1950	1960	1970	1980
Rate of Use	40.0	91.6	136.4	202.7	322.9	411.2	597.1
Dependable Supply	95.0	125.0	245.0	270.0	315.0	395.0	515.0

While average figures of this nature are informative as to the total national water problem and indicate that severe water crises lie ahead, such data do not give an indication of the usefulness of water, since this can only be judged by having enough water at the right place at the right time.

Many multi-purpose reservoirs have been constructed for the purpose of managing all phases of the water needs. These include flood control, low flow augmentation for pollution abatement and navigation improvement, power production, recreation, irrigation, and fisheries development. Development for multi-purpose uses has been more common in the Pacific Northwest than in other portions of the country.

The philosophy governing the development of multi-purpose reservoirs has previously been based primarily upon quantity factors that set requirements for necessary water volume. In recent years the importance of managing water resource systems to control quality factors throughout the full length of the region's streams has been recognized as an essential part of wise water resources utilization.

Water quality management must rely primarily upon:

1. The control of pollution by adequate and proper treatment of domestic and industrial wastes.

2. Dilution of treated waste effluents with adequate flows in the receiving streams.

3. Practices which minimize water pollution problems resulting from agricultural and watershed drainage areas.

Future scientific discoveries may make it possible to completely treat wastes, thereby restoring the water to its original degree of purity. However, technology of waste treatment and construction of waste treatment facilities has lagged behind the pollution problem, and it is not now economically feasible to remove all contaminants from water so that it can be returned to the stream in its original condition. While removal of 85 to 90 percent of the organic pollutants and removal of similar percentages of other contaminants from water is possible by modern-day methods, the resulting waste effluents from such treatment processes still contain significant pollutional loads. As population has increased, the volume of these pollutional loads of treated waste effluents has become sufficiently large to require further methods of treatment for water quality control. This has given rise to the use of low flow augmentation to control stream quality by diluting pollutants with water released from storage in reservoir systems.

Recognizing the importance of low flow regulation of streams, the 1961 Congress amended the Water Pollution Control Act (15, Sec. 2) to provide that:

1. The U. S. Army Corps of Engineers, Bureau of Reclamation, or other federal agencies involved in the survey and planning of any reservoir shall give consideration to the inclusion of storage for the purpose of water quality control by regulation of stream flow.
2. Any such storage and water releases shall not be provided

as a substitute for adequate treatment or other methods of controlling wastes at their source.

3. The Secretary of Health, Education, and Welfare shall provide to other agencies advice on:

    a) the need for storage for purposes of water quality control.

    b) the value of storage for water quality control.

4. The views of the Secretary of Health, Education, and Welfare shall be set forth in any report or presentation to the Congress by the concerned agencies proposing authorization or construction of any reservoir, including storage for water quality control purposes.

5. The value of storage for water quality control shall be taken into account in determining the economic value of the entire project of which it is a part.

6. The cost to be allocated for the purpose of water quality control should be appraised in a manner which would insure that all project objectives share equitably in the benefits of multi-purpose construction.

7. Costs of water quality control features incorporated in any federal reservoir or other impoundments under the provisions of the Federal Water Pollution Control Act shall:

    a) be determined,

    b) the beneficiaries identified, and

c) if the benefits are widespread or national in scope, the cost of such features shall be non-reimburseable.

In enacting this legislation, the Congress has specifically charged the U. S. Public Health Service with determining water supply and pollution abatement needs and has further provided that close cooperation shall exist between all water management agencies to insure maximum water utilization.

The methods for making such water quality studies have been only partially developed. This thesis concerns itself with analysis of dissolved oxygen as a quality parameter, since methods for making such an analysis have been well defined by previous investigators (13, p. 18). However, in terms of judging quality, all such parameters should be identified.

Unfortunately, dependable methods for predicting variations in many quality parameters do not exist, and detailed studies considering the variation of these qualities must await suitable mathematical formulation of their behavior in streams.

OBJECTIVE AND SCOPE

To be meaningful, a method for determination and management of water must:

1. Be broad in scope and provide for analysis and management of the entire river system as a unit.
2. Be capable of projection over the economic life of the

structures involved.

3. Be able to treat complex systems in a rapid and repetitive manner, making possible studies of a large variety of possible water use plans and pollutional situations in order to provide data for management decisions aimed toward the best possible development.

When applied to complex systems, existing methods of analysis for dissolved oxygen resources versus pollutional loads are so laborious and time-consuming that they prohibit extensive studies. The objective of this thesis was established with the above criteria in mind and is stated as follows:

Development of a digital computer program for the analysis of the oxygen resources of a complex river system for a variety of stream flows and pollution loadings, such loadings to represent various stages of economic development anticipated in a river basin and stream flows to be those which can be achieved by low flow augmentation through the development of multi-purpose reservoirs.

Pollution loadings are assumed to be those reaching the stream after the wastes have received maximum treatment according to the best technology available at the time. The relation of maximum untreated pollution load versus treatment required can, therefore, be determined and will establish waste treatment requirements and influence water resource development of river basins. A general approach to this problem was used so that the program can be applied to any drainage basin. Further, the program has been prepared in such a fashion that only its central core need be changed to consider other quality parameters at some future date when the relationships of their behavior in streams are known and suitable mathematical functions are available to describe such behavior.

A detailed description of the program that has been developed and its application to a river basin is discussed in later sections of this thesis. A general description of the calculations performed by the program may be briefly summarized as follows:

1. Input data on stream flow, waste loadings, reaction coefficients and other basic stream data are loaded into the computer which
2. Determines the pollutional situation that will result from the above conditions in terms of dissolved oxygen and
3. Decides whether additional flow is necessary to maintain satisfactory conditions.
4. If flow augmentation is necessary, the computer searches for and adds necessary stream flow, if available, and resolves the entire upstream river system for the new flow conditions.
5. If no extra flow is available, or if none is necessary, the computer continues on to the next downstream section until the study is concluded.
6. Suitable print out of information is provided at the completion of calculations for each river section and at the end of the study.

A complex river basin similar to the Willamette River may contain fifty or more lengths or stretches of river called "reaches" which must be analyzed individually, but are mutually dependent. Since they are mutually dependent, an entire new analysis is necessary when flow and/or waste loading changes are made. A large number of iterations or cycles are therefore necessary for the completed analysis and many man hours of hand calculations would be required. On preliminary or test "runs," an IBM 1620 computer using this program provided the same analysis in a few minutes.

Other digital computer programs proposed for solution of problems of this type are confined to single solution of the oxygen sag equations (4, p. 5-15)(7, p. 3-11). The program presented here has the ability to consider a complete river system, determine flows required to maintain minimum dissolved oxygen concentration, and automatically adjust flows to the required level if storage is available.

Analog computers (6, p. 31-59) have also been adapted to solution of the dissolved oxygen sag equations. However, this type of computer is limited to single solution of a fixed problem and does not provide for automatic flow adjustment.

DISSOLVED OXYGEN RELATIONSHIPS IN STREAMS

The concentration of dissolved oxygen present in a stream is controlled by two opposing reactions. The biochemical utilization of oxygen during degradation of wastes results in a decrease in oxygen concentration and is called deoxygenation. Replenishment of the oxygen is termed reaeration, and is accomplished either through absorption of atmospheric oxygen or photosynthesis. This latter process is not considered in the following developments.

Deoxygenation

The dissolved oxygen content of a stream is intimately related to the biochemical changes which are occurring in the stream (13, p. 5). Deoxygenation has been described by H. W. Streeter and E. B. Phelps as a first order reaction wherein the rate of oxygen utilization is a function of the oxidizable organic matter present. The basic reaction is described in differential form by

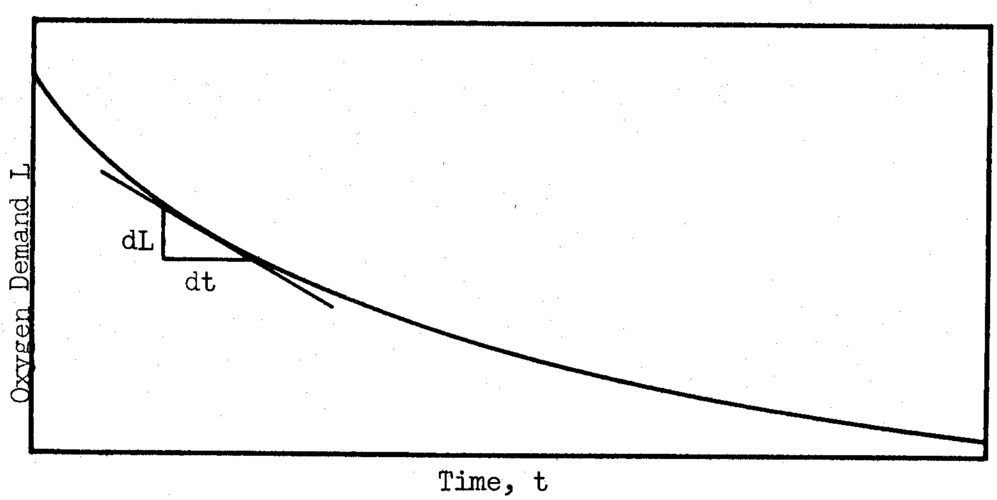


Figure 1. Curve showing relationship of oxygen demand and time.

$$-\,dL/dt = K_1 L \qquad \text{Eq. 1}$$

wherein L is the oxidizable matter present and K_1 is a reaction rate coefficient having the units of 1/days. Time, t, is measured in days. The reaction rate constant is designated K_1 to differentiate it from the reaeration coefficient described in a later section.

The above equation describes the utilization rate of organic matter which, in turn, is measured by its oxygen consuming capacity. The rate of utilization, dL, is therefore equal to the rate of dissolved oxygen utilization, d(DO)/dt, and

$$- dL/dt = d(DO)/dt = K_1L \qquad \text{Eq. 2}$$

Integration of this equation between appropriate limits yields the following useful equations:

$$\mathrm{Log}(L_a/L_b) = K_1t \qquad \text{Eq. 3}$$

$$L_b = L_a e^{-K_1 t} \qquad \text{Eq. 4}$$

Wherein:

L_a is initial oxidizable organic matter, referred to as initial BOD.

L_b is oxidizable organic matter remaining, referred to as BOD remaining.

e is the base of natural or Naperian logarithms = 2.71828.

K_1 is the coefficient defining the rate of deoxygenation.

t is elapsed time, in days.

The reaction coefficient, K_1, is dependent on the character of the organic substance involved. It has been found that wastes of similar character exhibit similar values of K_1. However, the reaction coefficient can vary widely and knowledge of its value is necessary in application of the equations.

Temperature also influences K_1 to a significant degree. In the range of temperature normally found in domestic and industrial wastes, an increase in temperature would result in an increase in K_1. This relationship has been empirically described by Streeter and Phelps (13, p. 7-8) as follows:

$$K_{1_{(T^\circ)}} = K_{1_{(20^\circ)}} \; 1.047^{(T-20)} \qquad \text{Eq. 5}$$

Reaeration

The amount of atmospheric oxygen that can be dissolved in water is a function of temperature, partial pressure of oxygen in the atmosphere, and salt concentration of the water. Water is said to be saturated when it has absorbed all of the oxygen that can be dissolved in it. The saturation values at various temperatures for chloride free water at one atmosphere of pressure are given in Table 2, (1, p. 312).

TABLE 2

SOLUBILITY OF OXYGEN IN WATER EXPOSED TO WATER-SATURATED AIR*

Temp. °C.	Dissolved Oxygen mg/l	Temp. °C.	Dissolved Oxygen mg/l
0	14.6	13	10.6
1	14.2	14	10.4
2	13.8	15	10.2
3	13.5	16	10.0
4	13.1	17	9.7
5	12.8	18	9.5
6	12.5	19	9.4
7	12.2	20	9.2
8	11.9	21	9.0
9	11.6	22	8.8
10	11.3	23	8.7
11	11.1	24	8.5
12	10.8	25	8.4

*At a total pressure of 760 mm Hg. Under any other barometric pressure, **P** (mm; or **P'**, in.), the solubility, S' (mg/l), can be obtained from the corresponding value in the table by the equation:

$$S' = S \frac{P - p}{760 - p}$$

in which S is the solubility at 760 mm (29.92 in.) and p is the pressure (mm) of saturated water vapor at the temperature of the water. For elevations less than 3,000 feet and temperatures below 25° C., p can be ignored. The equation then becomes:

$$S' = S \frac{P}{760} = S \frac{P}{29.92}$$

Dry air is assumed to contain 20.90 percent oxygen.

Where pollution is present, the draft imposed on the oxygen supply by progressive satisfaction of the oxygen demand reduces the oxygen concentration to something less than saturation. When this occurs, the oxygen content is depressed below saturation, and absorption of oxygen from the atmosphere takes place. The rate of reaeration is directly proportional to the saturation deficit, or the amount that the dissolved oxygen content is depressed below saturation. (13, p. 15) The rate at which absorption takes place is defined by the reaeration coefficient, K_2. If K_2 is expressed in terms of saturation deficit, it can be written in differential form as follows:

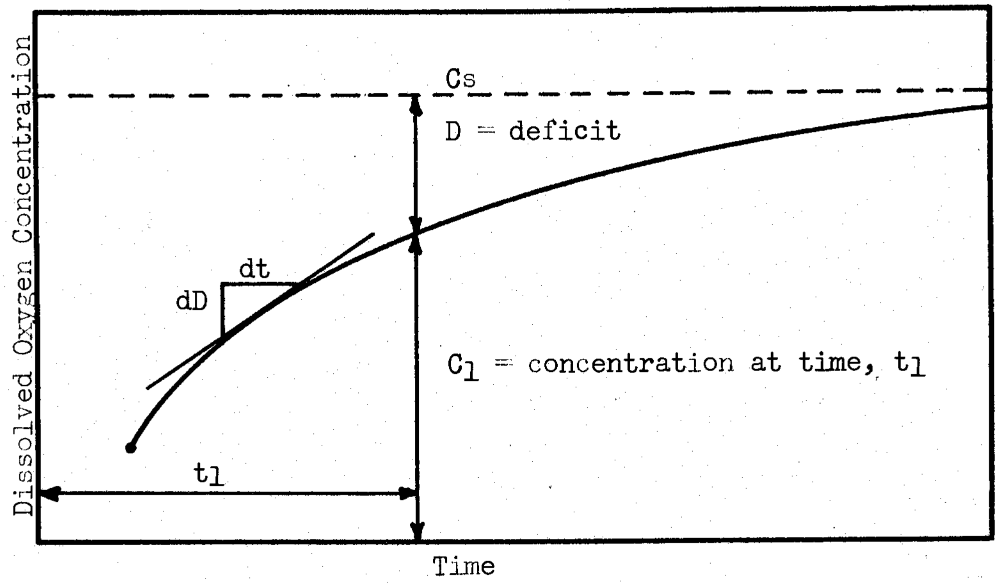


Figure 2. Plot showing relationship of reaeration rate curve and time of flow.

$$D = C_s - C \qquad \text{Eq. 6}$$

$$dD/dt = -K_2D \qquad \text{Eq. 7}$$

Wherein:

C = dissolved oxygen concentration at any time, "t"
C_s = dissolved oxygen concentration at saturation
t is time of reaction in days
D is oxygen saturation deficit of the water
dD/dt is the rate of reaeration, in terms of oxygen saturation deficit
K_2 is a coefficient defining the rate of reaeration

The above equation describes gross effects and must be examined more thoroughly to study the significance of K_2.

Fick's (8, p. 55) diffusion equation has been derived on film theory and concentration gradient considerations and is expressed as:

$$\frac{\partial C}{\partial t} = D_m \frac{\partial^2 C}{\partial x^2} \qquad \text{Eq. 8}$$

Where:

Dm denotes molecular diffusivity (L^2/T)
C denotes concentration of the gas
t denotes time
x denotes distance in the liquid phase.

Examination of this equation indicates that the rate at which a gas diffuses is controlled by both the air-liquid film phase and the concentration gradient in the liquid phase. Diffusion under quiescent conditions is so slow as to be negligible as a source of oxygen in a pollutional situation. Stream turbulence, which greatly increases the concentration gradient in the surface film and mechanically carries water from the surface to a depth, is of major significance in oxygen transfer.

Several methods which consider both turbulence and depth factors have been suggested for estimating a gross value for K_2. For the work of this thesis, the method proposed by D. J. O'Connor (10, p. 35-36) has been selected. This choice is arbitrary as other methods of determining K_2 could have been used with comparable success.

There are two forms of O'Connor's equation and are as follows:

$$k_2 = 480 \frac{D_L^{1/2} S^{1/4}}{H^{5/4}} \qquad \text{Eq. 9}$$

$$k_2 = \frac{(D_L U)^{1/2}}{2.31H^{3/2}} \qquad \text{Eq. 10}$$

Where:

k_2 is to base 10
D_L = coefficient of diffusion of oxygen in water in square feet/day
U = velocity of forward flow in feet per day
H = depth of flow in feet
S = slope of channel in feet per foot
480 incorporates the necessary dimensions and constants

Equation 9 is for use on relatively shallow streams with non-isotropic flow, and equation 10 is for relatively deep streams with flow characteristics which approach isotropic (the same in all directions) conditions.

There is some question as to what constitutes a deep stream or a shallow stream. Dr. O'Connor (9, p. 17)(10, p. 36) has used the Chezy coefficient, C, as a criterion to differentiate between shallow and deep streams and suggests a C of 17 as the dividing line between isotropic and non-isotropic flow. A sharp line of demarcation does not exist, but rather a gradual transition, probably defined by a range of C from 14 to 20.

Basic Hydrologic and Physical Data Required

The Willamette River basin has been used as the river system for development of the oxygen sag program dealt with in this thesis. This selection was made because data on waste loadings and hydrologic data needed for evaluation of parameters such as K_2 are relatively abundant. To determine K_2, river cross-section data for three stages of measured flow were obtained from the U. S. Army Corps of Engineers and used to calculate average depths and velocities for the main stem of the Willamette. The average depth was taken to be cross-sectional area divided by surface width, and the average velocity was obtained by dividing the measured flow in cubic feet per second by cross-sectional area. When specific data were unavailable, slopes were obtained from United States Geological Survey river profile sheets or contour maps and depths were estimated to allow calculation of a value for K_2. Values of the diffusion coefficient, D_L, were obtained from two sources (5, p. 446)(12, p. 174) and an average value of 1.70×10^{-3} ft^2/day was used.

These values were used in O'Connor's equations to evaluate K_2 for each reach in the river system. An equation developed by Churchill, et al, (3, p. 34) was also used to calculate a k_2 for each reach. This equation is stated as follows:

$$k_{2_{(20°)}} = 5.026V^{0.969}R^{-1.673} \qquad \text{Eq. 11}$$

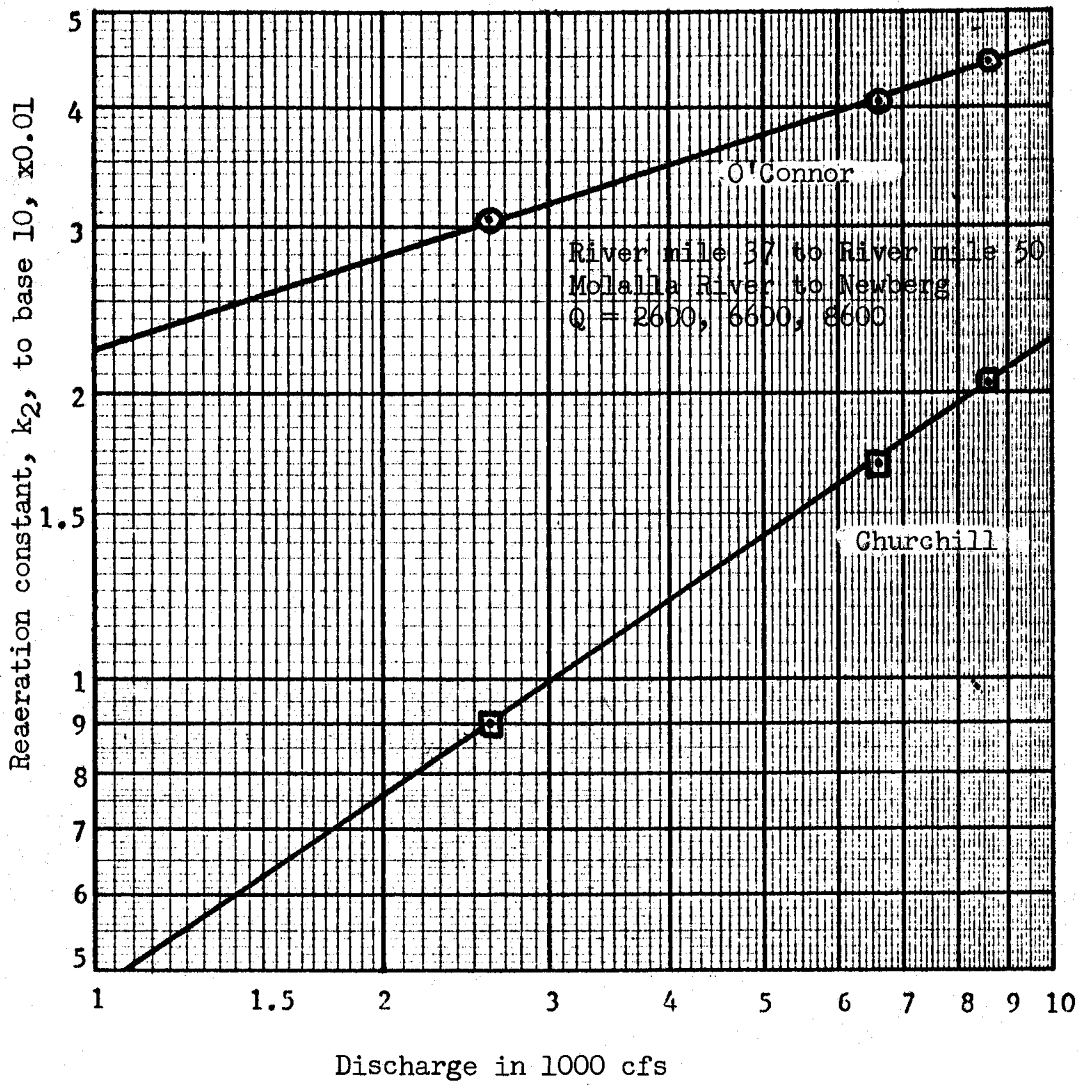
where V is mean velocity in feet per second and R is mean depth in feet. When k_2 had been computed for each reach by both methods and for three stages of flow, plots of k_2 versus flow were made on log-log paper (see Appendix) and yielded the relationship shown in Figure 3. Since k_2 will vary with flow, an equation to describe this relationship was necessary for use in the computer program to recalculate k_2 when changes in flow occur. It was found that an equation of the form

$$k_2 = aQ^b \qquad \text{Eq. 12}$$

could be written from the straight line relation obtained on log-log paper. If "a" and "b" are determined for each reach, then Q is the only variable required to evaluate k_2 in this program. No extensive work has been done to verify the relationship used above, but it was reasoned that so long as a river remains within its natural banks, such a relationship would be sufficiently valid for practical use. This latter condition will always be satisfied during low flow-critical dissolved oxygen periods.

An equation of the same form was developed to relate velocity of forward flow to flow. This equation was also developed from log-log plots (see Appendix), and is written as

$$V = cQ^d \qquad \text{Eq. 13}$$



$$b = 120/376 = 0.319$$

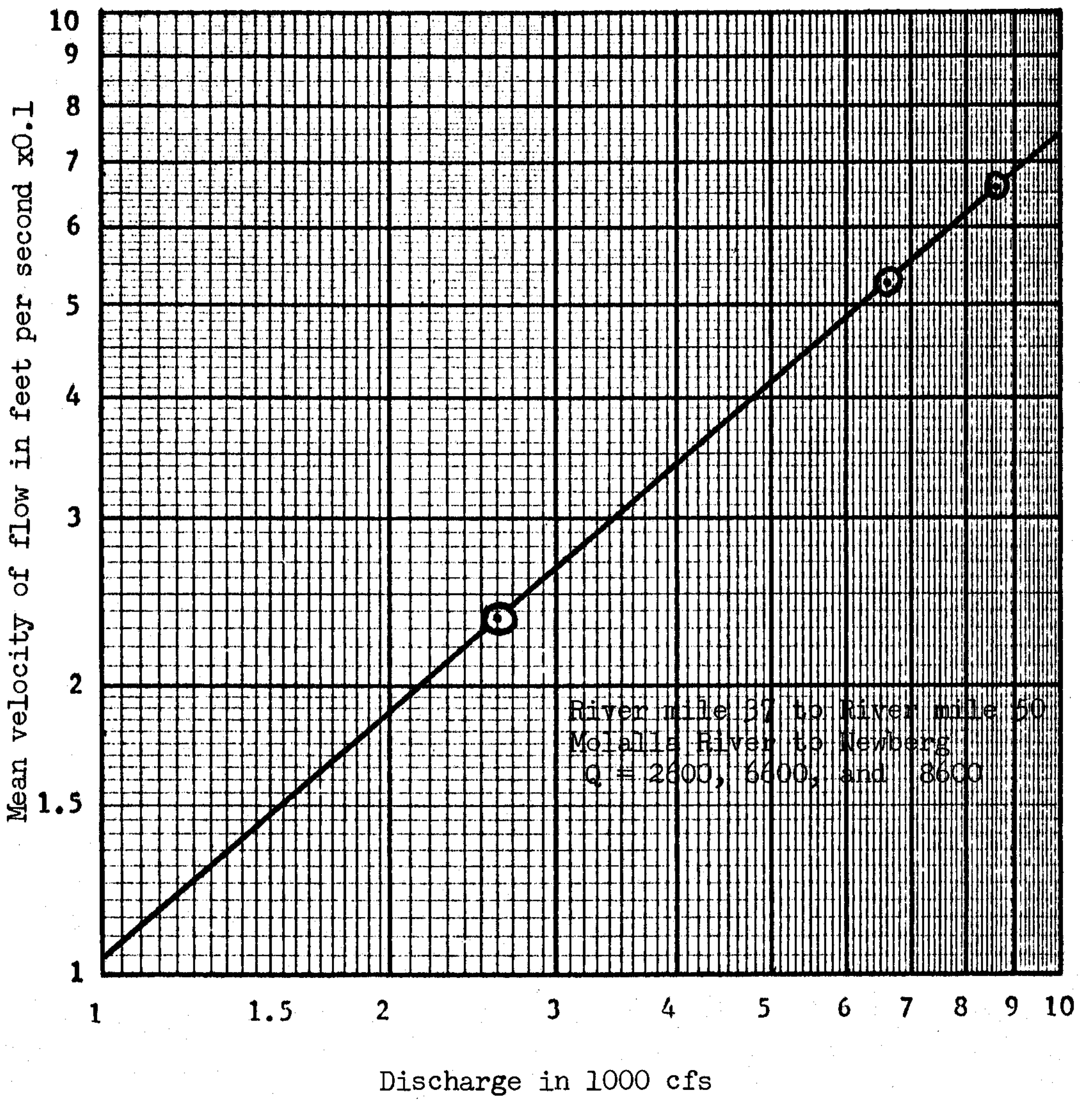
$$k_2 = 0.0275 \text{ when } Q = 1950$$

$$0.0275 = aQ^b$$

$$a = \frac{0.0275}{11.2} = 0.002455$$

$$\text{So } k_2 = 0.002455\ Q^{0.319}$$

Figure 3



$$d = 323/376 = 0.859$$

$$\text{when } Q = 1350,\ \text{Vel.} = 0.135$$

$$0.135 = cQ^d$$

$$c = 0.135/490 = 0.0002755$$

$$\text{So } V = 0.0002755\ Q^{0.859}$$

Figure 4

The results of this computation together with distances along the river facilitated calculation of travel times.

Data are relatively complete for the main stem of the Willamette River, but many data are missing for tributary and branch streams. Where data were lacking, an estimate was made for K_2 or velocity. When an estimate had to be used in the program, the method employed was to set the estimate equal to the coefficient in the K_2-flow or velocity-flow relationship and the exponent was set to zero. Since the exponentiation is performed first by the computer, this allowed the estimate to appear as the final value for K_2 or velocity. Both the coefficient and the exponent are entered into the program on data cards, so they can be easily changed or corrected at a later date when more accurate data become available.

Temperature effects must also be considered in evaluating K_2. An empirical formula (2, p. 378) relating K_2 at 20° C to K_2 at other temperatures has been developed as follows:

$$K_{2_{(T^\circ)}} = K_{2_{(20^\circ)}} \; 1.0159^{(T-20)} \qquad \text{Eq. 14}$$

Since, in this program, temperature for each reach remains constant during the complete solution of the river system analysis, the easiest method of applying a temperature correction is by incorporating it with the coefficient, "a", in the K_2-flow relationship.

Response to a Pollutional Load

The net effect of a stream's response to a pollutional load may be shown by graphical illustrations (Figure 5 and Figure 6) of the deoxygenation-reaeration relationships as follows:

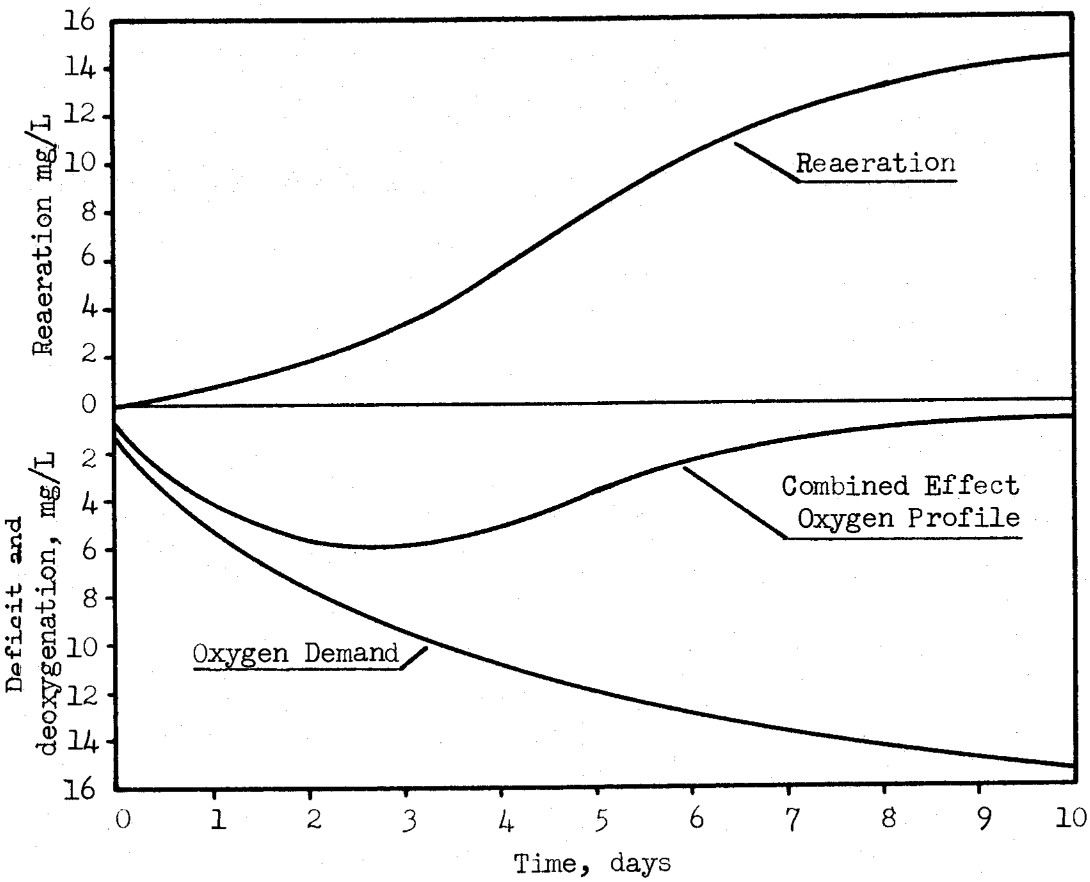


Figure 5. Curves showing combined effects of deoxygenation and reaeration.

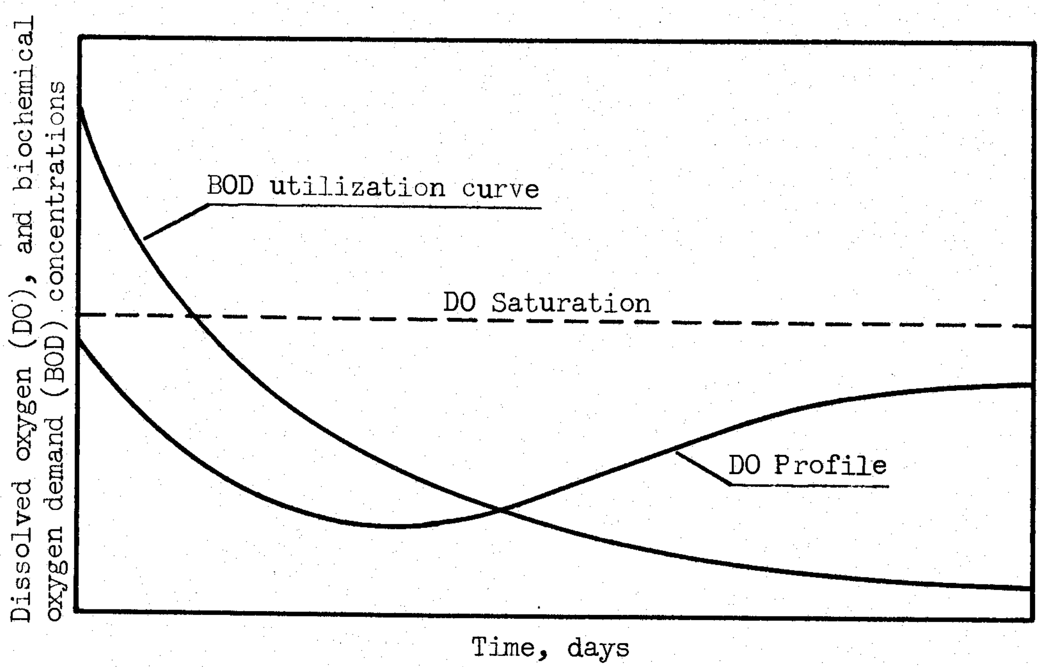


Figure 6. Plots showing utilization of biochemical oxygen demand and its relationship to the dissolved oxygen profile.

A summation of deoxygenation and reaeration describes the response of a stream to a pollutional load and can be expressed mathematically (13, p. 17-18) as follows:

$$dD/dt = K_1L - K_2D \qquad \text{Eq. 15}$$

When this equation is integrated it becomes:

$$D = \frac{K_1L_a}{K_2 - K_1} \; e^{-K_1t} - e^{-K_2t} + D_a e^{-K_2t} \qquad \text{Eq. 16}$$

Wherein:

D_a = initial dissolved oxygen saturation deficit of the water
D = saturation deficit after an elapsed time, t
L_a = initial oxygen demand of the organic matter in the water
K_1 = coefficient defining the rate of deoxygenation
K_2 = coefficient defining the rate of reaeration
t = elapsed time, in days
e = base of natural or Naperian logarithms = 2.71828

Summary of Equations

The following short summary and discussion of the mathematical expressions involved in describing how a stream responds to a pollutional load is presented prior to the use of these equations in the succeeding portions of this thesis.

Biochemical Oxygen Demand. The amount of dissolved oxygen used by bacteria for respiration in utilizing organic matter for food can be expressed as follows:

$$-dL/dt = K_1L \qquad \text{Eq. 17}$$

$$L_b = L_a e^{-K_1t} \qquad \text{Eq. 18}$$

Wherein:

t = elapsed time, in days
L_b = oxidizable organic matter remaining referred to as BOD remaining
L_a = initial oxidizable organic matter referred to as initial BOD
e = the base of natural or Naperian logarithms = 2.71828
K_1 = coefficient defining the rate of deoxygenation

In terms of oxygen utilization, deoxygenation can be expressed as follows:

$$dD_1/dt = K_1L \qquad \text{Eq. 19}$$

Reaeration of Streams. A mathematical expression of reaeration in terms of saturation deficit can be written as follows:

$$dD/dt = -K_2D \qquad \text{Eq. 20}$$

Wherein:

D = saturation deficit
t = elapsed time
K_2 = coefficient defining rate of reaeration

<u>Response to a Pollutional Load</u>. A summation of deoxygenation and reaeration describes the response of a stream to a pollutional load and can be expressed mathematically as follows:

$$dD/dt = K_1L - K_2D \qquad \text{Eq. 21}$$

Integration of this expression yields:

$$D = \frac{K_1L}{K_2 - K_1} e^{-K_1t} - e^{-K_2t} + D_a e^{-K_2t} \qquad \text{Eq. 22}$$

The above equations do not include oxygen demand by sludge deposits and miscellaneous organic loads entering from land drainage, tree leaves, etc. Since the sludge load and bank load can exert a significant influence, the above equation was modified (14, p. 3-5) to include them as follows:

$$D = \frac{K_1L_a}{K_2 - K_1} e^{-K_1t} - e^{-K_2t} + \frac{24B_LV}{K_2} \frac{K_2(1 - e^{-K_1t}) + K_1(1 - e^{-K_2t})}{K_2 - K_1}$$

$$+ \frac{24S_LV}{K_2}(1 - e^{-K_2t}) + D_a e^{-K_2t} \qquad \text{Eq. 23}$$

Wherein:

- D = saturation deficit after an elapsed time
- L_a = initial BOD of the stream
- K_1 = coefficient defining rate of deoxygenation
- K_2 = coefficient defining rate of reaeration
- e = base of natural or Naperian logarithms = 2.71828
- t = elapsed time, in days
- 24 = constant to convert miles per hour to miles per day
- B_L = bank load which has been defined as a uniform oxygen demand such as tree leaves, etc., which may enter the stream along its banks
- V = velocity of stream flow in miles per hour

S_L = sludge load which has been defined as the oxygen demand imposed by the benthal deposits on the stream bottom
D_a = initial saturation deficit of the stream

Other equations developed (14, p. 3-5) for use in this program are expressions for critical time and critical deficit and are as follows:

$$t_c = \frac{1}{K_2 - K_1} \frac{L_a K_1 K_2 + (K_2 - K_1)(24 S_L V - D_a K_2) - 24 B_L V K_1}{K_1^2 D_a - 24 B_L V K_1} \qquad \text{Eq. 24}$$

$$D_c = \frac{D_a e^{-K_1 t_c} + 24 B_L V (1 - e^{-K_1 t_c}) + 24 S_L V}{K_2} \qquad \text{Eq. 25}$$

Where:

t_c = time in days to critical point in dissolved oxygen sag
D_c = saturation deficit at critical point in dissolved oxygen sag
All other terms are the same as defined for Eq. 23 above.

These equations are also standard forms modified to include sludge load and bank load. Such modifications were used to allow more complete analysis when data for sludge load and bank load become available.

Equations 23, 24, and 25 are divided into several simple parts to be used in the computer program. For example, "x" is set equal to $K_2 - K_1$ ($x = K_2 - K_1$) and "z" is set equal to 24 times the sludge load multiplied by the velocity of flow (z = 24 * SLOAD * VEL). (See page 66 and page 72.)

Simplifying the equations in this manner speeds up their solution by the computer and in many cases reduces the number of mathematical operations required, because once "x" or "z" is defined by appearing on the left-hand side of an arithmetic statement, it will retain its value until redefined. This allows recall of values for use in the solution of succeeding equations in which the same set of conditions applies.

DISCUSSION OF LOGIC USED IN COMPUTER PROGRAM

Discussion of Flow Diagram

The following is a narrative discussion of the basic flow diagram used in writing the computer program presented in this thesis and included in the Appendix. The definition of variables is also included in the Appendix. The boxes in the flow diagram, Figure 8, have been numbered, and these numbers will be used to indicate which bit of logic is being considered.

The reach numbering system used is designed so that the smallest reach number will be nearest the mouth of the river system, and the largest number at the uppermost point, as shown in Figure 9. Stepwise solution proceeds in accordance with the flow diagram as follows:

1. At this point all the data for each reach are read into core storage. These data include the reach number, stream order number, flow in the reach, physical data for the stream, temperature of the water, and all pertinent characteristics of the water and wastes entering the reach. The data are stored in a manner such

that any item may be recalled at any time by using coordinates of a two-dimensional array such as the one shown in Figure 7. As an example, the number 26 would be recalled by specifying coordinates (2, 2) and the number 31 would be recalled by the coordinates (1, 4).

Column	1	2	3	4
Row 1	13	19	4	31
Row 2	8	26	3	16
Row 3	21	7	17	14

Figure 7. Simple array illustrating recall of data from core storage.

In this program the letter "I" is used as a general row number and set equal to a finite value of I = 1 at the start of the program. I is increased by an increment of 1 at the completion of computations for each reach, thereby causing the computer to proceed to the next reach. Columns are specified as exact numbers. A particular item could be recalled by specifying the co-ordinates, (I, 12).

All the data for one reach are stored on one row, which includes the number of columns necessary to contain the required data. In this program the array has a maximum dimension of 61 by 30, allowing for 60 rows of 30 columns each to describe each of 60 river reaches plus 1 row of data which tells the computer that it has completed the study. Any number of reaches from 1 through 60 may be used. Each reach will be described by 25 data read in at step 1 and five more items computed in step 4 will be included in the same array,

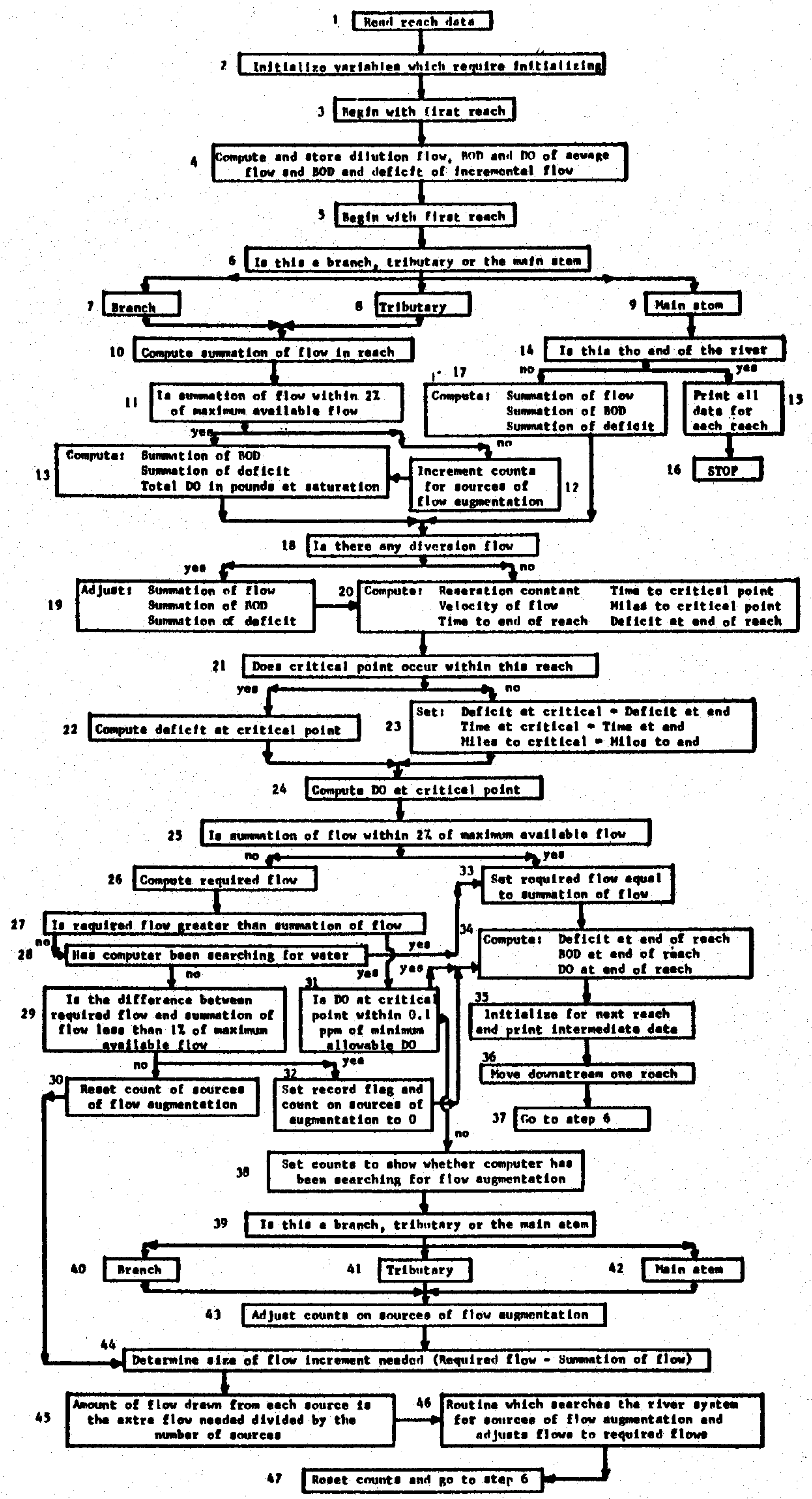


FIGURE 8

SIMPLIFIED FLOW DIAGRAM

to make a total of 30 columns. The program could easily be expanded for a greater array of data to accommodate more detailed river systems by redefining TAB (the name of the array).

2. At this point it is necessary to define any variables which do not first appear on the left-hand side of an arithmetic statement. If a variable first appears on the left-hand side of an arithmetic statement, this will serve to define it and it need not be set equal to zero or other predetermined values at this point in the program. For example, "LINE = 26" would define "LINE" and "QUP = QBUP + QTUP" would define "QUP."

3. After all the data for each reach have been read into core storage and all variables have been defined or set for initial conditions, it is necessary to return to the first reach to begin computation.

4. In this step the computer uses some of the data stored in the array described in step 1 to compute several variables which will retain the same value throughout the program and each will be used several times in other computations. These values are stored in the last 5 columns of the array for future reference.

5. When the computations described in step 4 have been completed for each reach, it is necessary to return to the first reach to begin the dissolved oxygen analysis of the river system.

6. Step 6 is a routine for determining which order (branch, tributary, or main stem) of stream is represented by the reach under consideration.

7, 8, & 9. There are three possible answers (branch, tributary, or main stem) which could be obtained in step 6. These are used to indicate which of three routines will be followed in the next step. All three routines are similar, but do have important differences which must be taken into account.

10. In this routine, all components of flow entering the reach are added together to obtain a summation of flow or QSUM. This routine is similar for both branches and tributaries, but must be kept separate in order to obtain the proper summation of flows at confluences. Also, some different flow components are involved.

11. After total flow in a given reach is known, this value is compared with the maximum flow available in this reach. In this work, a variation of plus or minus 2% of the maximum available flow was assumed to be reasonable. Any other percentage could be used if conditions warranted. If the flow is more than 2% greater than the maximum available flow, the computer "pauses" or goes to a programmed "halt" and prints an error finding routine (see last line of long format output sheets) to help locate the error which caused the flow (QSUM) in the reach to be greater than the maximum available flow (QMAX).

12. If the flow (QSUM) in the reach is more than 2% less than the maximum available flow (QMAX), the counts (N_1 and N_2) of sources of flow augmentation are increased by one. The count N_2 is the number of sources on a particular tributary and N_1 is the total number of sources in the basin upstream from the reach under consideration.

13. After increasing N_1 and N_2 (step 12) or in the case in which the flow in the reach is within 2% of the maximum available flow, the computer determines the total BOD, the dissolved oxygen that would be in the water at saturation and the total deficit at the point under consideration. All parameters except flow are calculated and accumulated in pounds at this point in the program.

From step 13 the computer proceeds to step 18.

14. If the answer to step 6 had been "main stem," the computer would proceed to step 14 and decide whether this main stem reach is the last one on the river. This is determined by the information in column 1 in the array which contains the reach data. If the number in column 1 for this row or reach is a "0," this indicates that the last reach has been solved and that the system analysis has been completed.

15. If the last reach has been solved, the computer prints out all the prescribed data for each reach in the form of an array as shown on page 52.

16. When the list of data is completed, the computer "pauses" and is ready to receive the next program, or if there are no other programs the computer stops.

17. If the answer to step 6 is "main stem" but the last reach has not been solved, the computer goes through a routine similar to step 13 and determines the total flow in the reach, the total BOD, the dissolved oxygen that would be in the water if it were saturated and the total deficit that exists in the reach.

18. After completion of step 13 or step 17, the computer checks to see if any flow has been diverted from the reach.

19. In cases where flow has been diverted, a proportionate amount of BOD and deficit will be carried with it. This necessitates adjusting these values so that the proper loading will be considered in succeeding steps.

20. After adjustments are made (step 19) or if there was no diversion flow, the computer computes the reaeration constant (K_2), the velocity of forward flow in the river (VEL), the time (TIMEC) to the critical point in the reach, the distance in miles (CRMILE) to the critical point, the time (TEND) to the end of the reach and the deficit (DEND) at the end of the reach.

21. Next the computer determines whether the critical point falls somewhere within the reach.

22. If the critical point falls within the reach under consideration, the deficit at the critical point is computed.

23. If the critical point is outside the reach under consideration, the critical point in the reach is at one end. If the critical time approaches 0, the stream is recovering and the critical point in the reach is the upstream end. (In certain cases, it is possible to compute a negative deficit. This was assumed to be a non-existent situation so the deficit at the end of the reach is set to 0.) When the critical time exceeds the time to the end of the reach, the oxygen profile of the stream is still declining and the critical point is at the downstream end. In this case, the critical and end points

are the same and conditions at the critical point are set equal to those computed for the end of the reach.

24. Next the dissolved oxygen content at the critical point is computed in pounds and converted to parts per million (ppm) so that it may be compared with the minimum allowable dissolved oxygen in parts per million.

25. The function of this step is to determine whether water is available for flow augmentation in case the dissolved oxygen concentration at the critical point is less than the minimum allowable dissolved oxygen concentration.

26. At this point, the flow required to maintain the minimum dissolved oxygen content is computed. This computation is only an estimate due to the changes in reaeration constant and travel time which may result from the increase in flow. This would apply only to the case where flow augmentation is needed.

27. This step determines whether the flow required to maintain the minimum allowable dissolved oxygen content is greater than the flow presently in the reach. If the required flow is smaller than the flow present, the computer proceeds to step 28. If the required flow is larger than that present, the computer proceeds to step 31.

28. In the majority of cases, the computer will not have been searching for flow augmentation because the flow required to maintain minimum allowable dissolved oxygen content is less than the summation of flow in the reach. If there has been no searching for flow augmentation, the computer proceeds to step 33.

29. When the computer has been searching for flow augmentation, it is possible for the summation of flow to be larger than the required flow due to an over-estimate in step 26. This situation could result when the computer proceeded through steps 26, 27, 31, and 38 through 47 in that order and returned to step 6 to compute the conditions existing for the new flow. On this "run" to compute conditions for the new flow, the answer to step 28 would be "yes" and then step 29 is needed to determine the magnitude of the variation involved. If the answer to step 29 is "yes" the computer proceeds to step 32.

30. If the answer to step 29 is "no" it becomes necessary to "return" some of the flow to its original storage locations so the count on the number of sources of augmentation is reset to the value retained from the initial search. In this way an increment of flow can be "returned" to the same sources from which it was taken. After resetting the count (NHOLD=N=N_1 or N_2) to its original value, the computer proceeds to step 44.

31. Step 31 is a comparison between the dissolved oxygen content at the critical point and the minimum allowable dissolved oxygen, both in parts per million. Since an exact comparison is impractical on a digital computer, it was decided that the minimum allowable dissolved oxygen content plus or minus 0.1 part per million would be acceptable. Even though the required flow is greater than the summation of flow, no searching for flow augmentation would be done when the critical dissolved oxygen content was within 0.1 part

per million of the minimum allowable dissolved oxygen content. Extra flow would be sought when the 0.1 part per million limit was exceeded and the computer would proceed to step 38 to search for the necessary flow augmentation. The 0.1 ppm limit is for satisfying computer routine and should not be taken as a practical value for application.

32. A "yes" answer to step 29 would cause the computer to proceed to step 32 and set to 0 the count (NHOLD) which is used to indicate the number of sources from which water was originally taken and the count (LFLAG) which shows that the computer has been searching for flow augmentation. Step 34 follows step 32.

33. If the answer to step 25 is "yes," this means that no flow augmentation is available and the required flow cannot exceed the maximum flow available. In this case the required flow is set equal to the summation of flow which is within two percent of the maximum available flow.

34. At this point a flow which satisfies the minimum allowable dissolved oxygen content has been determined for the reach and the conditions at the end of the reach are computed. These are in parts per million for print out of data.

35. Here the computer resets to initial conditions certain variables to get ready to start the next reach and prints out some intermediate data.

36. Here the "I" mentioned in step one is increased by one and the next downstream reach is ready to be considered.

37. The computer returns to step 6 to begin the analysis of the new reach.

38. This step is used only when a search for flow augmentation is underway. The count (LFLAG) which indicates that the computer has been searching for extra flow is set to one in preparation for step 28 if needed. A zero indicates that no search has been made.

39. This is the same procedure as used in step 6 and its purpose is to determine which of the three orders of streams is being considered.

40, 41, & 42. These are the three possible answers to step 39 (branch, tributary or main stem) and are used to determine how the counts (N_1 and N_2) for sources of flow augmentation will be adjusted.

43. Here the counts (N_1 and N_2) are adjusted to determine from how many sources flow augmentation will be drawn.

44, 45. At this point the total amount of extra flow needed is computed and divided by the number of sources from which flow augmentation is available. This determines the amount of flow to be drawn from each source. The flow increment from each source may be either positive or negative depending on whether water is being "released" from storage or "returned" to storage. The negative increment would result in water being "returned" and would originate from an over-estimate of flow required in step 26 on the previous "run" through the analysis of this reach. The over-estimate would be detected in step 29 and the magnitude of the negative increment (-QEACH) would be determined in step 44.

46. The search for flow augmentation begins on the reach under consideration and works upstream one reach at a time until a source of extra flow is located. When a source of flow augmentation is located, the increment to be contributed by each source (QEACH) is added to the summation of flow in the reach on which extra flow was available. If more than one source is to contribute flow, the computer proceeds upstream one reach at a time until all sources have been tapped. These sources of flow augmentation are located only on the uppermost reach of any stream and normally extra flow would be available only below a reservoir. When all sources of extra flow have been utilized, the computer proceeds to the first reach in the system and resolves each reach for the new flow conditions.

47. This step resets the various counts (NHOLD, N, N_3) and resets to initial conditions pertinent variables in preparation for resolving the reach for the new flow conditions. This is accomplished by returning to step 6 and going through the program again.

Limitations and Restrictions

This program has the capacity to analyze a river system which includes one to three orders (main stem, tributary, or branch) of streams, including not more than 60 reaches which are defined as the stretch of river between two points at which a significant change occurs. Any number of reaches from one through sixty can be used. The program can be expanded easily for more detailed systems.

The reach numbering system, described below, must be organized so that the smallest reach number will be the reach nearest the mouth of the river system. Likewise, the largest number will be the most upstream reach and will be the first to be considered in analysis of the river system by the computer.

When the uppermost reach has been selected and given a number, the reaches are numbered in a downstream direction in descending order such that the second reach has a number smaller than the first, the third smaller than the second, etc. When a confluence is reached, the uppermost reach on the new stream will receive a number smaller than the number of the last reach of the stream just completed. The diagram in Figure 9 serves to illustrate the numbering system.

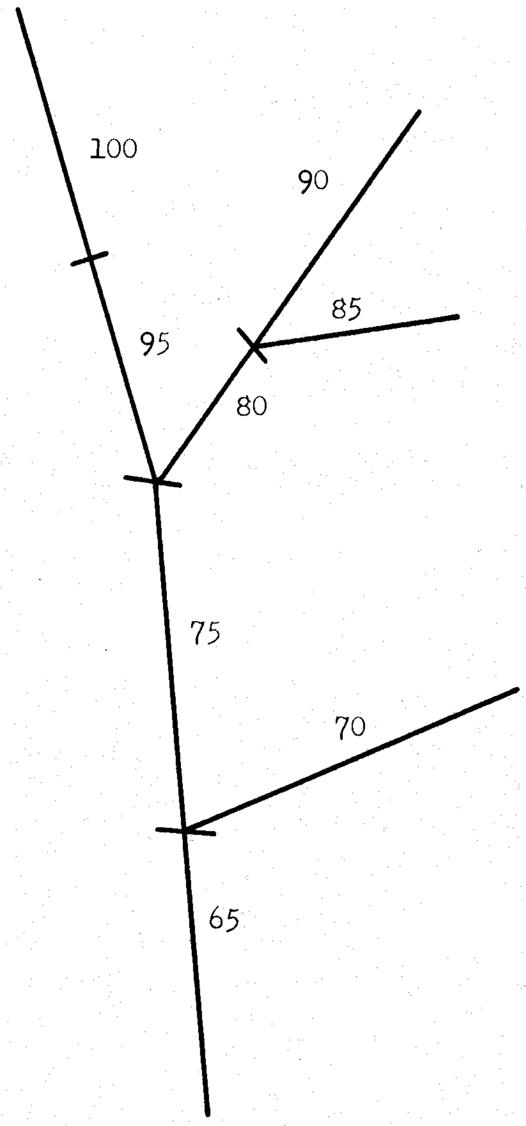


Figure 9. Simple river system to illustrate reach numbering system. See Limitations and Restrictions.

The reaches must be numbered in descending order in a downstream direction. It is advisable to leave gaps between the numbers so that new reaches can be inserted without disrupting the whole numbering system. The only restriction on the size of numbers used is that the largest cannot be larger than 999, and the smallest is one.

When analysis of the river system begins, the computer will start with the reach having the largest number (this is always a tributary reach) and proceed to the reach having the next smaller number. A reach number of zero is used to tell the computer when the last reach has been considered. Thus, the last data card must always contain a zero in the column for reach numbers.

The first reach or the reach having the largest number must always be designated as a tributary reach due to the way the program is written. This reach can be located anywhere in the river system so long as the reach numbering proceeds downstream in descending order from that point.

The uppermost reach on any particular stream starts at the most downstream reservoir on that stream or, in cases where reservoirs are absent, the uppermost reach would normally start at the farthest upstream point at which pollutional loading can be anticipated.

Each reach is identified on the data cards as being main stem, tributary, or branch by the numbers 3, 2, and 1, respectively. Numbering of reaches must be such that the computer would never proceed from branch to main stem or the reverse.

On reaches where no storage is available, the flows must be carefully checked to be sure the summation of the flow is within plus or minus two percent of the QMAX specified for that reach. If this restriction is not satisfied, a false source of flow augmentation is indicated to the computer.

In preparing data for this program it is necessary to determine relatively accurately the flow in each reach. This must be done for each level of flow to be considered in order to determine QMIN and QMAX for each reach.

In selecting reaches, the river system is divided into varying lengths in which a significant change occurs. Situations normally calling for the beginning of a new reach are: the confluence of two streams, the imposition of a significant waste load, or a decided change in slope or depth of the stream.

Reservoirs have not been included as reaches in this program because of a lack of data to determine velocities and reaeration rates. When data become available to determine the assimilation characteristics of reservoirs, they should be included as reaches in the river system. This would be especially useful in cases in which important waste loads are imposed upstream from a reservoir.

In cases in which reservoirs have turbulent spillways it may require introduction of a very short reach with a very high K_2 value to account for the reaeration which takes place over the spillway.

CONSIDERATIONS FOR APPLICATION TO A TYPICAL DRAINAGE BASIN

Description of Basin

The Willamette River system is located in northwestern Oregon and drains an area approximately 11,200 square miles in extent. The Willamette River Basin is oriented on a north - south axis at an approximate right angle to the lower main stem of the Columbia River. The river flows north to join the Columbia at Portland. The basin is roughly rectangular in shape with a north - south dimension of about 150 miles and an average width of about 75 miles. The Cascade Range, rising to elevations in excess of 10,000 feet, forms the eastern boundary and separates the Willamette and Deschutes River Basins. The Calapooya Mountains which rise to about 5,000 feet, form the southern boundary and separate the Willamette and Umpqua River Basins. On the west, the Coast Range rising to about 3,000 feet elevation separates the Willamette River Basin from the coastal drainage. The northern boundary separates the Willamette and Columbia River drainage and is formed by a range of low hills varying from 200 to 1,000 feet in elevation.

The Willamette River Basin is, in general, dish-shaped with the main valley floor located slightly west of center and foothills sloping up to rugged mountainous terrain on the east, south, and west boundaries. The Valley floor, comprised largely of rich agricultural land, is approximately 3,500 square miles in area and extends from above Eugene to the vicinity of Oregon City. The mean elevation of the valley floor is below 500 feet. A map of the river basin is shown in Figure 10.

The low water profile of the Willamette River upstream from Willamette Falls is typical of a stream with an unstable bed and consists of a series of relatively long, deep pools and short, steep bar crossings.

Flow Variations in the Basin

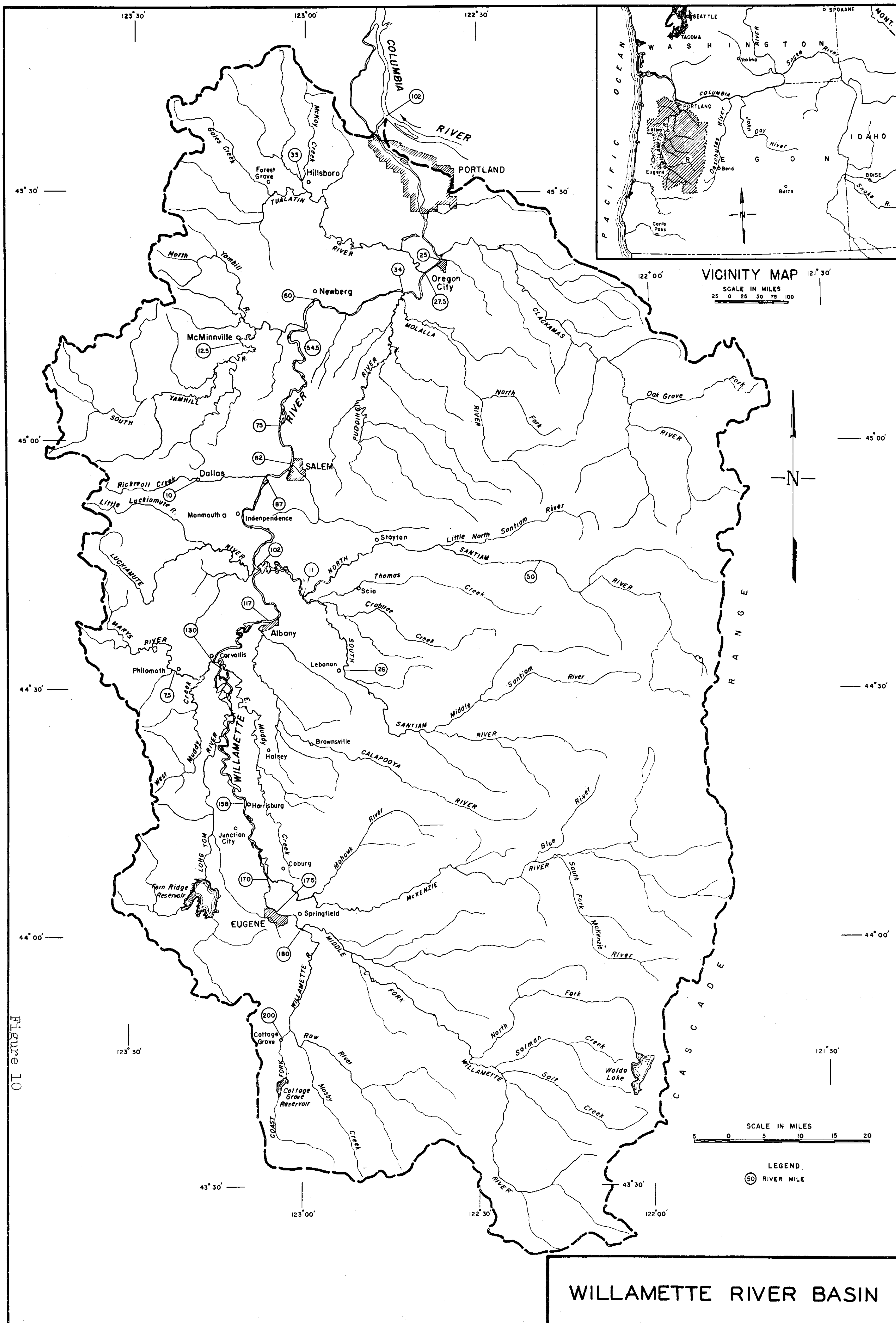
The Willamette River Basin is covered by a relatively complete network of U. S. Geological Survey gaging stations, and flow data obtained from these gaging stations are recorded in Part 14 of the U. S. Geological Survey Water-Supply Papers.

Table 3 lists some pertinent flow data for various stations on the main stem of the Willamette River and for one station on each of the major tributaries.

TABLE 3

Stream and Location of Station	Max. Flow of Record cfs	Av. Annual Flow cfs	Min. Flow of Record cfs	* Approx. Average Flow, cfs July	Aug.	Sept.
Willamette						
Salem	348,000	23,370	2,470	8,066	5,967	7,124
Albany	266,000	14,430	1,840	5,612	4,685	5,087
Harrisburg	210,000	12,840	1,990	5,054	4,325	4,347
Santiam						
Jefferson	161,000	7,838	260	1,952	943	1,822
McKenzie						
Coburg	88,200	6,081	1,250	2,942	2,219	2,103
Middle Fork Willamette						
Jasper	94,000	4,070	366	1,741	1,512	1,995
Coast Fork Willamette						
Goshen	58,500	1,760	36	353	743	462

* Flows shown in the last three columns of Table 3 are an average of the mean flow for each month over the ten year period from 1952 through 1961. An exception is the Middle Fork Willamette River at Jasper, which is taken for the eight year period from 1954 through 1961.



VICINITY MAP
SCALE IN MILES
25 0 25 50 75 100
PACIFIC OCEAN
WASHINGTON
OREGON
IDAHO
MONT.
SEATTLE
TACOMA
SPOKANE
Yakima
PORTLAND
Salem
Eugene
Bend
Burns
BOISE
Grants Pass
COLUMBIA RIVER
Snake River
Snake R.
Deschutes River
John Day River
COLUMBIA RIVER
PORTLAND
Hillsboro
Forest Grove
Gales Creek
McKay Creek
TUALATIN RIVER
North Yamhill R.
Newberg
Oregon City
McMinnville
SOUTH YAMHILL R.
MOLALLA RIVER
PUDDING RIVER
CLACKAMAS RIVER
North Fork
Oak Grove Fork
SALEM
Dallas
Rickreall Creek
Little Luckiamute R.
Monmouth
Independence
Stayton
Little North Santiam River
NORTH SANTIAM RIVER
Thomas Creek
Scio
Crabtree Creek
LUCKIAMUTE RIVER
Albany
MARYS RIVER
Philomath
Corvallis
Lebanon
SOUTH SANTIAM
Middle Santiam River
SANTIAM RIVER
Muddy Creek
West Muddy River
WILLAMETTE RIVER
Brownsville
Halsey
CALAPOOYA RIVER
Harrisburg
Junction City
LONG TOM
Creek
Coburg
Mohawk River
Blue River
McKENZIE RIVER
South Fork McKenzie River
Fern Ridge Reservoir
EUGENE
Springfield
MIDDLE FORK
WILLAMETTE R.
North Fork
Salmon Creek
Salt Creek
Waldo Lake
Cottage Grove
Row River
Mosby Creek
COAST FORK
Cottage Grove Reservoir
WILLAMETTE RIVER
CASCADE RANGE
N
SCALE IN MILES
5 0 5 10 15 20
LEGEND
50 RIVER MILE
102
35
25
34
50
27.3
54.5
12.5
75
82
10
87
102
11
50
117
130
26
7.5
158
170
175
180
200
45° 30'
45° 00'
44° 30'
44° 00'
43° 30'
123° 30'
123° 00'
122° 30'
122° 00'
121° 30'
WILLAMETTE RIVER BASIN

Figure 10

Most of the flow data in Table 3 have been influenced to some extent by regulation of releases from reservoirs in the Basin. There are several reservoirs in operation at present and several more are either under construction or in planning stages. Table 4 lists the reservoirs which have been completed, are under construction, or have been authorized for construction in the Willamette River Basin and indicates their present state of development. Table 5 shows the location of the reservoirs on the streams, the drainage area above the reservoir and the various types and amounts of storage in each reservoir.

TABLE 4

Reservoir	Present Stage of Development	Stream
Cottage Grove	Operational 1942	Coast Fork Willamette River
Dorena	Operational 1949	Row River
Hills Creek	Operational 1961	Middle Fork Willamette River
Lookout Point	Operational 1954	Middle Fork Willamette River
Dexter (Rereg)	Operational 1954	Middle Fork Willamette River
Fall Creek	Under Construction	Fall Creek
Cougar	Under Construction	South Fork McKenzie River
Strube (Rereg)	Authorized	South Fork McKenzie River
Blue River	Under Construction	Blue River
Gate Creek	Authorized	Gate Creek
Fern Ridge	Operational 1941	Long Tom River
Holley	Authorized	Calapooya River
Cascadia	Authorized	South Santiam River
Green Peter	Under Construction	Middle Santiam River
Foster (Rereg)	Under Construction	South Santiam River
Detroit	Operational 1953	North Santiam River
Big Cliff	Operational 1953	North Santiam River
Fern Ridge (Modification)	Authorized	Long Tom River

TABLE 5

Reservoir	Stream Mile	Drainage Area sq. mile	Proposed Storage--acre feet Flood Control	Dead	Power	Total
Cottage Grove	28.0	104	30,000	3,000	--	33,000
Dorena	7.0	265	70,000	6,000	--	76,000
Hills Creek	47.8	389	200,000	59,000	21,000	280,000
Lookout Point	21.3	991	340,000	88,000	28,000	456,000
Dexter (Rereg)	18.0	996	--	23,850	3,650	27,500
Fall Creek	7.1	184	115,000	10,000	--	125,000
Cougar	4.4	210	155,000	28,000	27,000	210,000
Strube (Rereg)	2.5	216	--	2,900	3,000	5,900
Blue River	0.6	88	85,000	5,000	--	90,000
Gate Creek	0.4	50	50,000	5,000	--	55,000
Fern Ridge	23.6	275	110,000	7,000	--	117,000
Holley	49.7	99	90,000	7,000	--	97,000
Cascadia	59.8	179	145,000	15,000	--	160,000
Green Peter	4.0	277	270,000	38,000	52,000	360,000
Foster (Rereg)	38.5	494	30,000	27,400	3,600	61,000
Detroit	48.5	438	300,000	115,000	40,000	455,000
Big Cliff	45.7	450	--	1,950	1,800	3,750
Fern Ridge (Modification)	23.6	275	15,000	--	--	15,000

When all the reservoirs listed in Tables 4 and 5 have been completed, it should be possible by controlling releases from storage, to maintain the flow in the Willamette River system throughout the year at levels desired by water management agencies. This relatively large amount of storage should provide adequate water for use in low flow augmentation for pollution abatement at nearly any point in the basin.

Economic Development of Basin

The Willamette River Basin had a population of 1,169,000 in 1960 of which more than half is concentrated in and near Portland in the lower end of the basin.

The economy of the Willamette River Basin is largely dependent on timber-based manufacturing, agriculture, and food processing. However, light metal industries, electronics industries and other diversified manufacturing along with service industries are becoming important contributors to the economy of the area.

The potential growth of the basin is expected to develop around the existing economic base activities.

Effective Pollutional Load in Basin

Current estimates of municipal and industrial waste production in the Willamette River Basin place the raw waste population equivalent at about 5.25 million. Most of these wastes receive some form of treatment which results in removal or satisfaction of about two-thirds of the BOD. The population equivalent of the treated wastes discharged into the streams of the basin is about 1.7 million.

Waste production by 1985 and 2010 is expected to increase by approximate factors of 1.3 and 1.9, respectively. Increases of this order in waste loadings during coming years will almost certainly cause a definite hazard to the oxygen resources of the streams in the basin during periods of low flow.

Increased use of irrigation in the Willamette River Basin can be expected in coming years. This will tend to increase the pollutional load in the river system in several ways. First, the use of more water in the fields will decrease the flow in the river unless releases from storage offset the extra draft. Also, there will be more irrigation return flow carrying insecticides, nutrients, and various other contaminants into the river. Probably the most important pollution problem created by more extensive use of irrigation will be an indirect one due to an expansion in the food processing industries. Such an expansion can be expected because irrigation will result in an increase in the acreage utilized for cannery crops and will increase yields from land now in production.

The digital computer program presented in this thesis can be used to predict the conditions which would exist under the future loadings described above and provide data to be used in reaching decisions on water resource management problems. Various loading situations and levels of flow can be tried to determine the most economical combination of treatment and flow augmentation. Computer output data for a single loading and a fixed level of flow is shown in the next section. Output data from a model river system is also shown to demonstrate the ability of the computer program to search for flow augmentation and adjust the flow to maintain a minimum allowable dissolved oxygen concentration. This latter analysis was performed on the model basin to test all features of the program which were not utilized by the Willamette River because of waste discharge-flow relations.

RESULTS AND OUTPUT DATA

Explanation of Output Data Sheets

This computer program incorporates two different output formats resulting in a short output data sheet of five columns and a long output data sheet of fifteen columns.

The short format (see page 51) is printed at the completion of the analysis of each reach and includes the reach number (RENO), the stream order number (DIGIT), the flow (QDUP) necessary to satisfy minimum dissolved oxygen requirements for this reach considering only upstream loadings, the velocity of flow (VEL) and the dissolved oxygen concentration at the critical point in the reach (DOCPPM). The purpose of this format is to show the flow, velocity and critical dissolved oxygen content in each reach the first time it is analyzed and to show the magnitude of flow increments used in adjusting flows to satisfy minimum requirements when necessary to search for flow augmentation. If no change in flow can be effected for a particular reach, the output data for that reach will be repeated exactly as it was printed the first time the reach was analyzed. In cases where flow augmentation is available, the size of increment needed is shown along with the effect of the change in flow on the critical dissolved oxygen content. For any reach, the difference between QDUP the first time it appears and the last time it appears will be the amount of extra flow which must be carried in the reach in order to satisfy downstream minimum dissolved oxygen requirements. The last time QDUP appears for any reach, it should be the same as the flow (QSUM in the long output format) necessary to meet minimum dissolved oxygen requirements, considering the whole river system and all loads imposed throughout the basin.

As an example, on the third row of data on page 51, the reach number (RENO) is 101, the stream order number (DIGIT) is 2, which indicates a tributary, the flow (QDUP) to satisfy minimum requirements for this reach considering only upstream loads is 922 cfs, the velocity of flow (VEL) in the river is 1.59 miles per hour and the dissolved oxygen content at the critical point (DOCPPM) is 10.48 ppm.

The data printed by the long output format describes the conditions which exist in the river system after it has been completely analyzed and the flows adjusted to satisfy all minimum requirements or all applicable sources of flow augmentation are exhausted. Explanation of column headings for the long format output data sheet can be found on pages 61 through 66.

The following pages are examples of output data printed by both formats and serve to illustrate the reason for having two output formats.

MODEL RIVER SYSTEM
SHORT FORMAT
OUTPUT DATA SHEET

RENO	DIGIT	QDUP	VEL	DOCPPM
105.	2.	1001.	1.59	10.48
103.	1.	40.	1.59	10.47
101.	2.	992.	1.59	10.48
96.	2.	551.	.72	9.48
95.	2.	651.	.77	1.87
105.	2.	1135.	1.59	10.49
103.	1.	40.	1.59	10.47
101.	2.	1056.	1.59	10.48
96.	2.	551.	.72	9.48
95.	2.	651.	.77	1.87
89.	3.	1738.	.93	7.03
105.	2.	1310.	1.59	10.49
103.	1.	40.	1.59	10.47
101.	2.	1232.	1.59	10.48
96.	2.	551.	.72	9.48
95.	2.	651.	.77	1.87
89.	3.	1914.	.98	7.35
88.	3.	1945.	.99	7.20
105.	2.	1760.	1.59	10.49
103.	1.	40.	1.59	10.47
101.	2.	1681.	1.59	10.49
96.	2.	551.	.72	9.48
95.	2.	651.	.77	1.87
89.	3.	2363.	1.10	7.95
88.	3.	2394.	1.11	7.75
87.	3.	2425.	1.12	7.77
86.	3.	2456.	1.13	7.84
85.	3.	2487.	1.14	8.04

LONG FORMAT OUTPUT DATA FOR MODEL RIVER SYSTEM

RENO	DIGIT	QSUM	DOCPPM	DCP	DOEND	DENDPM	BODEND	TIMEC	TEND	CRMILE	RELEN	RIVMI	REK2	TEMP
105.	2.	1760.	10.49	0.00	10.49	0.00	0.0	0.000	.182	0.0	7.0	18.0	4.18341	13.4
103.	1.	40.	10.47	.02	10.49	0.00	0.0	0.000	.187	0.0	7.2	7.2	8.67636	13.4
101.	2.	1681.	10.49	0.00	10.49	0.00	0.0	0.000	.286	0.0	11.0	11.0	4.18341	13.4
96.	2.	551.	9.48	.01	9.49	0.00	0.0	0.000	.462	0.0	8.0	28.0	5.85816	18.0
95.	2.	651.	1.87	7.62	4.02	5.47	30.9	.423	1.071	7.9	20.0	20.0	4.95033	18.0
89.	3.	2363.	7.95	2.04	7.95	2.04	6.9	.412	.412	11.0	11.0	187.0	1.18030	16.0
88.	3.	2394.	7.75	2.24	7.75	2.24	5.5	.409	.409	11.0	11.0	176.0	1.17948	16.0
87.	3.	2425.	7.77	2.22	7.82	2.17	4.4	.096	.406	2.6	11.0	165.0	1.17868	16.0
86.	3.	2456.	7.84	2.15	8.02	1.97	3.6	0.000	.403	0.0	11.0	154.0	1.17788	16.0
85.	3.	2487.	8.04	1.95	8.26	1.73	2.9	0.000	.400	0.0	11.0	143.0	1.17709	16.0

RENO	HUNT	DIGIT	TIMEC	DOCPPM	KNT	KOUNT	N1	N2	N3	N4	LFLAG	QREQD	QOVER	QSUM
105.	87.	2.	0.000	10.494	1	2	0	0	0	0	1	1760.	1807.	1760.

WILLAMETTE RIVER SYSTEM SHORT FORMAT OUTPUT DATA SHEET

RENO	DIGIT	QDUP	VEL	DOCPPM
105.	2.	1760.	1.59	9.49
103.	1.	40.	2.72	9.57
101.	2.	1680.	1.59	10.00
99.	2.	650.	1.74	8.59
97.	1.	135.	1.16	8.59
96.	2.	801.	.85	9.33
95.	2.	811.	.86	9.45
93.	3.	2491.	1.14	10.04
91.	3.	2521.	1.15	9.98
89.	3.	2541.	1.11	9.86
85.	2.	1445.	4.08	9.99
81.	2.	1680.	1.53	9.99
79.	2.	1790.	1.49	9.99
77.	2.	1840.	1.36	9.70
75.	3.	4381.	2.10	9.50
73.	3.	4502.	2.13	9.35
71.	2.	35.	.51	8.32
70.	2.	35.	.34	8.79
69.	3.	4612.	1.47	9.26
67.	2.	20.	.51	8.22
65.	3.	4703.	1.69	9.13
64.	2.	30.	2.04	8.70
63.	2.	30.	1.02	9.14
62.	2.	30.	.68	9.15
61.	3.	4802.	1.53	9.02
59.	2.	1230.	4.08	10.27
57.	2.	1330.	3.40	10.00
55.	1.	180.	1.90	8.82
54.	1.	60.	.48	9.21
53.	1.	74.	.48	7.50
51.	2.	724.	1.53	9.74
47.	3.	5602.	1.76	9.05
43.	3.	5901.	1.84	8.81
39.	2.	40.	.34	7.86
37.	3.	5961.	1.43	8.72
35.	3.	6111.	.33	7.62
33.	2.	20.	1.63	5.13
32.	2.	30.	1.63	5.07
31.	3.	6222.	.43	7.42
29.	2.	10.	.20	7.47
27.	2.	15.	.20	5.56
26.	2.	35.	.20	5.03
25.	2.	44.	.20	5.35
23.	2.	25.	.20	5.66
21.	3.	6247.	.43	7.36

LONG FORMAT OUTPUT DATA FOR WILLAMETTE RIVER SYSTEM

RENO	DIGIT	QSUM	DOCPPM	DCP	DOEND	DENDPM	BODEND	TIMEC	TEND	CRMILE	RELEN	RIVMI	REK2	TEMP
105.	2.	1760.	9.49	1.00	10.01	.48	.5	0.000	.182	0.0	7.0	18.0	4.18341	13.4
103.	1.	40.	9.57	.92	10.14	.35	0.0	0.000	.110	0.0	7.2	7.2	8.67636	13.4
101.	2.	1680.	10.00	.49	10.32	.17	.5	0.000	.286	0.0	11.0	11.0	4.18341	13.4
99.	2.	650.	8.59	.90	9.34	.15	.4	0.000	.167	0.0	7.0	7.0	11.22660	18.0
97.	1.	135.	8.59	.90	9.43	.06	.4	0.000	.287	0.0	8.0	28.0	10.11780	18.0
96.	2.	801.	9.33	.16	9.46	.03	.4	0.000	.584	0.0	12.0	20.0	5.85816	18.0
95.	2.	811.	9.45	.04	9.46	.03	.4	0.000	.387	0.0	8.0	8.0	4.95033	18.0
93.	3.	2491.	10.04	.15	10.04	.15	.5	0.000	.072	0.0	2.0	187.0	1.17698	15.0
91.	3.	2521.	9.98	.01	9.98	.01	.5	.180	.180	5.0	5.0	185.0	1.17623	16.0
89.	3.	2541.	9.86	.03	9.86	.03	1.4	.149	.149	4.0	4.0	180.0	.86203	16.6
85.	2.	1445.	9.99	0.00	9.99	0.00	0.0	.030	.030	3.0	3.0	56.0	11.09724	16.0
81.	2.	1680.	9.99	0.00	9.99	0.00	0.0	.408	.408	15.0	15.0	53.0	3.46500	16.0
79.	2.	1790.	9.99	0.00	9.99	0.00	0.0	.779	.779	28.0	28.0	38.0	3.11688	16.0
77.	2.	1840.	9.70	0.00	9.69	0.00	.3	.306	.306	10.0	10.0	10.0	2.20228	17.0
75.	3.	4381.	9.50	0.00	9.49	0.00	.9	.237	.237	12.0	12.0	176.0	1.28694	18.0
73.	3.	4502.	9.35	.04	9.35	.04	.8	.409	.409	21.0	21.0	164.0	1.28472	18.5
71.	2.	35.	8.32	.57	8.81	.08	.9	0.000	1.029	0.0	12.6	23.6	4.46985	21.5
70.	2.	35.	8.79	.10	8.82	.07	.8	0.000	1.347	0.0	11.0	11.0	4.46985	21.5
69.	3.	4612.	9.26	.03	9.26	.03	.7	.225	.225	8.0	8.0	143.0	.93786	19.5
67.	2.	20.	8.22	.77	8.85	.14	1.7	0.000	.612	0.0	7.5	7.5	5.30838	21.0

RENO	DIGIT	QSUM	DOCPPM	DCP	DOEND	DENDPM	BODEND	TIMEC	TEND	CRMILE	RELEN	RIVMI	REK2	TEMP
65.	3.	4703.	9.13	.16	9.13	.16	1.2	.369	.369	15.0	15.0	135.0	1.41510	19.5
64.	2.	30.	8.70	.50	9.14	.05	.2	0.000	.204	0.0	10.0	50.0	12.01200	20.0
63.	2.	30.	9.14	.05	9.19	0.00	.2	0.000	.408	0.0	10.0	40.0	9.27072	20.0
62.	2.	30.	9.15	.04	9.17	.02	.4	0.000	1.837	0.0	30.0	30.0	6.85030	20.0
61.	3.	4802.	9.02	.17	9.02	.17	1.3	.298	.298	11.0	11.0	120.0	1.27046	20.0
59.	2.	1230.	10.27	.52	10.60	.19	.4	0.000	.212	0.0	20.8	45.8	5.10579	12.0
57.	2.	1330.	10.00	0.00	10.00	0.00	.4	.306	.306	25.0	25.0	25.0	4.43242	16.0
55.	1.	180.	8.82	.57	9.21	.18	1.0	0.000	.273	0.0	12.5	27.5	5.36451	19.0
54.	1.	60.	9.21	.18	9.30	.09	.9	0.000	.255	0.0	3.0	15.0	5.08200	19.0
53.	1.	74.	7.50	1.69	7.85	1.34	19.8	.104	1.020	1.2	12.0	12.0	5.08200	20.0
51.	2.	724.	9.74	.05	9.74	.05	1.3	.299	.299	11.0	11.0	11.0	3.35643	16.5
47.	3.	5602.	9.05	.24	9.05	.24	1.0	.591	.591	25.0	25.0	109.0	1.40927	19.5
43.	3.	5901.	8.81	.38	8.81	.38	1.8	.655	.655	29.0	29.0	84.0	1.38613	20.0
39.	2.	40.	7.86	.93	7.88	.91	2.0	.913	1.347	7.4	11.0	11.0	.87549	22.0
37.	3.	5961.	8.72	.27	8.72	.27	1.7	.145	.145	5.0	5.0	55.0	.49425	21.0
35.	3.	6111.	7.62	1.27	7.62	1.27	1.4	1.744	1.744	14.0	14.0	50.0	.09430	21.5
33.	2.	20.	5.13	4.06	5.13	4.06	24.1	.382	.382	15.0	15.0	26.0	.34650	20.0
32.	2.	30.	5.07	4.12	5.07	4.12	15.8	.280	.280	11.0	11.0	11.0	.34650	20.0
31.	3.	6222.	7.42	1.47	7.42	1.47	1.2	.671	.671	7.0	7.0	36.0	.14073	21.5
29.	2.	10.	7.47	1.32	7.51	1.28	.7	1.715	2.654	8.4	13.0	59.0	.27720	22.0

RENO	DIGIT	QSUM	DOCPPM	DCP	DOEND	DENDPM	BODEND	TIMEC	TEND	CRMILE	RELEN	RIVMI	REK2	TEMP
27.	2.	15.	5.56	3.23	5.56	3.23	3.9	1.429	1.429	7.0	7.0	46.0	.27720	22.0
26.	2.	35.	5.03	3.76	5.05	3.74	2.6	1.957	2.245	9.5	11.0	39.0	.27720	22.0
25.	2.	44.	5.35	3.44	6.37	2.42	.8	.989	4.491	4.8	22.0	28.0	.27720	22.0
23.	2.	25.	5.66	3.13	5.66	3.13	2.3	1.118	1.225	5.4	6.0	6.0	.27720	22.0
21.	3.	6247.	7.36	1.53	7.36	1.53	1.1	.286	.286	3.0	3.0	29.0	.14089	21.5

RENO	HUNT	DIGIT	TIMEC	DOCPPM	KNT	KOUNT	N1	N2	N3	N4	LFLAG	QREQD	QOVER	QSUM
105.	0.	2.	0.000	9.498	1	2	0	0	0	0	0	1760.	0.	1760.

CONCLUSIONS

1. A digital computer can be readily adapted to the solution of the Streeter-Phelps oxygen sag equations and can apply the results of such solutions to the determination and adjustment of flows required to maintain a minimum allowable dissolved oxygen concentration in streams.

2. This digital computer program can provide in a few minutes, data which would normally require many man hours of hand computations. Such data can be applied to provide answers to water management problems that would otherwise be hindered by the massive computations involved.

3. Management decisions on future water use must be based upon maximum benefits which can be obtained from the existing water resources. Such decisions must be predicated upon a knowledge of the results of water utilization practices. Prudent judgment demands that all possible uses be considered. An analysis of this magnitude is beyond the limited manpower capabilities at the present time and can be significantly aided by application of digital computer techniques.

4. Many types of studies are needed for water management. The program presented can be adapted to the analysis of various water quality perameters and can possibly provide a basis of solution for some of the problems that exist regarding waste treatment, flow augmentation and planned development based upon resource.

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APPENDIX

Explanation of Variables Used in Program

A	$e^{-K_1 \text{ TEND}}$.
AA	Z/K_2.
AK2	Coefficient of Q in $K_2 = aQ^b$.
B	$e^{-K_2 \text{ TEND}}$.
BB	ZSL/K_2.
BK2	Exponent of Q in $K_2 = aQ^b$.
BKLOD	Bank load, pounds/mile/day. This is the uniform load which is assumed to be exerted along the banks of any stream. Might also include load exerted by algae die-off. (This last item might be included as SLOAD.)
BOD	Biochemical oxygen demand.
BODBU	BOD of branch reach immediately upstream in total pounds.
BODD	BOD of dilution flow (QDIL) in ppm.
BODDP	BOD of dilution flow (QDIL) in total pounds.
BODEND	BOD at end of reach, ppm.
BODI	BOD of incremental flow (QI), ppm.
BODIP	BOD of incremental flow, total pounds.
BODMU	BOD of main stem reach immediately upstream in total pounds.
BODNDP	BOD at end of reach in total pounds.
BODS	BOD of sewage, ppm.
BODSP	BOD of sewage, total pounds.
BODTU	BOD of tributary reach immediately upstream in total pounds.
BODTUT	BOD in first of two tributaries in the case where two tributaries come together. Replaces BODTU for this specific case.
C	$(K_1 \text{SUMBOD}/X)$ (A - B).

C1	K_1 (SUMBOD).
CC	e^{-K_1} TIMEC.
CC1	K_1 (CC) (SUMBOD).
cfs	Cubic feet per second.
CRMILE	Miles to critical point from head of reach.
CVEL	Coefficient of Q in $V = cQ^d$.
DCLBS	Critical deficit, total pounds.
DCPPM	Critical deficit, ppm.
DD	Deficit of dilution water (QDIL), ppm.
DDP	Deficit of dilution water, total pounds.
DEFSUM	Summation of all the deficits within the reach, total pounds. DEFSUM = (DOSAP - DOTUP - DOBUP - DOSP) + DIP + DDP.
DELTAQ	QREQD - QSUM. This is the estimated extra flow (cfs) needed to satisfy DOMIN requirements.
DEND	Deficit at end of reach, total pounds.
DI	Deficit of incremental flow (QI), ppm.
DENDPM	Deficit at end of reach in ppm.
DIGIT	An identification number or stream order number. (1) for branches; (2) for tributaries; and (3) for main stem.
DIP	Deficit of incremental flow, total pounds.
DO	Dissolved oxygen.
DOBUP	DO in branch reach immediately upstream in total pounds.
DOCLBS	Critical DO in total pounds.
DOCPPM	Critical DO in ppm.
DOEND	DO at end of reach, ppm.
DOENDP	DO at end of reach, total pounds.
DOMIN	Minimum desired dissolved oxygen, ppm, in any reach.

DOMUP	DO in main stem reach immediately upstream in total pounds.
DOS	DO of sewage flow, ppm.
DOSAP	Dissolved oxygen, at saturation total pounds per day in any reach.
DOSAT	Dissolved oxygen, ppm, at saturation in water in any reach.
DOSP	DO of sewage (QS) in total pounds.
DOTUP	DO in tributary reach immediately upstream in total pounds.
DOTUPT	DO in first of two tributaries in the case where two tributaries come together. Replaces DOTUP for this specific case.
DOXKI	Deoxygenation constant K_1 (base e). Units of 1/days.
DVEL	Exponent of Q in $V = cQ^d$.
E	e = 2.71828 = base of natural or Naperian logs.
F	K_2 (1 - A).
FNUM	The count N changed from fixed point to floating point notation (FNUM = N).
G	K_1 (1 - B).
HUNTER	A device used to tell when the computer has returned to the original reach where the flow was insufficient to maintain DOMIN. Will be used only when computer has been looking for extra flow.
K	The number of reaches in a particular river system.
KNT	A count used to indicate the case where two tributaries come together.
KOUNT	A count used to tell the computer when computations for the last reach have been completed.
LFLAG	Record flag. This is an index to show whether computer has been looking for extra water.
LINE	The number of lines of printing on the output sheets.
N	Replaces N_1 or N_2 when looking for flow augmentation.

N_1	Number of sources of flow augmentation in entire basin.
N_2	Number of sources of flow augmentation on any tributary (the one being considered).
N_3	Used to keep track of sources used as compared to sources available. N_3 is incremented by 1 each time a source is tapped and when $N_3 = N$, all sources have been used.
N_4	Number of sources of flow augmentation on the second tributary in the case where two tributaries come together to form the main stem.
NHOLD	A device for retaining the value of N after a QEACH has been calculated. Needed for the case where QEACH is too large.
ppm	Parts per million = mg/L = milligrams per liter.
Q	Flow in cfs.
Q539	5.39 (QSUM).
QBUP	Flow (cfs) in the branch reach immediately upstream from the one under consideration. In the case of the uppermost reach, by definition, there is no reach above it and, therefore, QBUP = 0. In this case, QMIN = QDIL will have a value. For reaches below uppermost reach, QBUP has a value and QMIN and QDIL = 0.
QDIL	Dilution flow, cfs.
QDUP	The flow (cfs) required to solve this reach considering only reaches upstream from this point.
QEACH	DELTAQ/N. This is the flow (cfs) that would be taken from each source of flow augmentation.
QI	Incremental flow, cfs. This flow is made up of ground water, small creeks and other flow which cannot be accounted for at the end of each reach.
QMAX	Maximum flow to be considered in any given reach, cfs. This flow will be the greatest flow which might be reasonably provided to assimilate wastes which are discharged into the streams of the basin. QMAX will vary for each reach.

QMIN	Minimum flow in any given reach, cfs. Normally, 0 for all but uppermost reach on each tributary or branch. This is by definition and is done to aid in searching for reaches where supplemental flow is available.
QMUP	Flow (cfs) in main stem reach immediately upstream from reach being considered. Same explanation as above for QBUP applies here.
QOUT	Diversion flow, cfs. This is the flow taken out of the river for irrigation or other purposes.
QOVER	Replaces QREQD when QREQD exceeds QMAX. Used as a device to keep track of extra flow (cfs) in case some was not needed. (When estimated QREQD was greater than actually needed.)
QREQD	Flow (cfs) needed to maintain DOMIN in the reach with the loads exerted.
QS	Flow of sewage or industrial waste, cfs.
QSUM	Summation of Q in the reach, cfs. QUP + QS + QDIL + QI (etc.)
QSUMP	Summation of Q for case where QOUT is not 0. QSUMP = QSUM - QOUT.
QTUP	Flow (cfs) in tributary reach immediately upstream from the one being considered. Same explanation as above for QBUP applies.
QTUPT	The flow in the first of two tributaries in the case where two tributaries come together. Replaces QTUP for this specific case.
QUP	QBUP + QTUP, cfs.
RATIO	QSUMP/QSUM.
REK2	Reaeration constant, k_2 (base 10), converted to base e within program. Units of 1/days.
RELEN	Reach length, miles.
RENO	Reach number.
RIVMI	The river mile to the head of each reach from mouth of the stream on which this particular reach happens to be.

SLOAD — Sludge load, pounds/mile/day, exerted by sludge deposits within any reach.

SUMBOD — Summation of BOD, total pounds.
SUMBOD = BODBU + BODTU + BODSP + BODIP + BODD + BODMU.

TAB — An abbreviation used to designate the array or table which contains all the reach data.

TEMP — Temperature in any reach, °C.

TEND — Time to end of reach, days.

TIMEC — Time to critical point in sag curve, days.

U — K_1^2 SUMBOD - K_1Z.

VEL — Velocity of flow (ft/sec), converted to miles per hour in program before used in any computations.

W — Y(SUMBOD) + X(ZSL - K_2 DEFSUM) - K_1Z.

X — $K_2 - K_1$ (both base e).

Y — $K_1 K_2$ (Both base e).

Z — 24(BKLOD)(VEL).

ZSL — 24(SLOAD)(VEL).

DIGITAL COMPUTER PROGRAM IBM FORTRAN II

OXYGEN SAG PROGRAM

```
C    THIS PROGRAM IS DESIGNED TO DETERMINE THE FLOW IN CFS
C    REQUIRED IN A STREAM AT A GIVEN POINT TO MAINTAIN A MINI-
C    MUM STATED DISSOLVED OXYGEN CONCENTRATION IN PARTS PER
C    MILLION.  IF REQUIRED FLOW AT ANY POINT IS GREATER THAN
C    THAT PRESENT, THE PROGRAM WILL SEARCH THE RIVER SYSTEM
C    FOR STORAGE RESERVOIRS FROM WHICH WATER COULD BE RELEASED
C    TO AUGMENT THE FLOW AND DETERMINE THE SIZE OF RELEASE
C    NECESSARY TO MEET DOWNSTREAM REQUIREMENTS.  DISSOLVED
C    OXYGEN CONCENTRATION IS THE ONLY QUALITY PARAMETER BEING
C    CONSIDERED.  ALL DECISIONS ARE BASED ON THIS PARAMETER.
0001 FORMAT(F4.0,F2.0,F5.1,F6.1,2F8.0,F6.1,F6.2,F6.1,3F4.1,F7.0/
    22F5.1,F4.1,F6.3,2F8.5,F8.6,F6.3,2F5.1,2F6.0)
     DIMENSION TAB(61,30)
0099 READ 103, K
0103 FORMAT (13)
     DO 110 I = 1,K
0110 READ1,TAB(I,1),TAB(I,2),TAB(I,3),TAB(I,4),TAB(I,5),TAB(I,6),
    2TAB(I,7),TAB(I,8),TAB(I,9),TAB(I,10),TAB(I,11),TAB(I,12),
    3TAB(I,13),TAB(I,14),TAB(I,15),TAB(I,16),TAB(I,17),TAB(I,18),
    4TAB(I,19),TAB(I,20),TAB(I,21),TAB(I,22),TAB(I,23),TAB(I,24),
    5TAB(I,25)
     I = 1
     KOUNT = 0
```

```
      HUNTER = 0.0
      LFLAG = 0
      N1 = 0
      LINE = 26
      N2 = 0
      N4 = 0
      N3 = 0
      QMUP = 0.0
      BODBU = 0.0
      BODTU = 0.0
      BODMU = 0.0
      DOBUP = 0.0
      DOTUP = 0.0
      DOMUP = 0.0
      KNT = 0
      QOVER = 0.0
0002  QDIL = TAB(I,5)
      TAB(I,30) = QDIL
      BODSP = 5.39 * TAB(I,24) * TAB(I,8)
      TAB(I,26) = BODSP
      DOSP = 5.39 *TAB(I,10) * TAB(I,8)
      TAB(I,27) = DOSP
      BODIP = 5.39 * TAB(I,22) * TAB(I,7)
      TAB(I,28) = BODIP
      DIP = 5.39 * TAB(I,11) * TAB(I,7)
```

```
      TAB(I,29) = DIP
      I = I + 1
      IF(1.0 - TAB(I,1))2,2,70
0070  I = 1
0004  IF(2.0 - TAB(I,2))27,6,6
0006  IF(1.0 - TAB(I,2))7,23,72
0007  IF(1.0 - TAB(I,5))111,121,121
0111  KNT = KNT + 1
      IF (2 - KNT)77,115,116
0115  QTUPT = QTUP
      BODTUT = BODTU
      DOTUPT = DOTUP
0116  QTUP = 0.0
      QBUP = 0.0
      BODTU = 0.0
      DOTUP = 0.0
0121  QUP = QTUP + QBUP
      QSUM = QUP + TAB(I,7) + TAB(I,8) + TAB(I,30)
      IF(1.0 - QUP)8,8,9
0009  IF(1.02 * TAB(I,6) - QSUM)77,201,201
0201  IF(0.98 *TAB(I,6)  - QSUM)8,8,10
0010  N1 = N1 + 1
      IF(2-KNT)77,311,310
0311  N4 = N4+1
      GO TO 8
```

```
0310 N2 = N2+1
0008 BODDP = 5.39 * TAB(I,23) * TAB(I,30)
     DDP = 5.39 * TAB(I,12) * TAB(I,30)
     SUMBOD = BODTU + BODBU + TAB(I,26) + TAB(I,28) + BODDP
     DOSAP = 5.39 * TAB(I,15) * (QUP + TAB(I,8))
     DEFSUM = (DOSAP - DOTUP - DOBUP - TAB(I,27)) + TAB(I,29) + DDP
     DOBUP = 0.0
     BODBU = 0.0
     QBUP = 0.0
     GO TO 101
0023 QSUM = QBUP + TAB(I,8) + TAB(I,7) + TAB(I,30)
     IF (1.0 - QBUP)26,26,24
0024 IF(1.02 * TAB(I,6) - QSUM)77,202,202
0202 IF(0.98 *TAB(I,6)  - QSUM)26,26,25
0025 N1 = N1 + 1
     IF(2-KNT)77,124,125
0124 N4 = N4 + 1
     GO TO 26
0125 N2 = N2 + 1
0026 BODDP = 5.39 * TAB(I,23) * TAB(I,30)
     DDP = 5.39 * TAB(I,12) * TAB(I,30)
     SUMBOD = BODBU + TAB(I,26) + TAB(I,28) + BODDP
     DOSAP = 5.39 *TAB(I,15) * (QBUP + TAB(I,8))
     DEFSUM = (DOSAP - DOBUP - TAB(I,27)) + TAB(I,29) + DDP
     GO TO 101
0027 N2 = 0
```

```
     N4 = 0
0117 QSUM = QMUP + QTUP + QTUPT + TAB(I,7) + TAB(I,8)
0119 SUMBOD = BODMU + BODTU + TAB(I,26) + TAB(I,28) + BODTUT
     KNT = 0
     QTUPT = 0.0
     DOSAP = 5.39 * TAB(I,15) * (QSUM - TAB(I,7))
     DEFSUM = (DOSAP-DOTUP-DOTUPT-DOMUP-TAB(I,27)) + TAB(I,29)
     QMUP = 0.0
     BODMU = 0.0
     DOMUP = 0.0
     BODTUT = 0.0
     DOTUPT = 0.0
     BODTU = 0.0
     QTUP = 0.0
     DOTUP = 0.0
0101 IF(1.0 - TAB(I,9))17,18,18
0017 QSUMP = QSUM - TAB(I,9)
     RATIO = QSUMP / QSUM
     SUMBOD = RATIO * SUMBOD
     DEFSUM = RATIO * DEFSUM
     QSUM = QSUMP
0018 REK2 = (TAB(I,18) * QSUM ** TAB(I,19)) * 2.31
     IF (REK2 - TAB(I,17))181,180,181
0180 REK2 = REK2 + 0.010
0180 VEL = (TAB(I,20) * QSUM ** TAB(I,21))/1.47
```

```
      X = REK2 - TAB(I,17)
      Y = TAB(I,17) * REK2
      Z = 24.0 * TAB(I,25) * VEL
      ZSL = 24.0 * TAB(I,13) * VEL
      W = (Y*SUMBOD) + (X * (ZSL - REK2 * DEFSUM))-(Z*TAB(I,17))
      U = (TAB(I,17) ** 2.0 * SUMBOD) -(TAB(I,17)*Z)
      R = W / U
      IF(R-0.00)20,20,80
 0080 TIMEC = (1.0 / X) * LOGF(R)
      IF (TIMEC - 0.02)20,20,19
 0020 TIMEC = 0.0
 0019 CRMILE = 24.0 * VEL * TIMEC
      TEND = TAB(I,3) / (24.0 * VEL)
      E = 2.71828
      A = E**(-TAB(I,17)*TEND)
      B = E ** (-REK2 * TEND)
      C1 = TAB(I,17) * SUMBOD
      C = (C1 / X) * (A - B)
      F = REK2 * (1.0 -A)
      G = TAB(I,17) * (1.0 - B)
      AA = Z / REK2
      BB = ZSL / REK2
      DEND = C + (AA *((F-G)/X)) + (BB *(1.0 - B)) + (B * DEFSUM)
      IF (DEND - 0.0)810,811,811
 0810 DEND = 0.0
 0811 IF (TAB(I,3) -CRMILE)21,21,81
```

```
0081 IF (0.02 - TIMEC)22,22,82
0082 DCLBS = DEFSUM
     GO TO 12
0021 DCLBS = DEND
     TIMEC = TEND
     CRMILE = TAB(I,3)
     GO TO 12
0022 CC = E ** (-TAB(I,17)*TIMEC)
     CC1 = TAB(I,17) * CC * SUMBOD
     DCLBS = (CC1 + (Z * (1.0 - CC)) + ZSL) / REK2
0012 DCPPM = DCLBS / (5.39 * QSUM)
     DOCPPM = TAB(I,15) - DCPPM
     IF (1 - N1)213,213,32
0213 IF(1.02 * TAB(I,6) - QSUM)77,203,203
0203 IF(0.98 * TAB(I,6) - QSUM)32,32,28
0028 QREQD = QSUM * (TAB(I,15)-DOCPPM)/(TAB(I,15)-TAB(I,16))
     IF (QSUM - QREQD)35,29,29
0029 IF(LFLAG - 1)32,30,77
0030 IF((0.01 * TAB(I,6)) - ABSF(QREQD - QSUM))31,33,33
0031 IF(HUNTER - TAB(I,1))34,90,77
0090 N = NHOLD
     HUNTER = 0.0
     GO TO 50
0032 QREQD = QSUM
     IF(DOCPPM - 0.0)77,77,34
```

```
0033 LFLAG = 0
     NHOLD = 0
0034 Q539 = 5.39 * QSUM
     DENDPM = DEND / Q539
     BODNDP = SUMBOD * A
     BODEND = BODNDP / Q539
     DOSAP = Q539 *TAB(I,15)
     DOENDP = DOSAP - DEND
     DOEND = DOENDP / Q539
     IF(2.0 - TAB(I,2))37,38,38
0037 QMUP = QSUM
     BODMU = BODNDP
     DOMUP = DOENDP
     GO TO 41
0038 IF(1.0 - TAB(I,2))39,40,40
0039 QTUP = QSUM
     BODTU = BODNDP
     DOTUP = DOENDP
     GO TO 41
0040 QBUP = QSUM
     BODBU = BODNDP
     DOBUP = DOENDP
0074 FORMAT(1H, 2F6.0,F10.0,4F9.2,F9.1,2F10.3,3F8.1,F12.5,F8.1)
0073 FORMAT(1H2,1X,4HRENO,3X,5HDIGIT,4X,4HQSUM,4X,6HDOCPPM,4X,5HDCP
    24X,5HDOEND,3X,6HDENDPM,3X,6HBODEND,5X,5HTIMEC,5X,4HTEND,3X,
```

```
    36HCRMILE,3X,5HRELEN,3X,5HRIVMI,7X,4HREK2,5X,4HTEMP)
0750 FORMAT(1H2,1X,4HRENO,3X,5HDIGIT,4X,4HQDUP,6X,3HVEL,4X,6HDOCPPM)
0041 QDUP = QSUM
     IF(1 - KOUNT)77,75,141
0760 PRINT 750
     LINE = 0
0141 IF(26 - LINE)760,760,98
0098 PRINT 74, TAB(I,1),TAB(I,2),QDUP,VEL,DOCPPM
     LINE = LINE + 1
0072 IF(1.0 - TAB(I,1))79,79,71
0071 KOUNT = KOUNT + 1
     QMUP = 0.
     BODMU = 0.0
     DOMUP = 0.0
     I = 1
     N1 = 0
     LINE = 26
     GO TO 4
0075 IF(1.0 - TAB(I,1))762,762,77
0762 IF(26 - LINE)763,763,76
0763 PRINT 73
     LINE = 0
0076 PRINT 74,TAB(I,1),TAB(I,2),QSUM,DOCPPM,DCPPM,DOEND,DENDPM,BODEND,
    2TIMEC,TEND,CRMILE,TAB(I,3),TAB(I,4),REK2,TAB(I,14)
     LINE = LINE + 1
0079 I = I + 1
```

```
      GO TO 4
0077 PAUSE
0102 FORMAT(1H,1X,4HRENO,2X,4HHUNT,2X,5HDIGIT,2X,5HTIMEC,2X,6HDOCPPM,
    23X,3HKNT,3X,5HKOUNT,2X,2HN1,4X,2HN2,4X,2HN3,4X,2HN4,3X,5HLFLAG,
    34X,5HQREQD,7X,5HQOVER,8X,4HQSUM)
1102 FORMAT(1H,3F6.0,2F7.3,7I6,3F12.0)
      PRINT 102
      PRINT 1102,TAB(I,1),HUNTER,TAB(I,2),TIMEC,DOCPPM,KNT,KOUNT,N1,N2,
    2N3,N4,LFLAG,QREQD,QOVER,QSUM
      IF(1.0 - TAB(I,6))99,13,13
0013 STOP
0035 IF(0.10 - ABSF(DOCPPM - TAB(I,16)))36,34,34
0036 HUNTER = TAB(I,1)
      IF(LFLAG - 1)43,45,77
0043 LFLAG = 1
      GO TO 44
0045 QOVER = 0.0
0044 IF(2.0 - TAB(I,2))46,47,47
0047 IF(1.0 - TAB(I,2))48,49,49
0049 N = 1
      N1 = N1 -1
      IF(2-KNT)77,126,127
0126 N4 = N4 - 1
      GO TO 50
0127 N2 = N2 - 1
```

```
     GO TO 50
0048 IF(2-KNT)77,147,148
0147 N = N4
     N1 = N1 -N4
     N4 = 0
     GO TO 50
0148 N = N2
     N1 = N1 - N2
     N2 = 0
     GO TO 50
0046 N = N1
     N1 = 0
0050 DELTAQ = QREQD - QSUM
     FNUM = N
     QEACH = DELTAQ / FNUM
0052 IF(1.0 - TAB(I,5))53,53,51
0051 I = I - 1
     GO TO 52
0053 IF(TAB(I,6)-(TAB(I,30)+TAB(I,7)+TAB(I,8)))54,54,55
0055 QDIL = TAB(I,30) + QEACH
     N3 = N3 +1
     QSUM = QDIL + TAB(I,7) + TAB(I,8)
     IF(1.01 *TAB(I,6) - QSUM)57,61,61
0057 QOVER = QSUM
     QDIL = TAB(I,6) - QSUM + QDIL
```

```
      QSUM = TAB(I,6)
0061 TAB(I,30) = QDIL
      IF(N - N3)77,59,51
0059 NHOLD = N
      N3 = 0
      GO TO 4
0054 IF(1.0 - QOVER)69,51,51
0069 IF(1.02 * TAB(I,6) - QSUM)77,205,205
0205 IF(0.98 * TAB(I,6) - QSUM)51,51,60
0060 N3 = N3 + 1
      QOVER = QOVER + QEACH
      IF(QOVER - TAB(I,6))62,62,61
0062 QDIL = QOVER - QSUM + QDIL
      QSUM = QOVER
      QOVER = 0.0
      GO TO 61
      END
```

Explanation of Input Data Sheets

There are two input data cards for each reach and these are listed in consecutive rows on the input data sheets such as shown on Page 80. The number 011 seen immediately at the top of the page is "K" or the number of reaches included in this river system. The top two rows are the data for the first reach, the third and fourth rows are the data for the second reach and etc. The format or column headings proceeding from left to right along the first row are: RENO, DIGIT, RELEN, RIVMI, QMIN, QMAX, QI, QS, QOUT, DOS, DI, DD, SLOAD; and across the second row: TEMP, DOSAT, DOMIN, DOXK1, AK2, BK2, CVEL, DVEL, BODI, BODD, BODS, and BKLOD.

INPUT DATA FOR MODEL RIVER SYSTEM

```
011
105  2   70  180   960   1760    400    100     00      00    00   00      0
 134  105   80  0253  181100  000000 2350000  0000    00   00  1    0
103  1   72   72    30     40    100    010    00    00    00   00     0
 134  105   80  0253  375600  000000 2350000  0000    00   00  1    0
101  2  110  110     0   1680    600    100 1800    00    00   00     0
 134  105   80  0253  181100  000000 2350000  0000    00   00  1    0
 96  2   80  280   550    550     00    100    00    00    00   00     0
 180   95   80  0750  253600  000000 0057700  0461    00   00  1    0
 95  2  200  200   000    650    850   1500    00    00    80   00     0
 180   95   80  0750  214300  000000 0057700  0461    00   00 3000  00
 89  3  110 1870     0   2360    300    100    00    00    00   00     0
 160  100   70  0500  077320 -005333 0018600  0576    00   00  1    0
 88  3  110 1760     0   2390    300    100    00    00    00   00     0
 160  100   72   500   77320 -005333   18600   576    00   00  1    0
 87  3  110 1650     0   2420    300    100    00    00    00   00     0
 160  100   78   500   77320 -005333   18600   576    00   00  1    0
 86  3  110 1540     0   2450    300    100    00    00    00   00     0
 160  100   50  0500  077320 -005333 0018600  0576    00   00  1    0
 85  3  110 1430     0   2480    300    100    00    00    00   00     0
 160  100   80  0500  077320 -005333 0018600  0576    00   00  1    0
000000000

 0 0   00    00        0     10    00   000    00   0
```

INPUT DATA FOR WILLAMETTE RIVER SYSTEM

046

105 2 70 180 1720 1760 400 031 00 00 10 10 0

134 105 60 253 181100 00000 2350000 000 10 06 16 0

103 1 72 72 30 40 100 000 00 00 10 09 0

134 105 60 253 375600 00000 4000000 000 01 00 0 0

101 2 110 110 0 1680 600 000 1800 00 10 00 0

134 105 60 253 181100 00000 2350000 000 10 00 0 0

99 2 70 70 630 650 200 000 00 00 10 09 0

180 95 60 312 486000 00000 100000 501 10 05 0 0

97 1 80 280 125 135 100 000 00 00 10 09 0

180 95 60 312 438000 00000 615000 208 10 05 0 0

96 2 120 200 0 800 150 101 00 00 10 00 0

180 95 60 312 253600 00000 057700 461 10 00 80 0

95 2 80 80 0 810 100 000 00 00 10 00 0

180 95 60 312 214300 00000 057700 461 10 00 0 0

93 3 20 1870 0 2490 00 009 00 00 10 00 0

150 102 60 270 77320 -005333 018600 576 10 00 161 0

91 3 50 1850 0 2520 240 605 00 00 10 00 0

160 100 60 282 77320 -005333 018600 576 10 00 28 0

89 3 40 1800 0 2540 50 1490 00 00 10 00 0

166 99 60 292 56690 -005333 006150 712 10 00 165 0

85 2 30 560 1435 1445 100 000 00 00 00 00 0

160 100 60 296 480400 00000 6000000 000 01 00 0 0

81 2 150 530 0 1680 2350 000 00 00 00 00 0

160	100	60	296	150000	00000	2250000		000	01	00	0	0
79	2	280	380	0	1790	1100	000	00	00	00	00	0
160	100	60	296	134930	00000	2200000		000	10	00	0	0
77	2	100	100	0	1840	400	1031	00	00	10	00	0
170	97	60	310	95337	00000	2000000		000	10		59	0
75	3	120	1760	0	4380	00	002	00	00	10	00	0
180	95	60	312	95147	-006383	022900		585	10	00	400	0
73	3	210	1640	0	4500	1200	056	00	00	10	00	0
185	94	60	320	95147	-006383	022900		585	10	00	185	0
71	2	126	236	30	35	50	000	00	00	10	05	0
215	89	60	345	193500	0000	750000		000	10	14	0	0
70	2	110	110	0	35	00	008	00	00	10	00	0
215	89	60	345	193500	00000	500000		000	10	00	180	0
69	3	80	1430	0	4610	750	000	00	00	10	00	0
195	93	60	335	40600	00000	006020		698	10	00	0	0
67	2	75	75	20	20	00	018	00	00	10	07	0
210	90	60	340	229800	0000	750000		000	10	16	65	0
65	3	150	1350	0	4700	450	2636	00	50	10	00	0
195	93	60	335	134600	-009309	032520		513	10	00	106	0
64	2	100	500	30	30	00	000	00	00	10	05	0
200	92	60	330	520000	00000	3000000		000	10	03	0	0
63	2	100	400	0	30	00	000	00	00	10	00	0
200	92	60	330	401330	00000	1500000		000	10	00	0	0
62	2	300	300	0	30	00	011	00	00	10	00	0
200	92	60	330	296550	00000	1000000		000	10	00	175	0

61	3	110	1200	0	4800	600	830	00	00	10	00	0	
200	92	60	342	437650	-024468	025900	527			10	00	145	0
59	2	208	458	1175	1230	550	000	00	00	10	05	0	
120	108	60	240	221030	00000	6000000	000			10	05	0	0
57	2	250	250	0	1330	1000	002	00	00	10	00	0	
160	100	60	296	191880	00000	5000000	000			10	00	300	0
55	1	125	275	160	180	200	039	00	00	10	05	0	
190	94	60	315	232230	00000	2800000	000			10	10	72	0
54	1	30	150	0	60	0	0	1200	0	0	0	0	
190	94	60	315	220000	00000	720000	000			10	10	0	0
53	1	120	120	0	75	0	1434	0	0	0	0	0	
200	92	60	323	220000	00000	720000	000			10	10	140	0
51	2	110	110	0	725	00	000	00	0	0	00	0	
165	98	60	303	145300	00000	2250000	000			10	00	0	0
47	3	250	1090	0	5600	750	000	00	00	10	00	0	
195	93	60	335	277544	-017553	088570	391			10	00	0	0
43	3	290	840	0	5900	2700	2948	00	00	10	00	0	
200	92	60	342	147679	-010372	038830	489			10	00	240	0
39	2	110	110	30	40	74	262	00	00	10	00	0	
220	88	60	350	37900	00000	500000	000			10	24	19	0
37	3	50	550	0	5960	200	000	00	00	10	00	0	
210	90	60	358	02435	25000	002410	779			10	00	0	0
35	3	140	500	0	6110	1450	527	00	00	10	00	0	
215	89	60	345	00253	31900	000275	859			10	00	1139	0
33	2	150	260	10	20	95	062	00	00	10	15	0	

200 92 60 300 15000 00000 2400000 000 06 06 860 0
32 2 110 110 0 30 100 019 00 00 10 00 0
200 92 60 300 15000 00000 2400000 000 06 00 158 0
31 3 70 360 0 6220 800 026 00 00 10 00 0
215 89 60 345 00571 27100 001666 681 10 00 145 0
29 2 130 590 10 10 00 007 00 00 10 10 0
220 88 60 350 12000 00000 300000 000 10 10 133 0
27 2 70 460 0 15 40 095 00 00 10 00 0
220 88 60 350 12000 00000 300000 000 10 00 92 0
26 2 110 390 0 35 170 339 00 00 10 00 0
220 88 60 350 12000 00000 300000 000 10 00 39 0
25 2 220 280 0 45 90 046 00 00 10 00 0
220 88 60 350 12000 00000 300000 000 10 00 150 0
23 2 60 60 0 25 12 397 250 00 10 00 0
220 88 60 350 12000 00000 300000 000 10 00 37 0
21 3 30 290 0 6245 00 012 00 00 10 00 0
215 89 60 345 00571 27100 01666 681 10 00 95 0
00 00
000000000

MOUTH OF TUALATIN R. TO MOUTH OF MOLALLA R.

R.M. 29 to R.M. 36
R.M. = River Mile

	Mean Velocity, fps			Mean Depth, ft		
Flow, cfs	2600	6600	8600	2600	6600	8600
1. R.M. 29	0.142	0.342	0.436	15.8	16.2	16.4
2. R.M. 30	0.407	0.973	1.236	22.0	22.3	22.6
3. R.M. 31	0.190	0.448	0.574	19.2	19.9	20.1
4. R.M. 33	0.276	0.565	0.690	13.2	14.9	15.4
5. R.M. 34	0.332	0.718	0.890	17.0	16.8	16.8
6. R.M. 35	0.420	0.862	1.05	11.8	12.8	13.2
7. R.M. 36	0.289	0.638	0.792	16.6	17.1	17.5
TOTAL	2.056	4.546	5.668	115.6	120.0	122.0
Average:	0.366	0.652	0.809	16.51	17.14	17.43

Using O'Connor's equation:

$$k_2 = \frac{(D_L\ U)^{\frac{1}{2}}}{2.31\ H^{3/2}} \quad @\ 20°\ C$$

D_L = Coefficient of diffusion

U = Mean forward flow velocity

H = Mean depth

$D_L = 6.7 \times 10^{-2}\ cm^2/hr.$ from F & G, p. 446 Rich, Unit Operation in San. Engr., p. 174.

$= 7.00 \times 10^{-s}\ ft^2/hr.$

$1.70 \times 10^{-3}\ ft^2/day$

$(1.70 \times 10^{-3}\ ft^2/day)(86,400\ sec/day)^* = \underline{\underline{146.88}}\ \frac{sec\ ft}{day^2}$

*Used to allow use of velocity in feet per second.

Q = 2600 cfs

$$k_2 = \left[\frac{(146.88)(0.366)}{2.31\ (16.51)^{3/2}}\right]^{\frac{1}{2}} = \frac{7.34}{155.5}$$

$k_2 = 0.0472$ ANS.

Q = 6600 cfs

$$k_2 = \left[\frac{(146.88)(0.652)}{2.31(17.14)^{3/2}}\right]^{\frac{1}{2}} = \frac{9.78}{164.2}$$

$k_2 = 0.0595$ ANS.

Q = 8600 cfs

$$k_2 = \left[\frac{(146.88)(0.809)}{2.31(17.43)^{3/2}}\right]^{\frac{1}{2}} = \frac{10.9}{166.5}$$

$k_2 = 0.0654$ ANS.

by Churchill equation

Q = 2600 cfs

$$k_2 = \frac{5.026(0.366)^{0.969}}{(16.51)^{1.675}} = \frac{1.89}{110}$$

$k_2 = 0.0171$ ANS.

Q = 6600 cfs

$$k_2 = \frac{5.026(0.652)^{0.969}}{(17.14)^{1.673}} = \frac{3.32}{116}$$

$k_2 = 0.0286$ ANS.

Q = 8600 cfs

$$k_2 = \frac{5.026(0.809)^{0.969}}{(17.43)^{1.673}} = \frac{4.09}{119}$$

$k_2 = 0.0343$ ANS.

MOUTH OF MOLALLA RIVER TO NEWBERG

R. M. 37 to R. M. 50

		Mean Velocity, fps			Mean Depth, feet		
Flow, cfs		2600	6600	8600	2600	6600	8600
	R.M.						
1.	37	0.216	0.485	0.609	18.88	20.70	21.25
2.	38	0.164	0.383	0.486	27.96	29.57	30.11
3.	39	0.238	0.526	0.657	16.97	18.69	19.24
4.	40	0.303	0.664	0.826	15.52	17.26	17.78
5.	41	0.232	0.510	0.637	16.37	18.19	18.76
6.	42	0.193	0.438	0.551	20.96	22.48	22.96
7.	43	0.259	0.575	0.718	17.26	18.64	19.11
8.	44	0.274	0.606	0.754	16.74	17.60	17.90
9.	45	0.258	0.559	0.694	14.53	16.37	16.94
10.	46	0.228	0.514	0.645	19.56	21.34	21.92
11.	47	0.276	0.606	0.755	16.21	17.86	18.34
12.	48	0.320	0.681	0.840	12.89	14.59	15.14
13.	49	0.223	0.498	0.625	18.48	20.34	20.92
14.	50	0.138	0.326	0.415	33.84	33.62	33.55
TOTAL		3.322	7.371	9.212	266.17	287.25	293.92
Average:		0.237	0.526	0.658	19.01	20.52	20.95

MOUTH OF MOLALLA RIVER TO NEWBERG

R. M. 37 to R. M. 50

For flow of 2600 cfs

$$k_2 = \frac{(146.88)(0.237)^{\frac{1}{2}}}{2.31(19.01)^{3/2}} = \frac{(34.81)^{\frac{1}{2}}}{191.73}$$

$$= \frac{5.9}{191.7} = \underline{\underline{0.0307}} \text{ ANS.}$$

For flow of 6600 cfs

$$k_2 = \frac{(146.88)(0.526)^{\frac{1}{2}}}{2.31(20.52)^{3/2}} = \frac{(77.25)^{\frac{1}{2}}}{215.7}$$

$$k_2 = \frac{8.79}{215.7} = \underline{\underline{0.0407}} \text{ ANS.}$$

For flow of 8600 cfs

$$k_2 = \frac{(146.88)(0.658)^{\frac{1}{2}}}{2.31(20.99)^{3/2}} = \frac{(96.64)^{\frac{1}{2}}}{221.7}$$

$$k_2 = \frac{9.83}{221.7} = \underline{\underline{0.0443}} \text{ ANS.}$$

$$k_2 = \frac{5.026\ V^{0.969}}{H^{1.673}}$$

For flow of 2600 cfs

$$k_2 = \frac{(5.026)(0.237)^{0.969}}{(19.01)^{1.673}} = \frac{1.246}{138}$$

$$k_2 = \underline{\underline{0.0090}} \quad \text{ANS.}$$

For flow of 6600 cfs

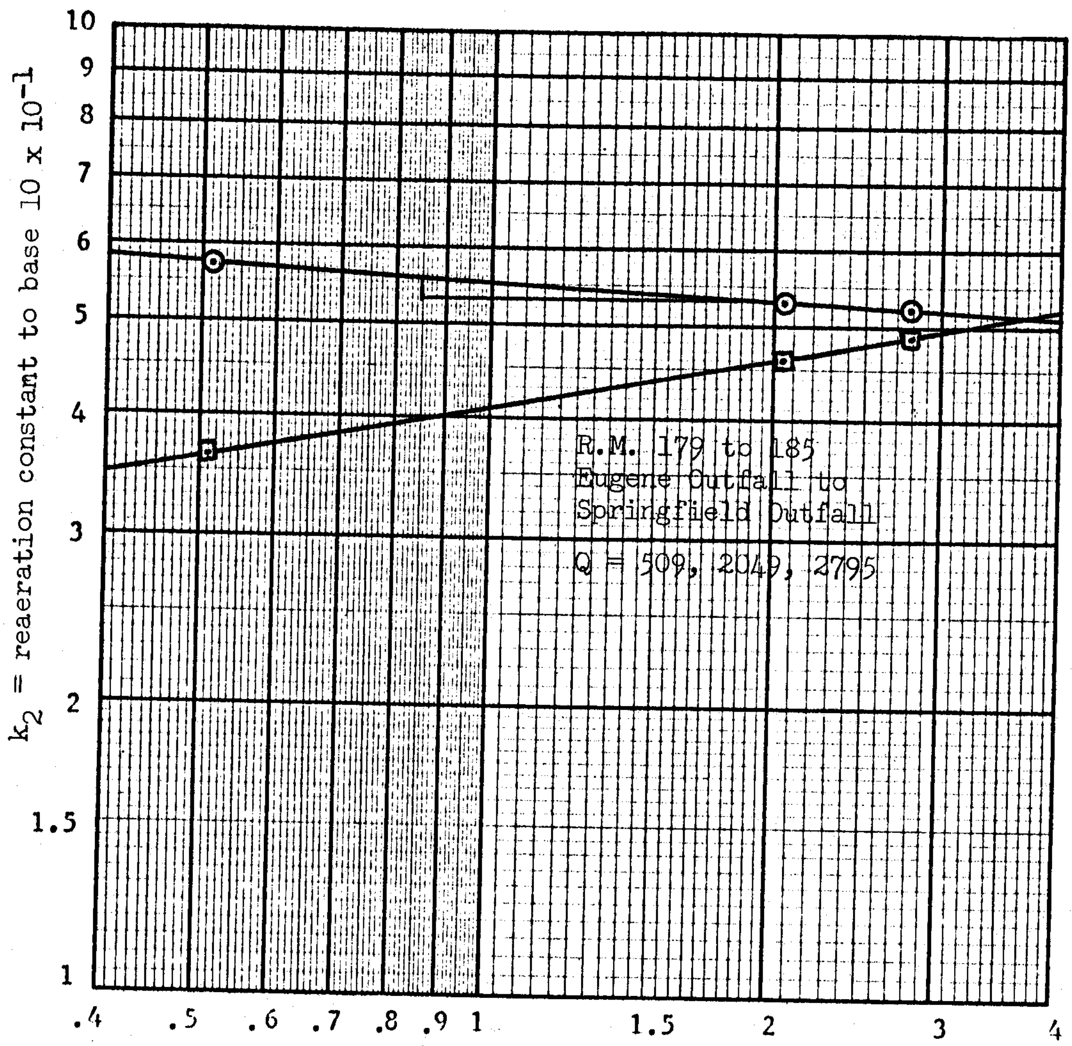
$$k_2 = \frac{(5.026)(0.526)^{0.969}}{(20.52)^{1.673}} = \frac{2.70}{158}$$

$$k_2 = \underline{\underline{0.0170}} \quad \text{ANS.}$$

For flow of 8600 cfs

$$k_2 = \frac{(5.026)(0.658)^{0.969}}{(20.99)^{1.673}} = \frac{3.35}{162}$$

$$k_2 = \underline{\underline{0.0206}} \quad \text{ANS.}$$



Discharge in 1000 cfs

⊙ = O'Connor Equation
⊡ = Churchill Equation

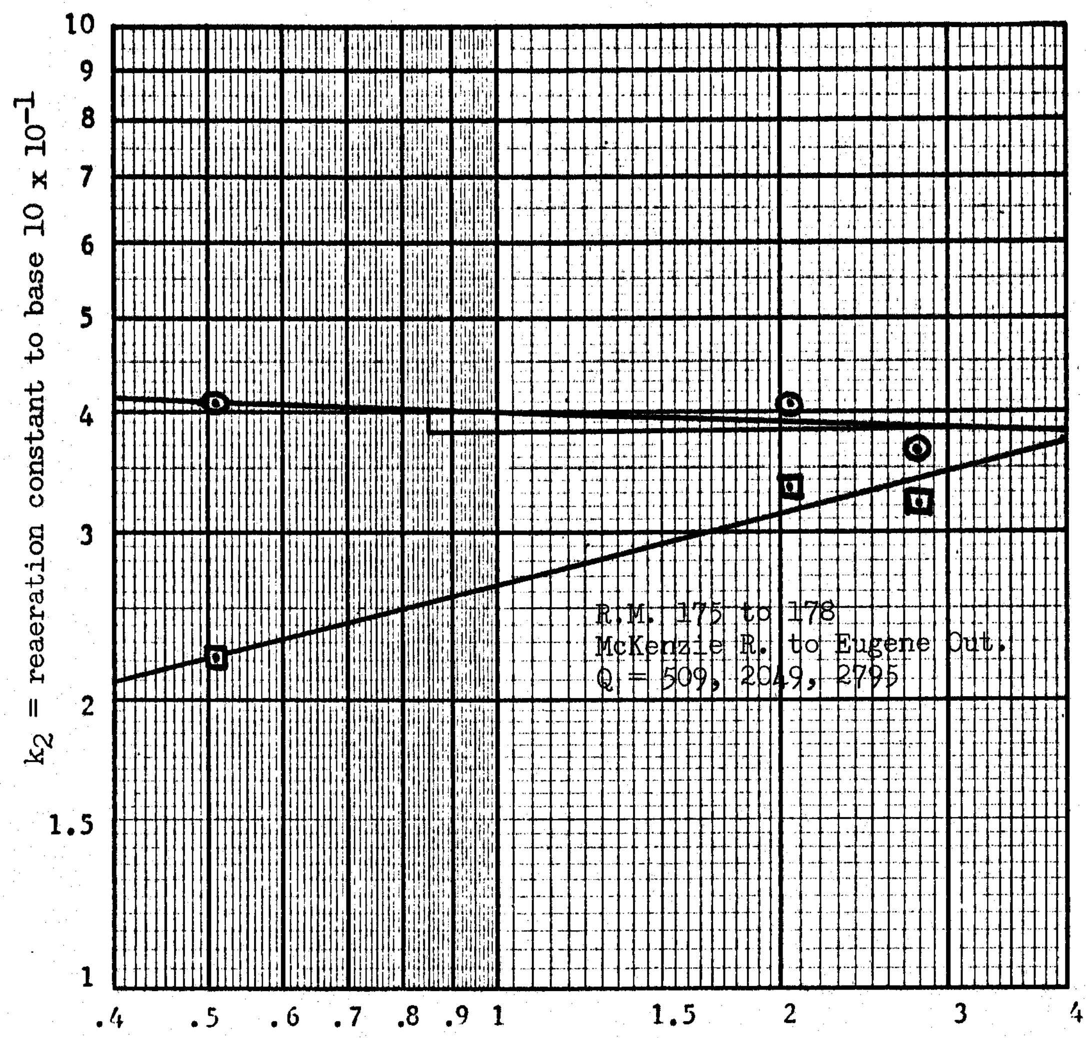
$b = \frac{-20}{375} = -0.05333$

$k_2 = 0.58$ @ $Q = 400$

$k_2 = aQ^{-b}$

$a = 0.58/0.7267 = 0.798$

So $k_2 = 0.798\ Q^{-0.05333}$



Discharge in 1000 cfs

⊙ = O'Connor Equation
▣ = Churchill Equation

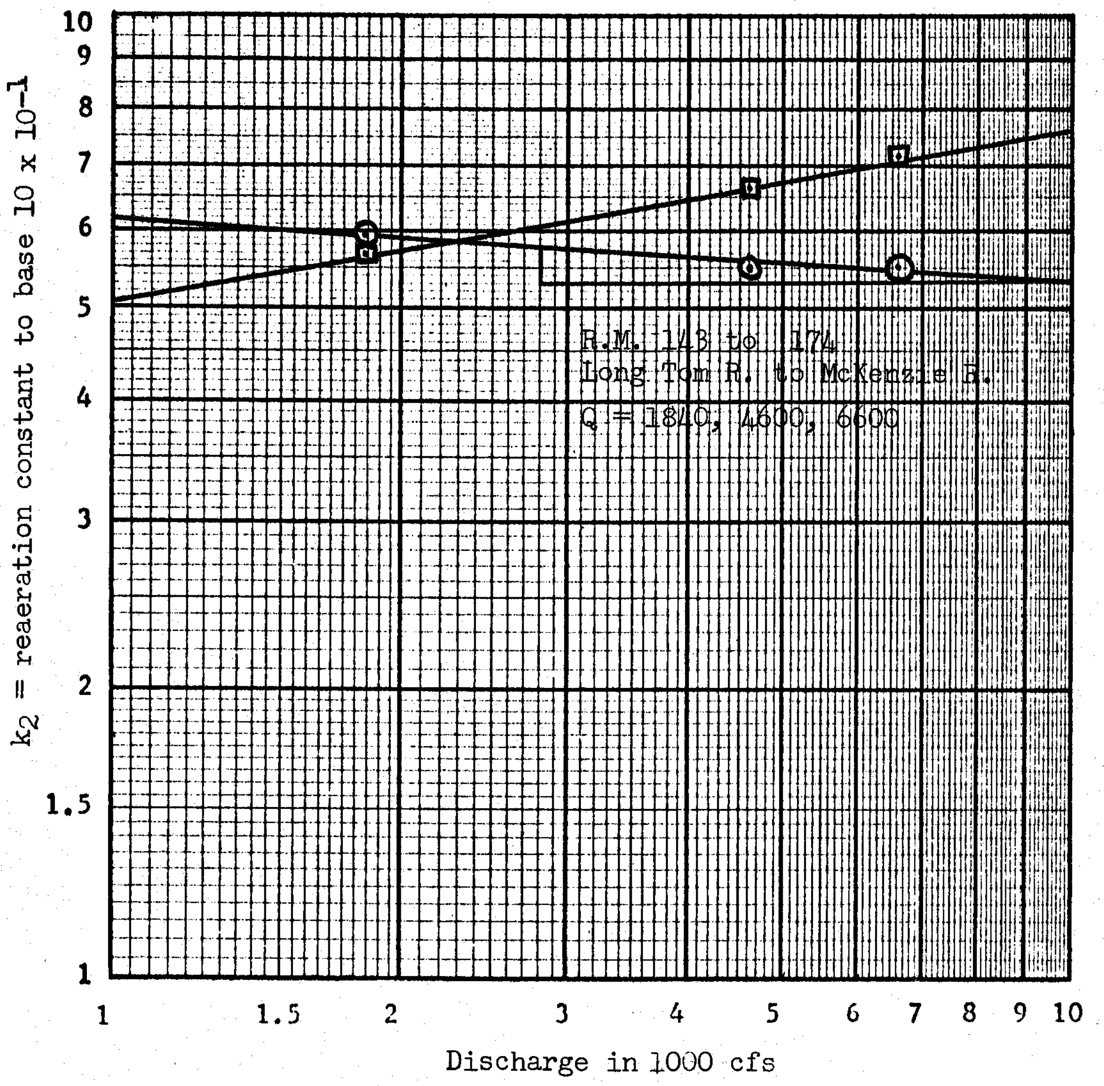
$b = \frac{-20}{375} = -0.05333$

$k_2 = 0.39$ @ $Q = 1500$

$k_2 = aQ^{-b}$

$a = 0.39/0.677 = 0.576$

So $k_2 = 0.576\ Q^{-0.05333}$



⊙ = O'Connor Equation

⊡ = Churchill Equation

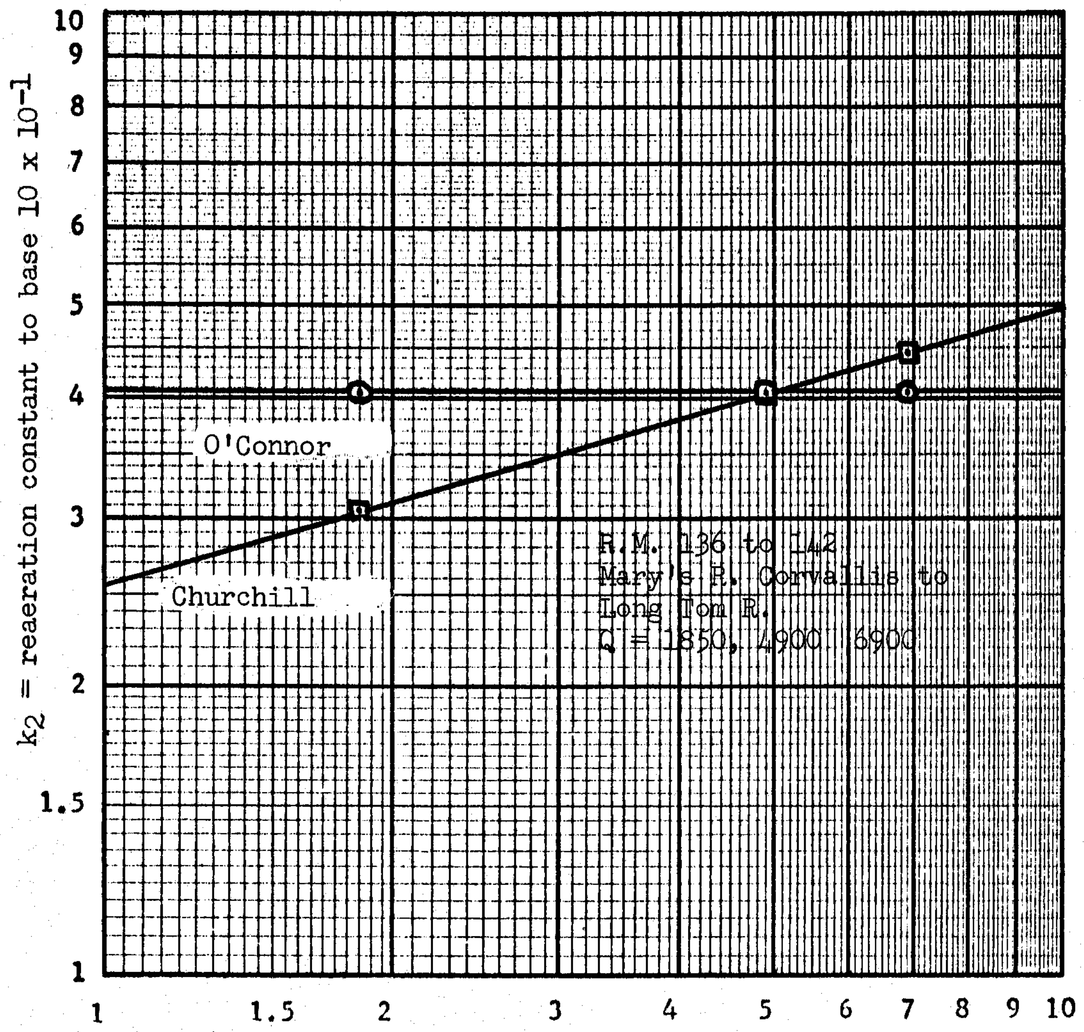
$$b = \frac{-24}{376} = -0.06383$$

$$k_2 = 0.58 \text{ @ } Q = 3000$$

$$k_2 = aQ^{-b}$$

$$a = \frac{0.58}{0.5999} = 0.9666$$

$$\text{So } k_2 = 0.9666\ Q^{-0.06383}$$



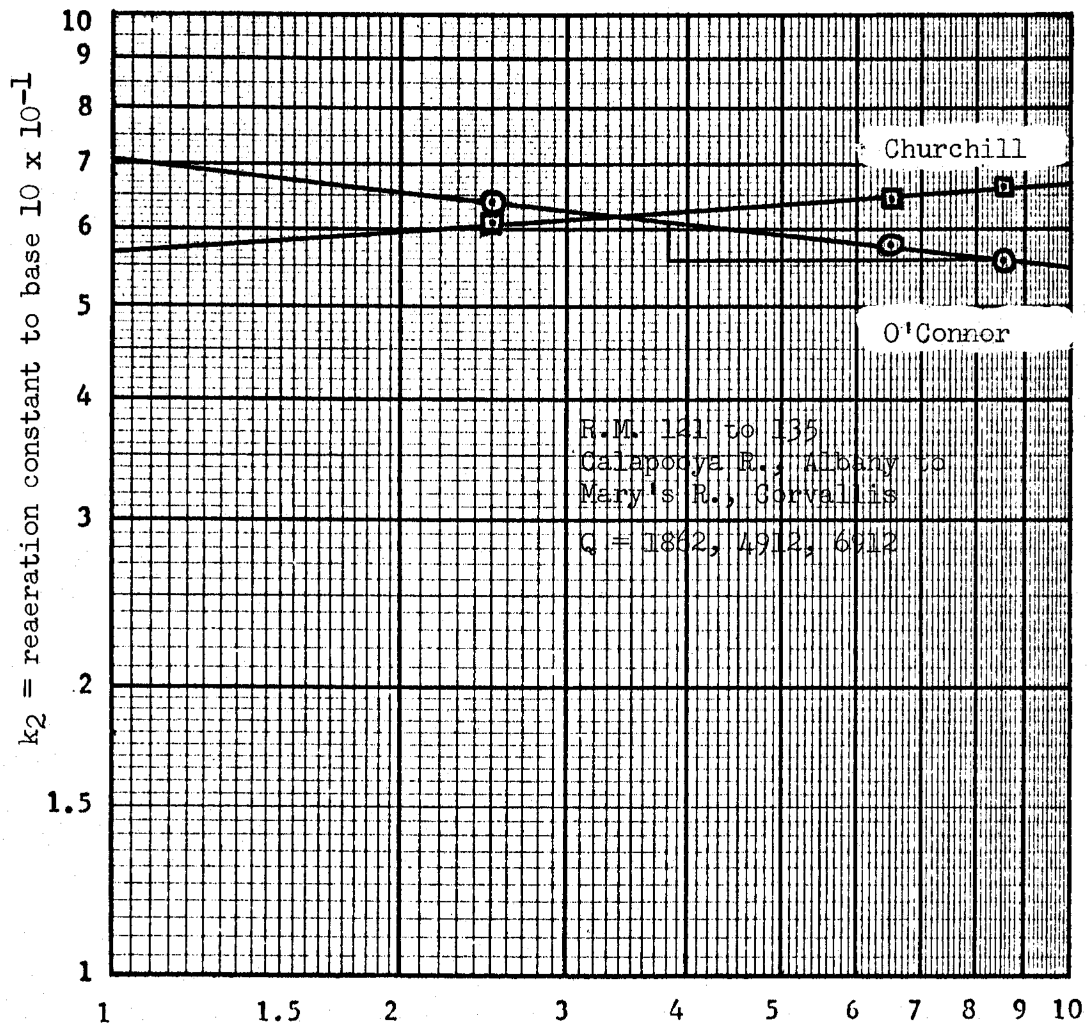
Discharge in 1000 cfs

$$b = \frac{0}{376} = 0$$

$$k_2 = aQ^b$$

$$a = 0.406$$

$$\text{So } k_2 = 0.406\ Q^0$$



Discharge in 1000 cfs

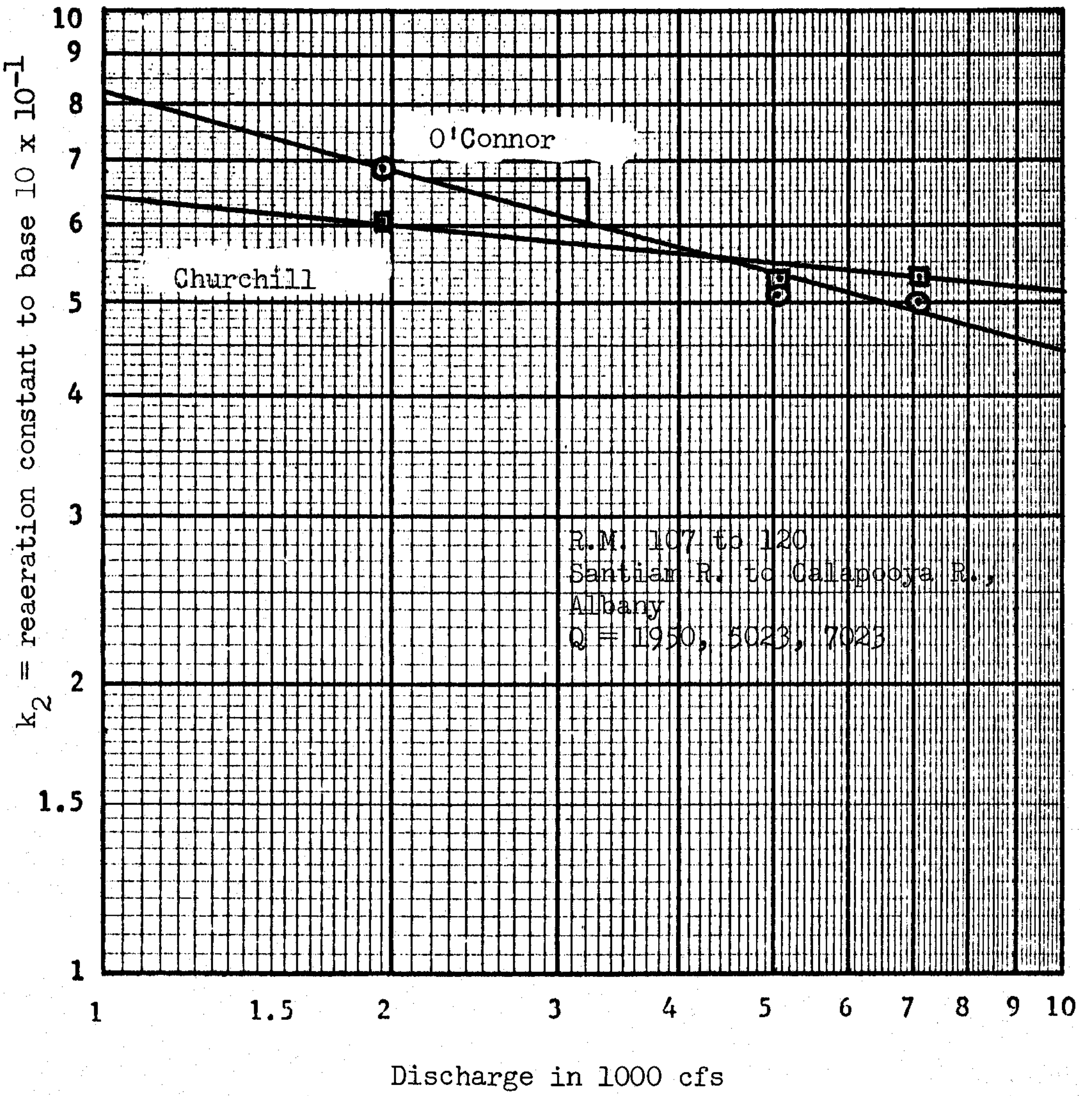
$$b = \frac{-35}{376} = -0.09309$$

$$k_2 = 0.63 \text{ @ } Q = 3500$$

$$k_2 = aQ^{-b}$$

$$a = \frac{0.63}{0.468} = 1.346$$

So $k_2 = 1.346\ Q^{-0.09309}$



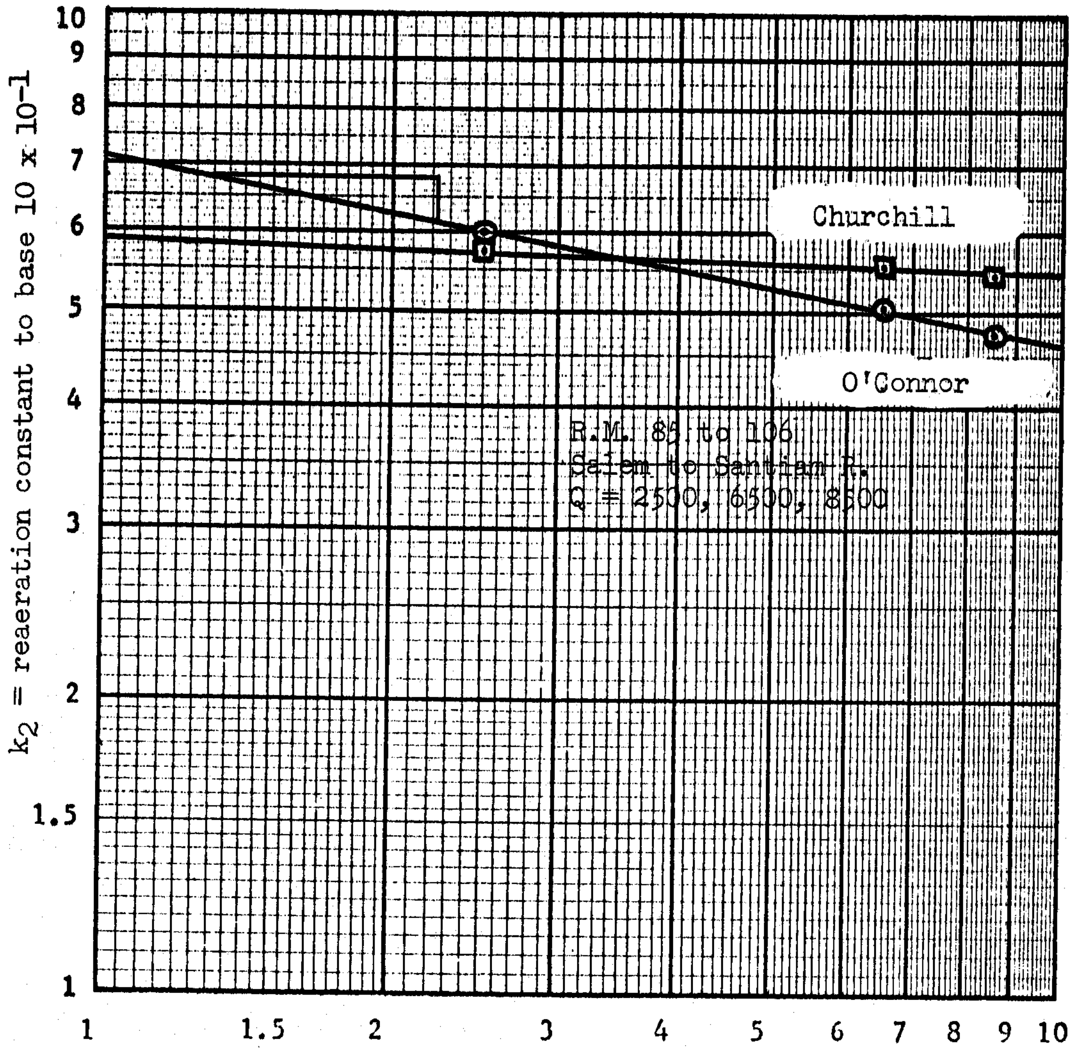
$$b = \frac{-92}{376} = -0.24468$$

$$k_2 = 0.67 \text{ @ } Q = 2000$$

$$0.67 = aQ^{-b}$$

$$a = \frac{0.67}{0.1555} = 4.308$$

$$\text{So } k_2 = 4.308\ Q^{-0.24468}$$



Discharge in 1000 cfs

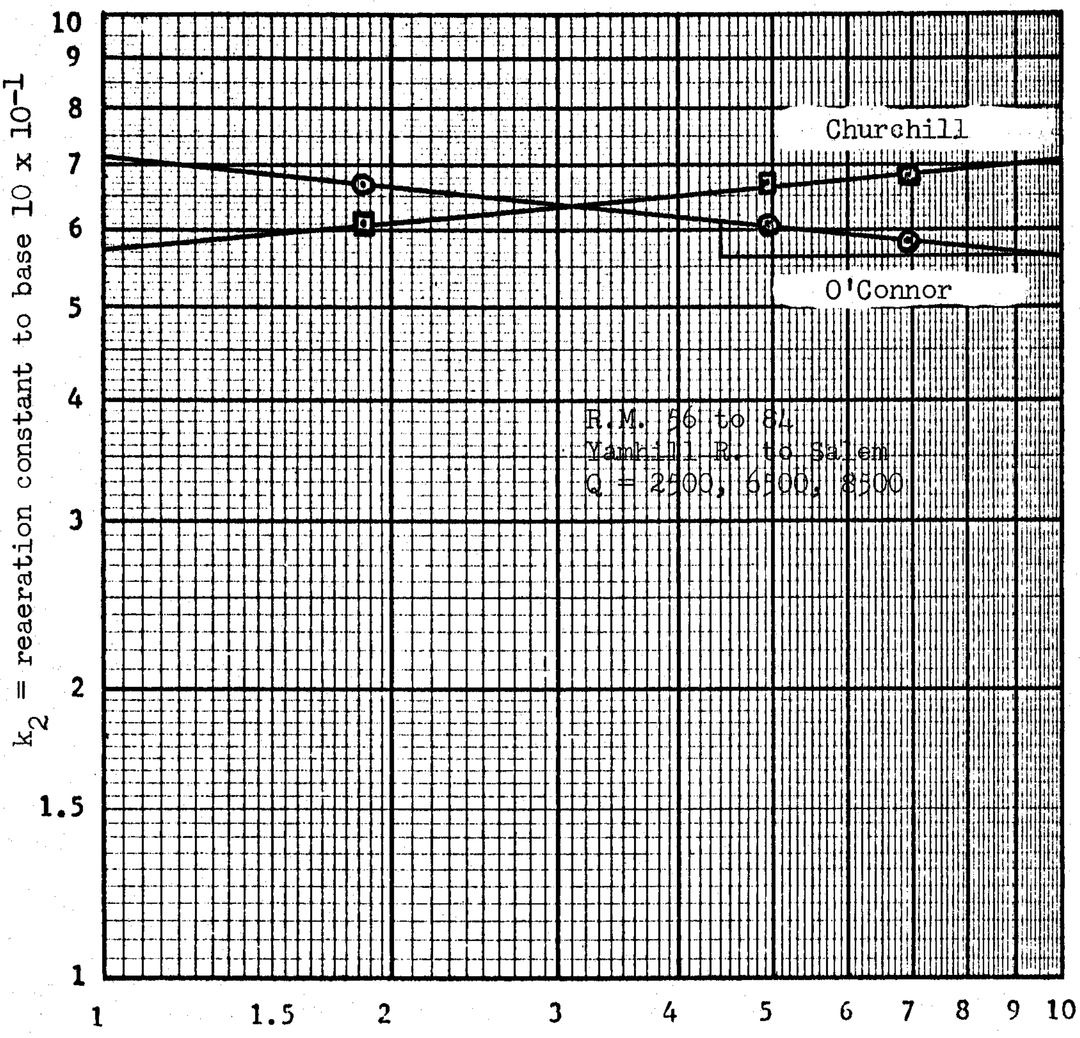
$$b = \frac{-66}{376} = -0.17553$$

$$k_2 = 0.65 \text{ @ } Q = 1600$$

$$0.65 = aQ^{-b}$$

$$a = \frac{0.65}{0.274} = 2.372$$

So $k_2 = 2.372\ Q^{-0.17553}$



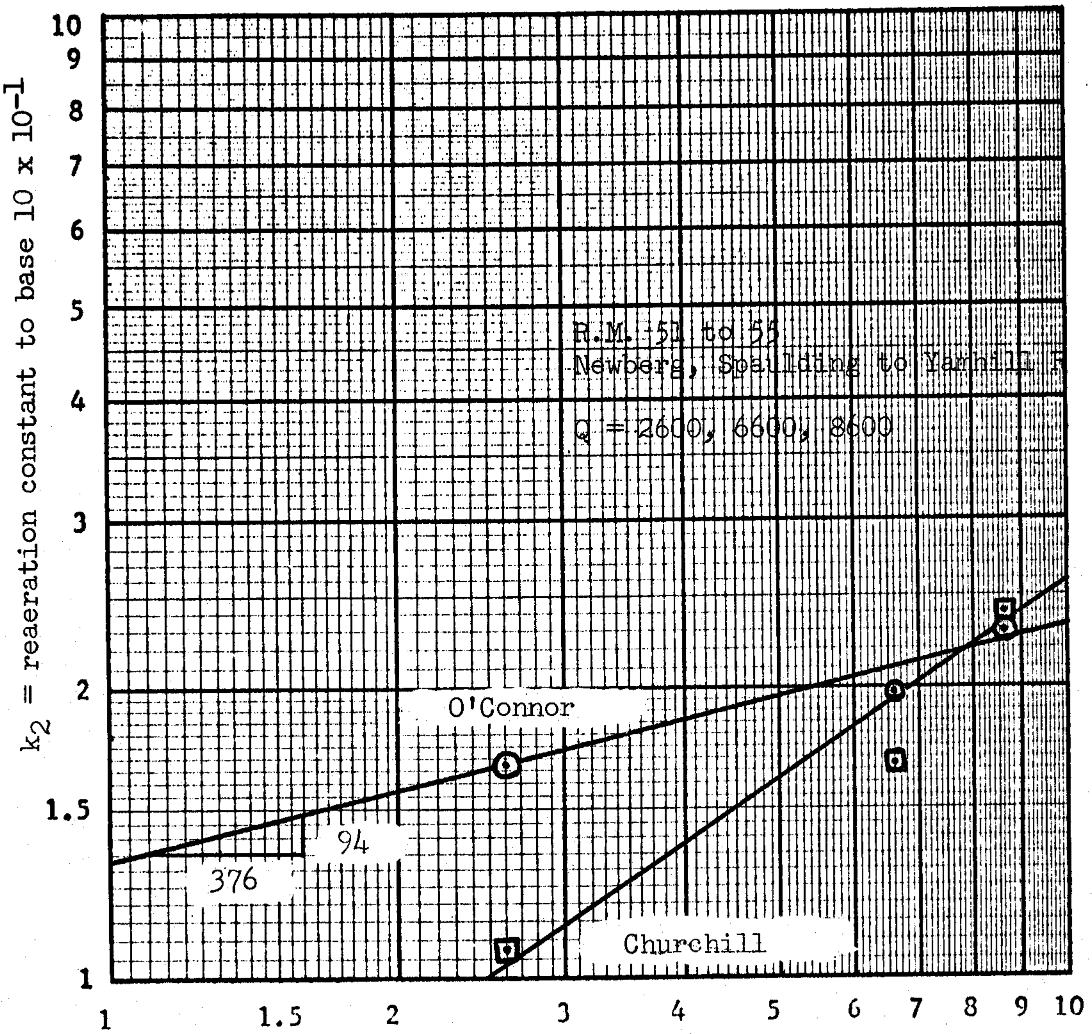
$$b = \frac{-39}{376} = -0.10372$$

$$k_2 = 0.70 \text{ @ } Q = 1000$$

$$0.70 = aQ^{-b}$$

$$a = \frac{0.70}{0.489} = 1.431$$

So $k_2 = 1.431\ Q^{-0.10372}$



Discharge in 1000 cfs

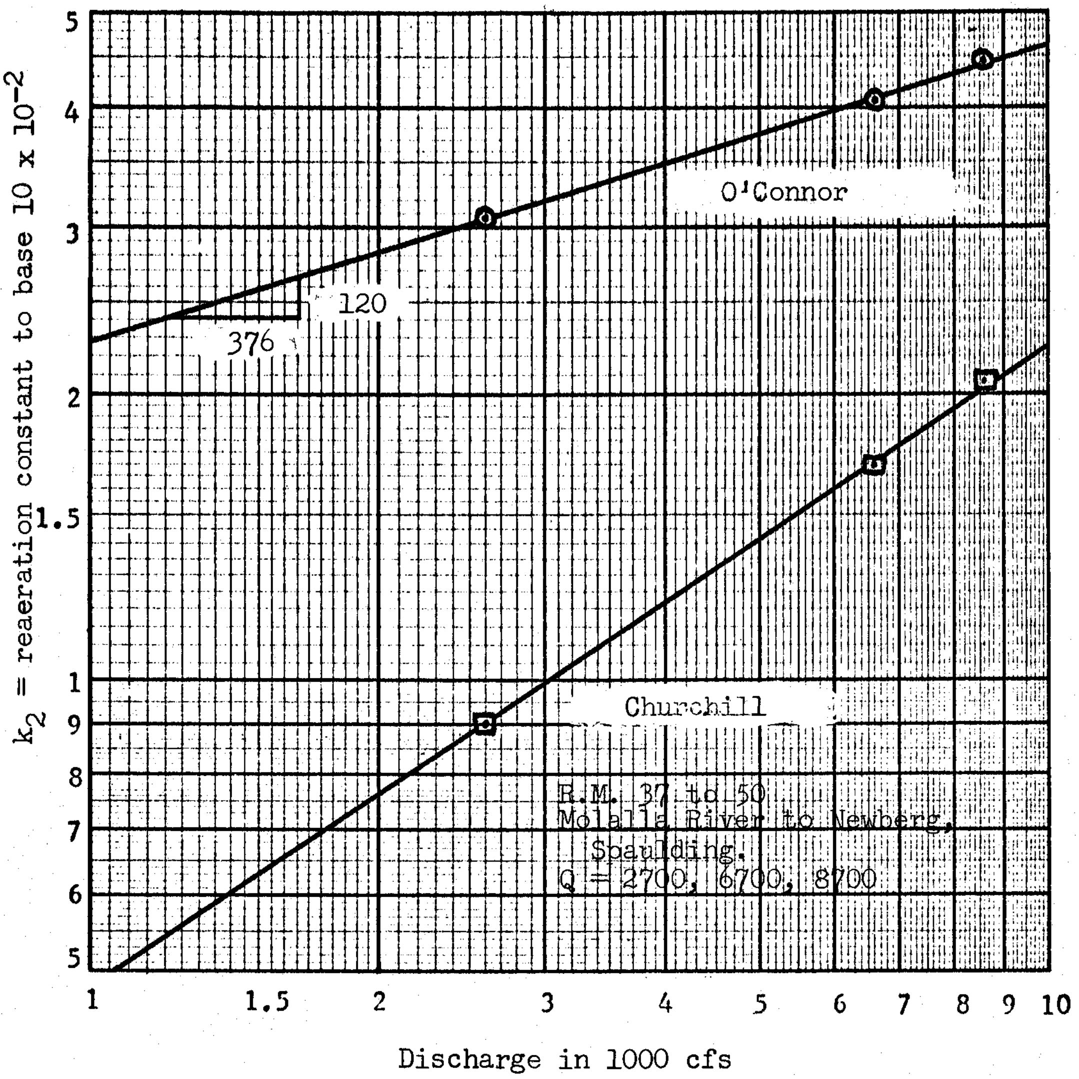
$$b = \frac{94}{376} = 0.250$$

$$k_2 = 0.2 \text{ @ } Q = 5200$$

$$0.2 = aQ^b$$

$$a = \frac{0.2}{8.48} = 0.0236$$

$$\text{So } k_2 = 0.0236\ Q^{0.250}$$



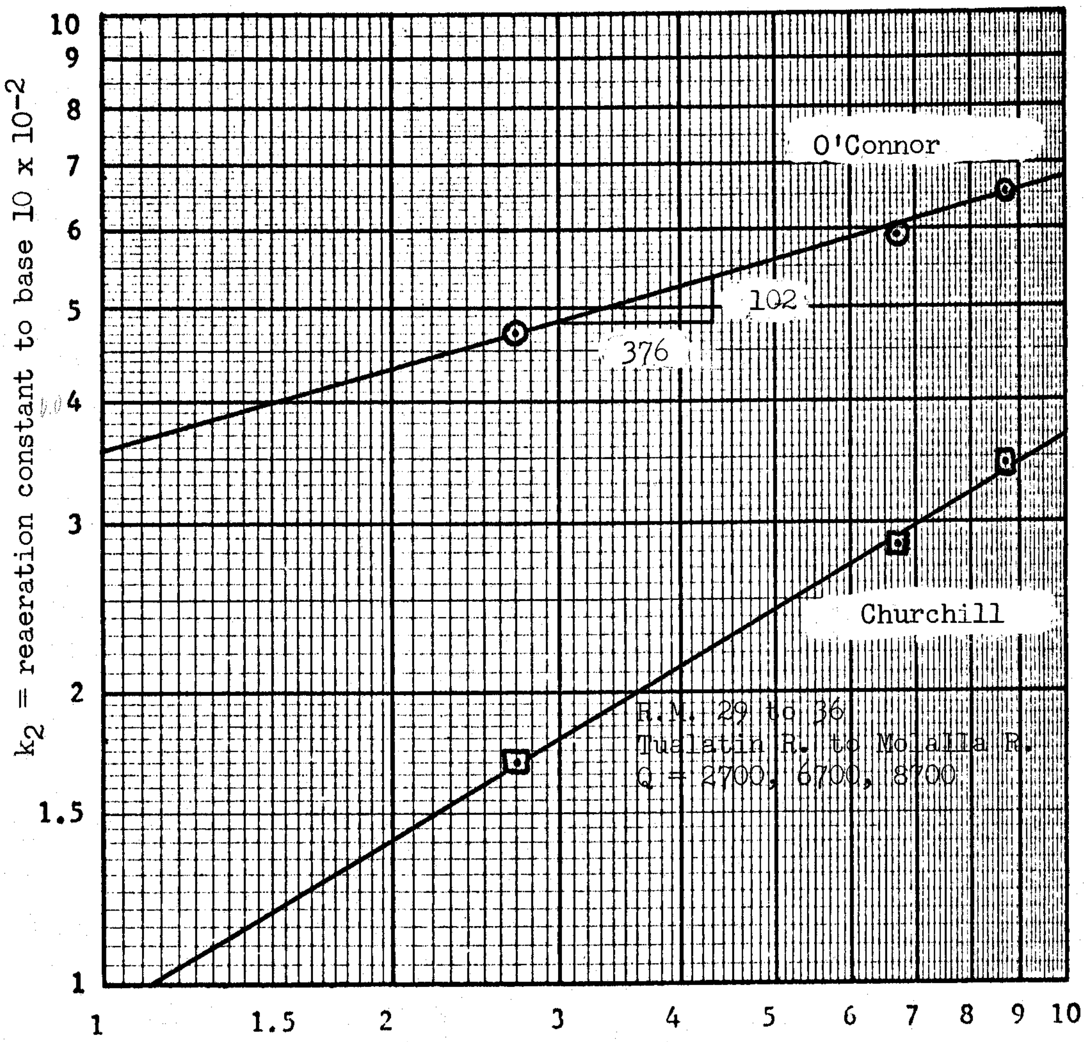
$$b = \frac{120}{376} = 0.319$$

$$k_2 = 0.0275 \text{ @ } Q = 1950$$

$$0.0275 = aQ^b$$

$$a = \frac{0.0275}{11.2} = 0.002455$$

$$\text{So } k_2 = 0.002455\ Q^{0.319}$$



Discharge in 1000 cfs

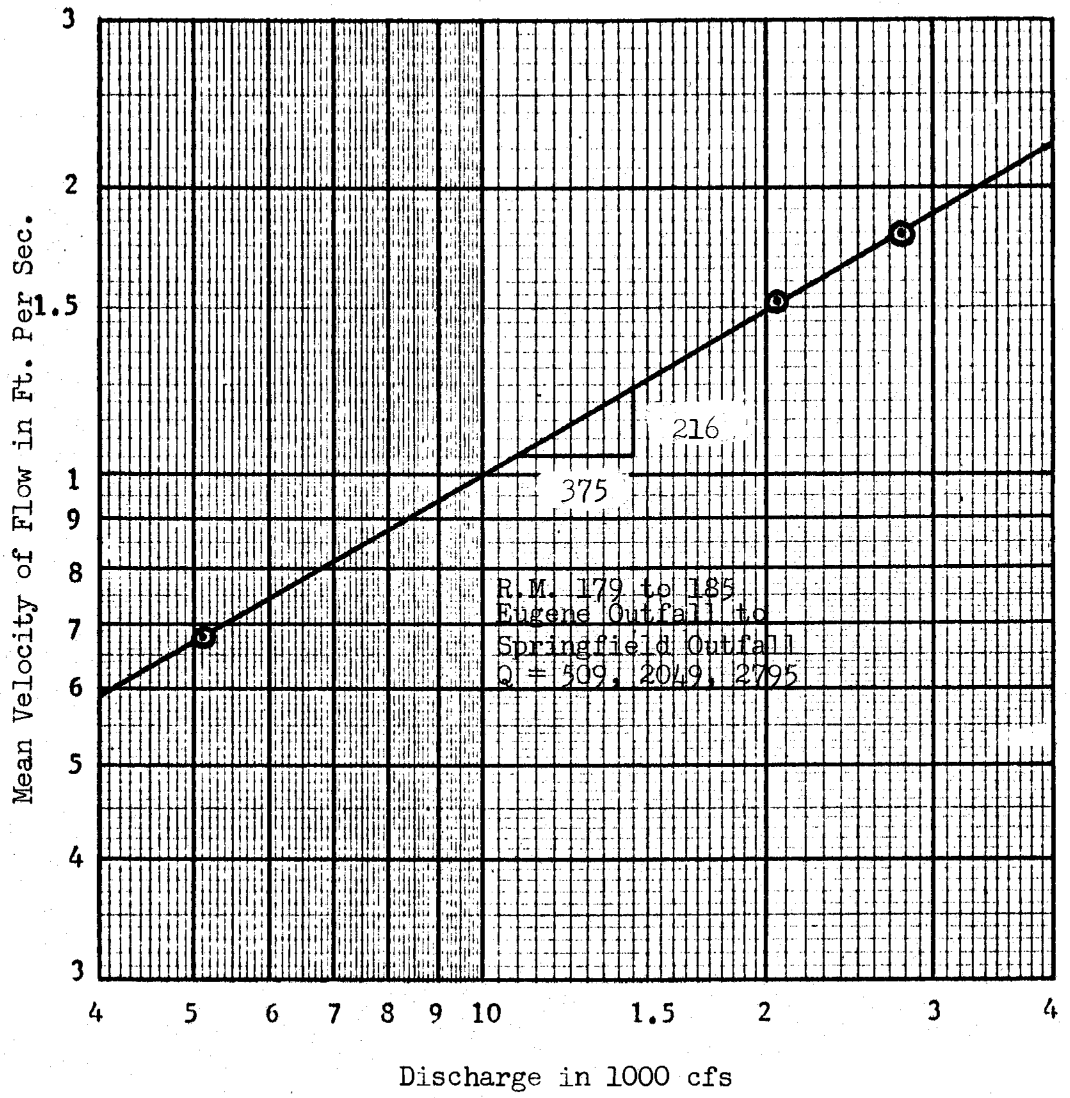
$$b = \frac{102}{376} = 0.271$$

$$k_2 = 0.042 \text{ @ } Q = 1750$$

$$0.042 = aQ^b$$

$$a = \frac{0.042}{7.59} = 0.005534$$

So $k_2 = 0.005534\ Q^{0.271}$



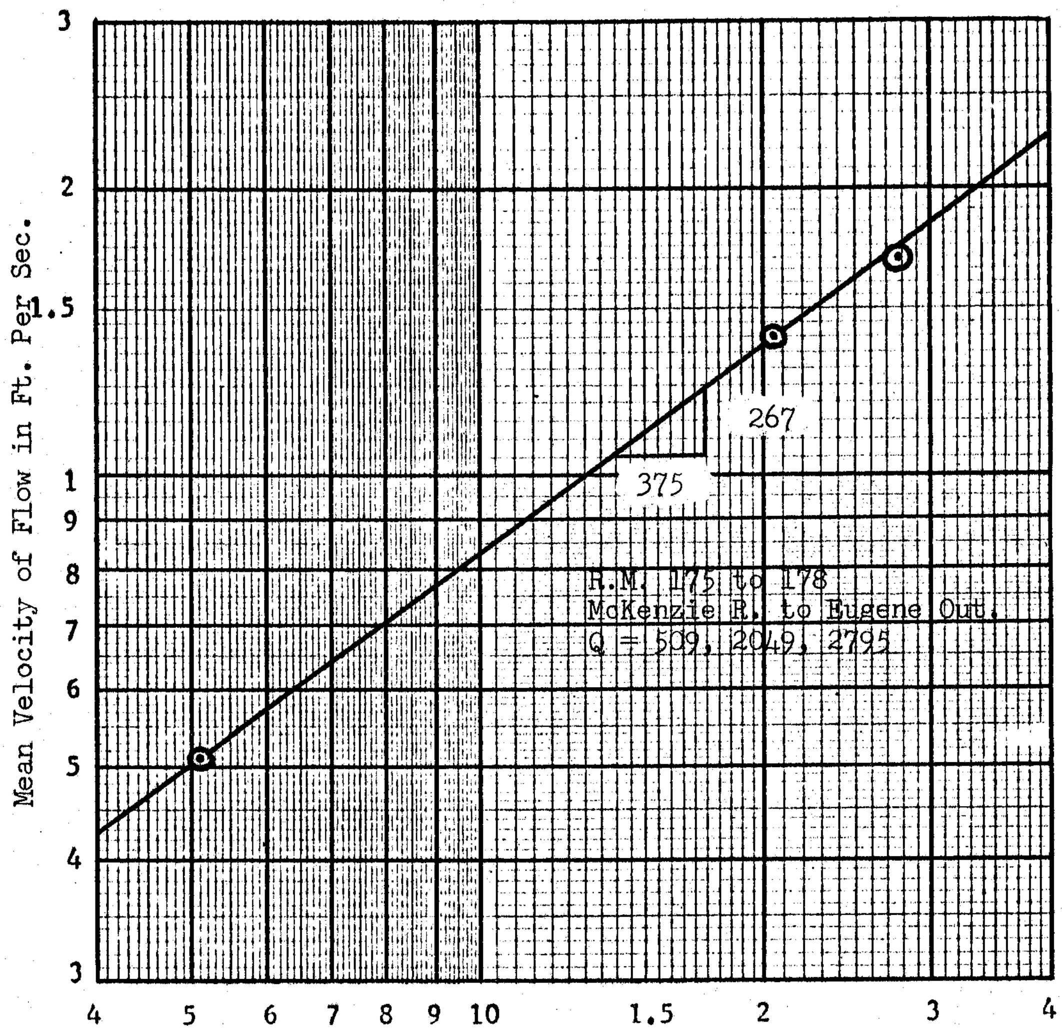
$$d = \frac{216}{375} = 0.576$$

@ V = 1.0, Q = 1000

$$1.0 = cQ^{d} = c1000^{0.576}$$

$$c = \frac{1}{53.5} = 0.0186$$

So $V = 0.0186\ Q^{0.576}$



Discharge in 1000 cfs

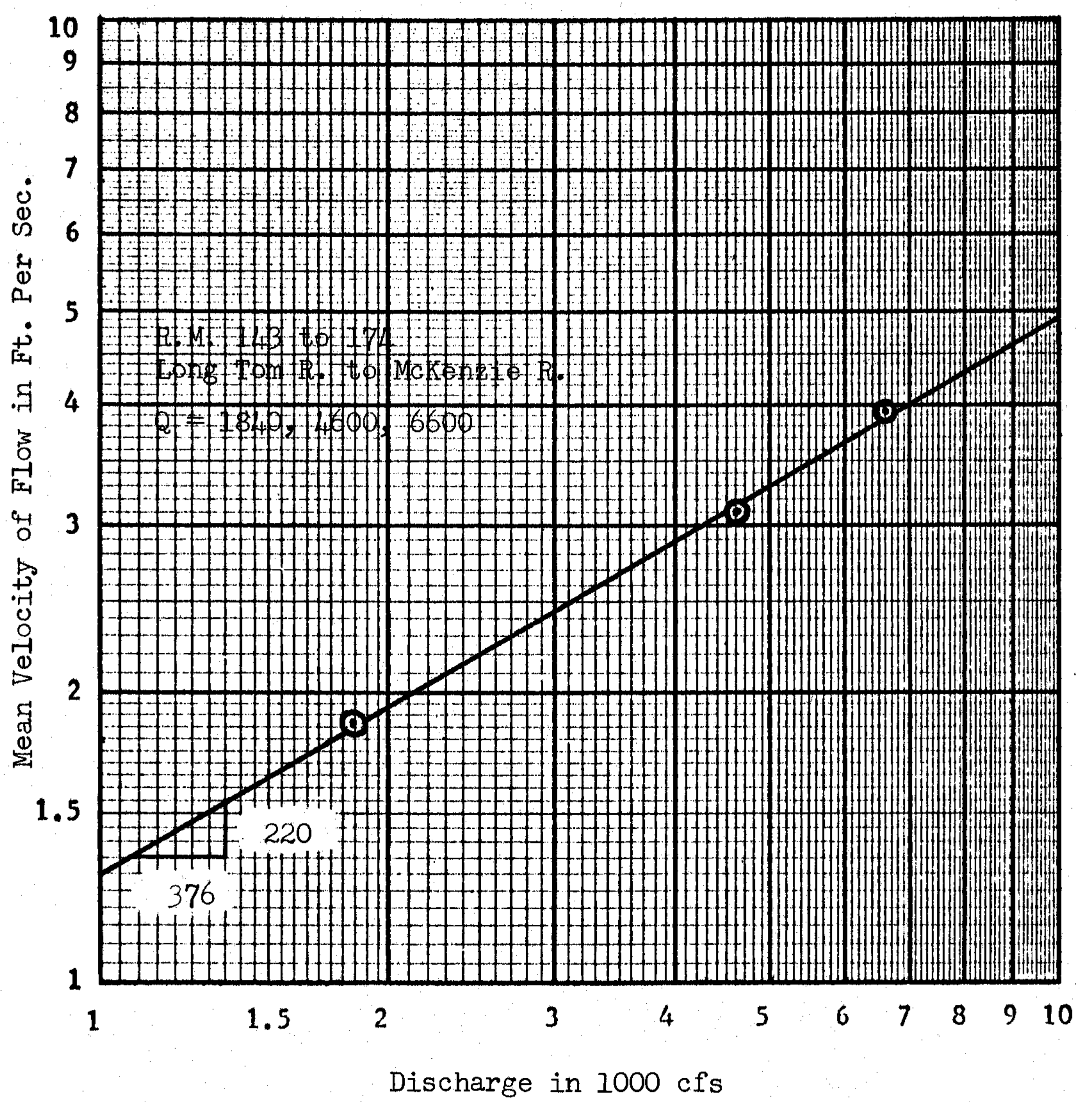
$$d = \frac{267}{375} = 0.712$$

@ Q = 1000, V = 0.84

$$0.84 = cQ^d = c1000^{0.712}$$

$$c = \frac{0.84}{136.5} = 0.00615$$

So $V = 0.00615\ Q^{0.712}$



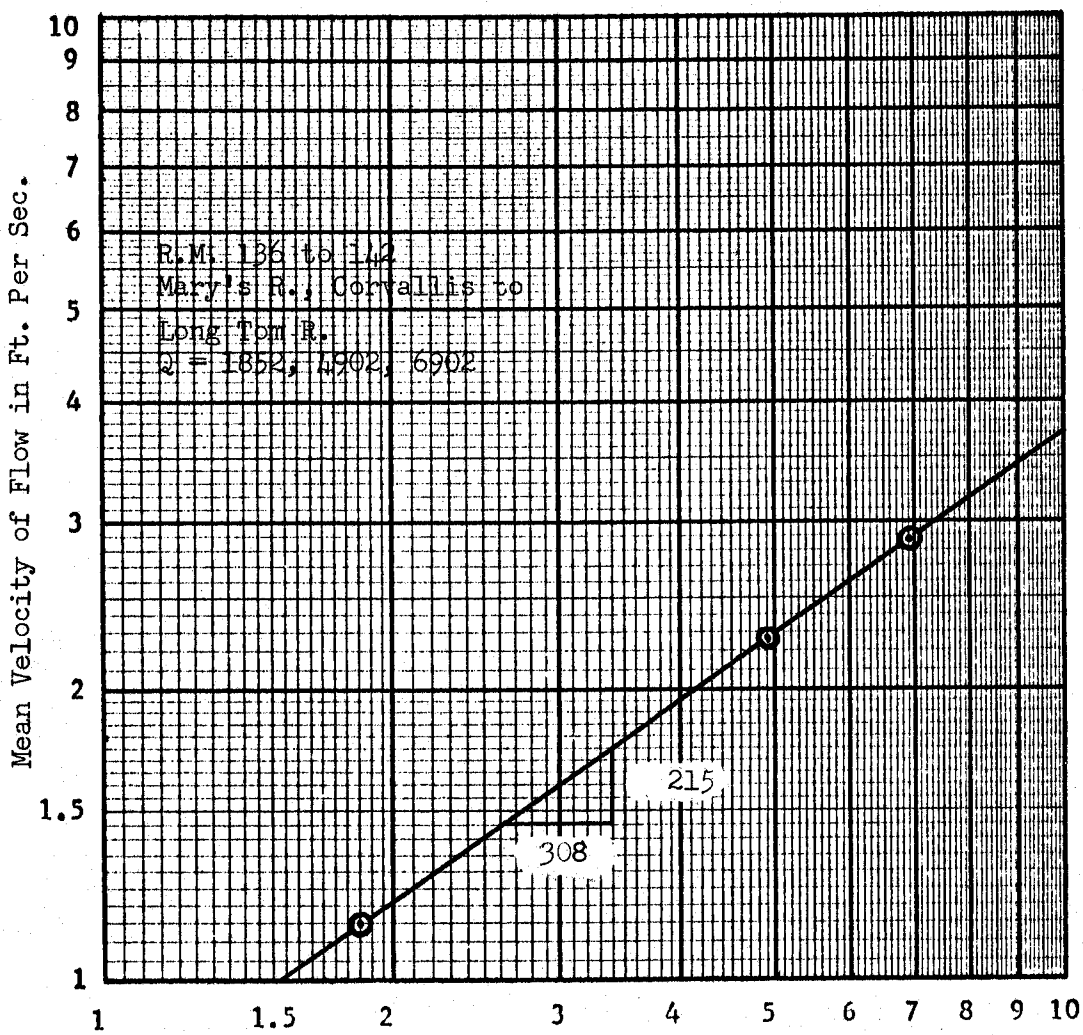
$$d = \frac{220}{376} = 0.585$$

@ Q = 1500, V = 1.65

$$1.65 = cQ^{d} = c1500^{0.585}$$

$$c = \frac{1.65}{72} = 0.0229$$

So $V = 0.0229\ Q^{0.585}$



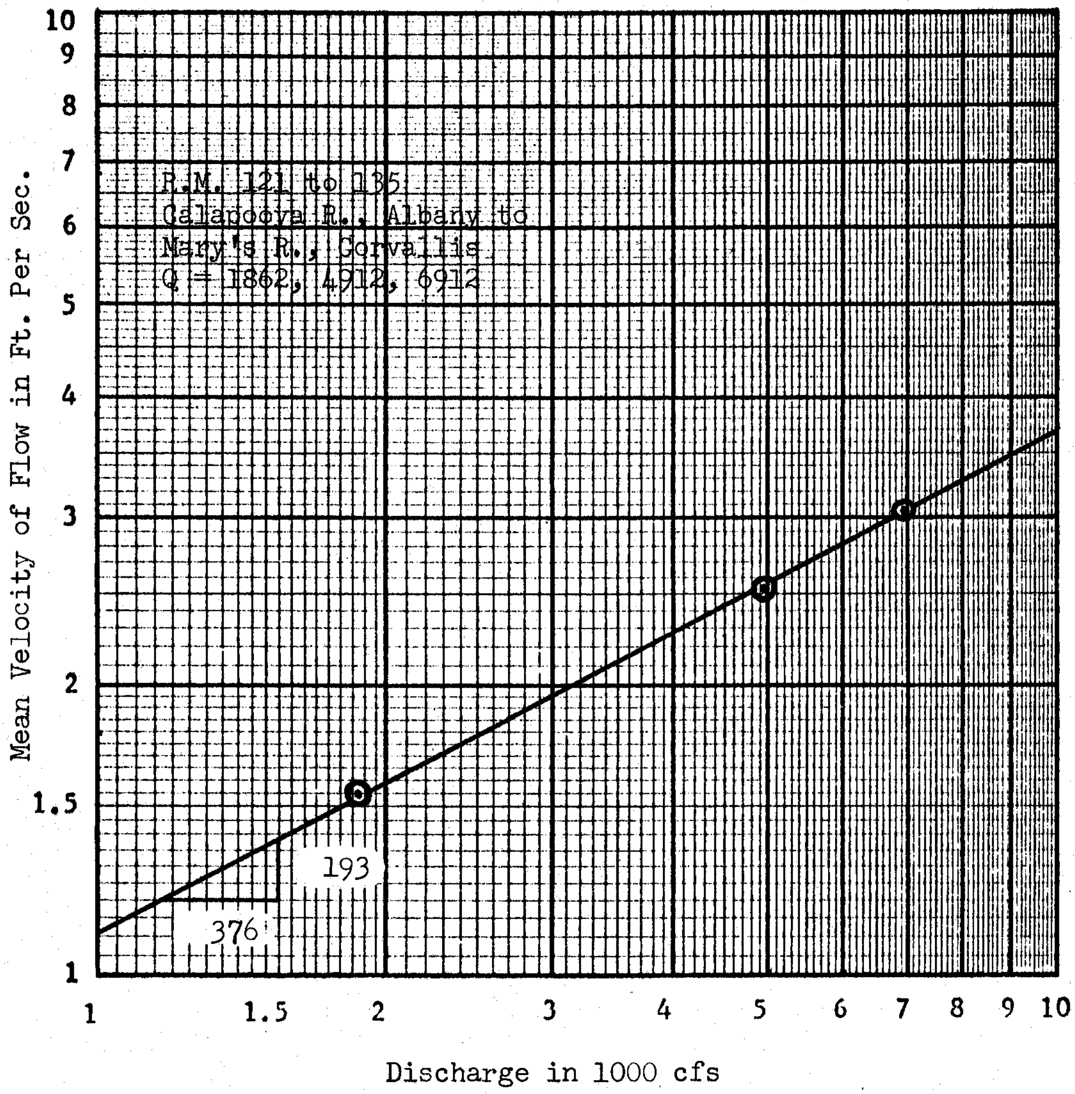
Discharge in 1000 cfs

$$d = \frac{215}{308} = 0.698$$

@ Q = 2200, V = 1.3

$$c = \frac{1.3}{216} = 0.00602$$

So $V = 0.00602\ Q^{0.698}$



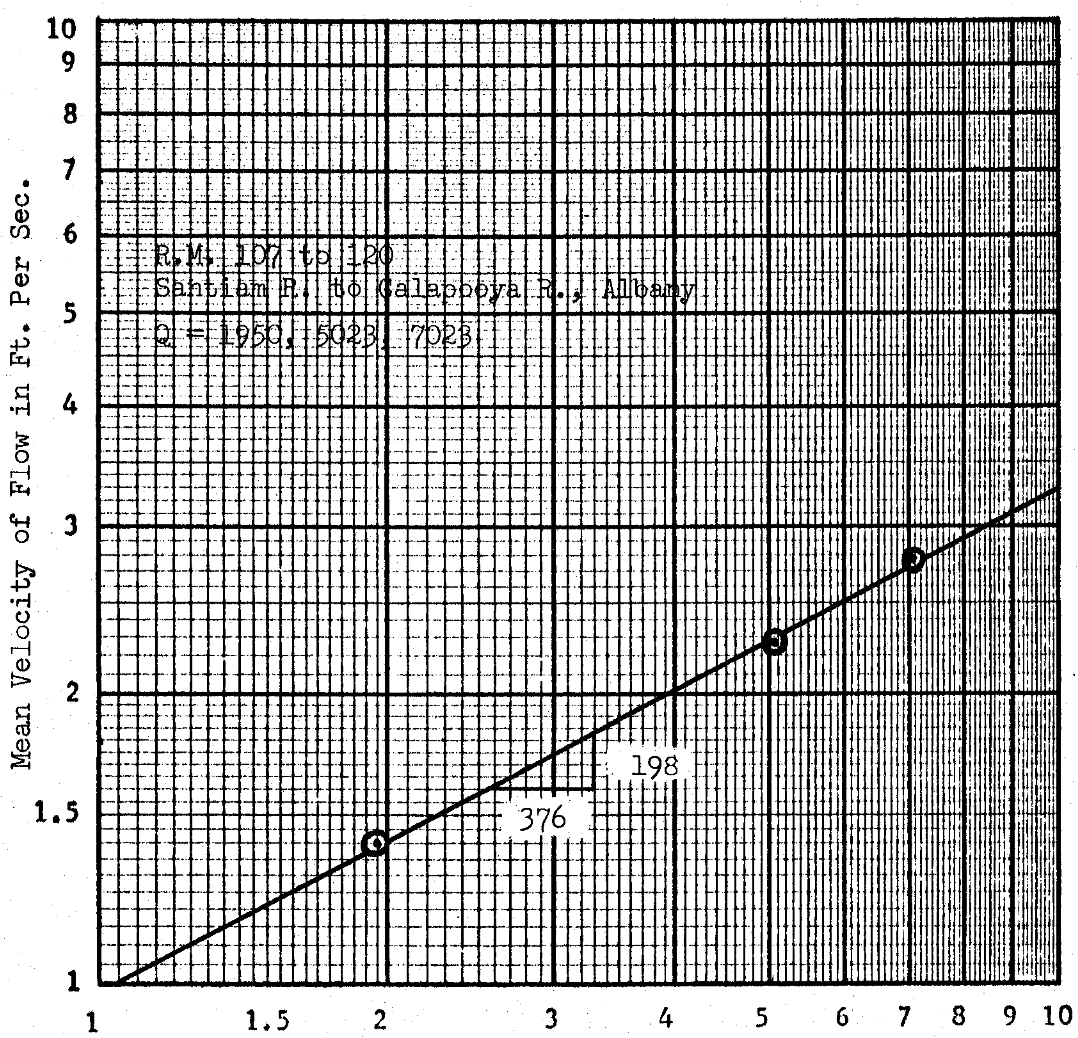
$$d = \frac{193}{376} = 0.513$$

@ Q = 2000, V = 1.6

$$1.6 = cQ^{d}$$

$$c = \frac{1.6}{49.2} = 0.03252$$

So $V = 0.03252\ Q^{0.513}$



Discharge in 1000 cfs

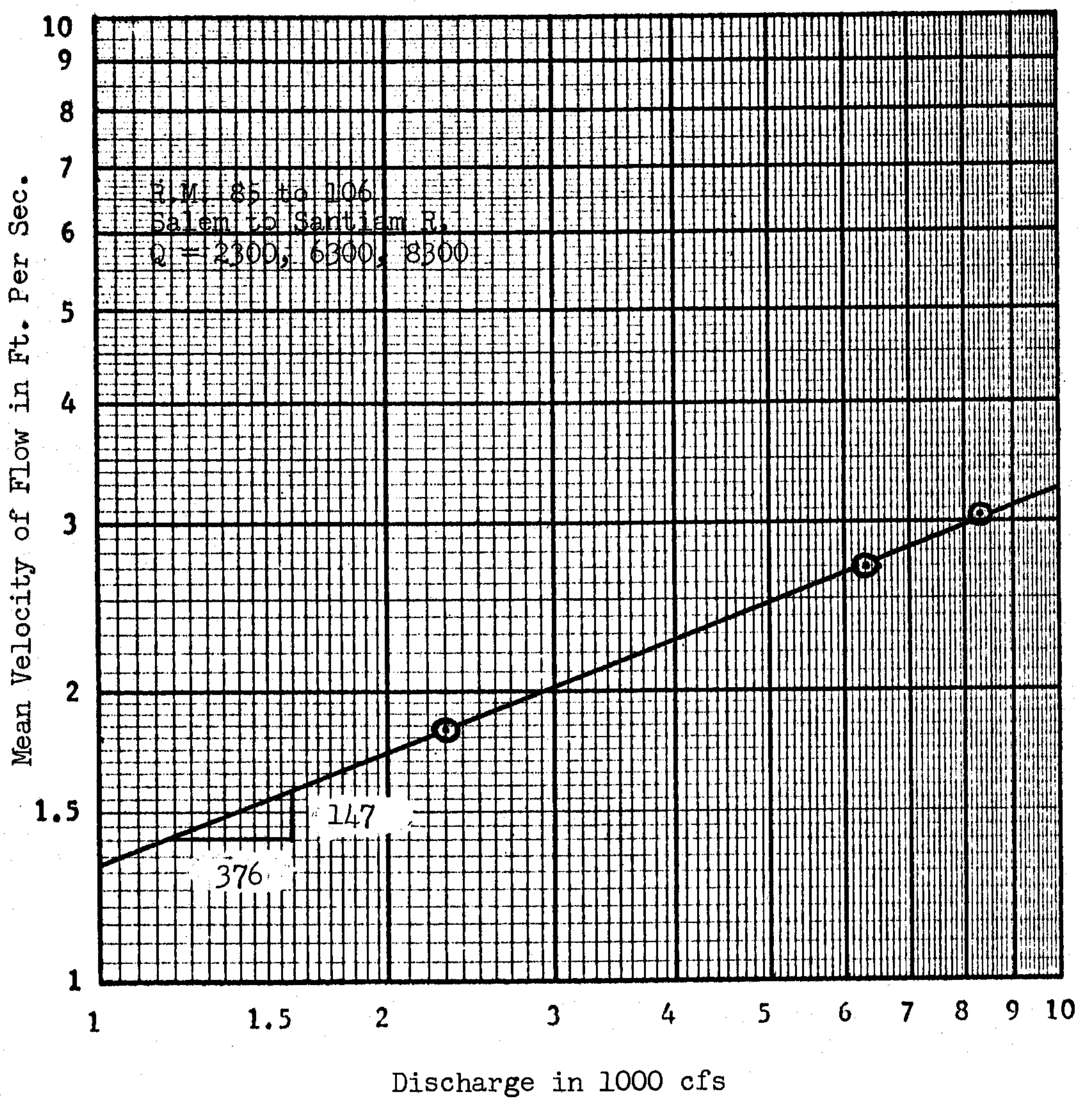
$$d = \frac{198}{376} = 0.527$$

@ Q = 1800, V = 135

$$1.35 = cQ^{d}$$

$$c = \frac{1.35}{52.1} = 0.0259$$

So $V = 0.0259\ Q^{0.527}$



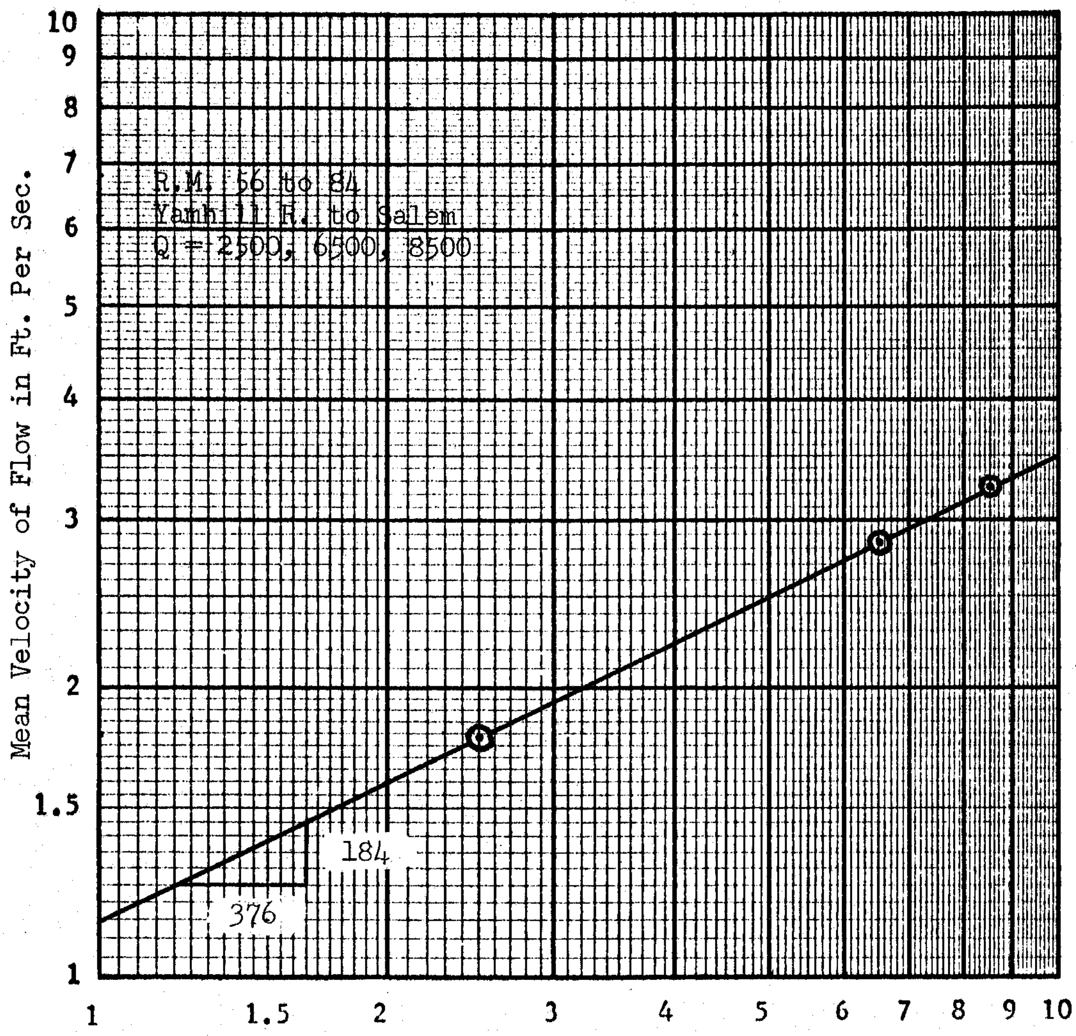
$$d = \frac{147}{376} = 0.391$$

@ Q = 1500, V = 1.55

$$1.55 = cQ^{d}$$

$$d = \frac{1.55}{17.5} = 0.08857$$

$$\text{So } V = 0.08857\ Q^{0.391}$$



Discharge in 1000 cfs

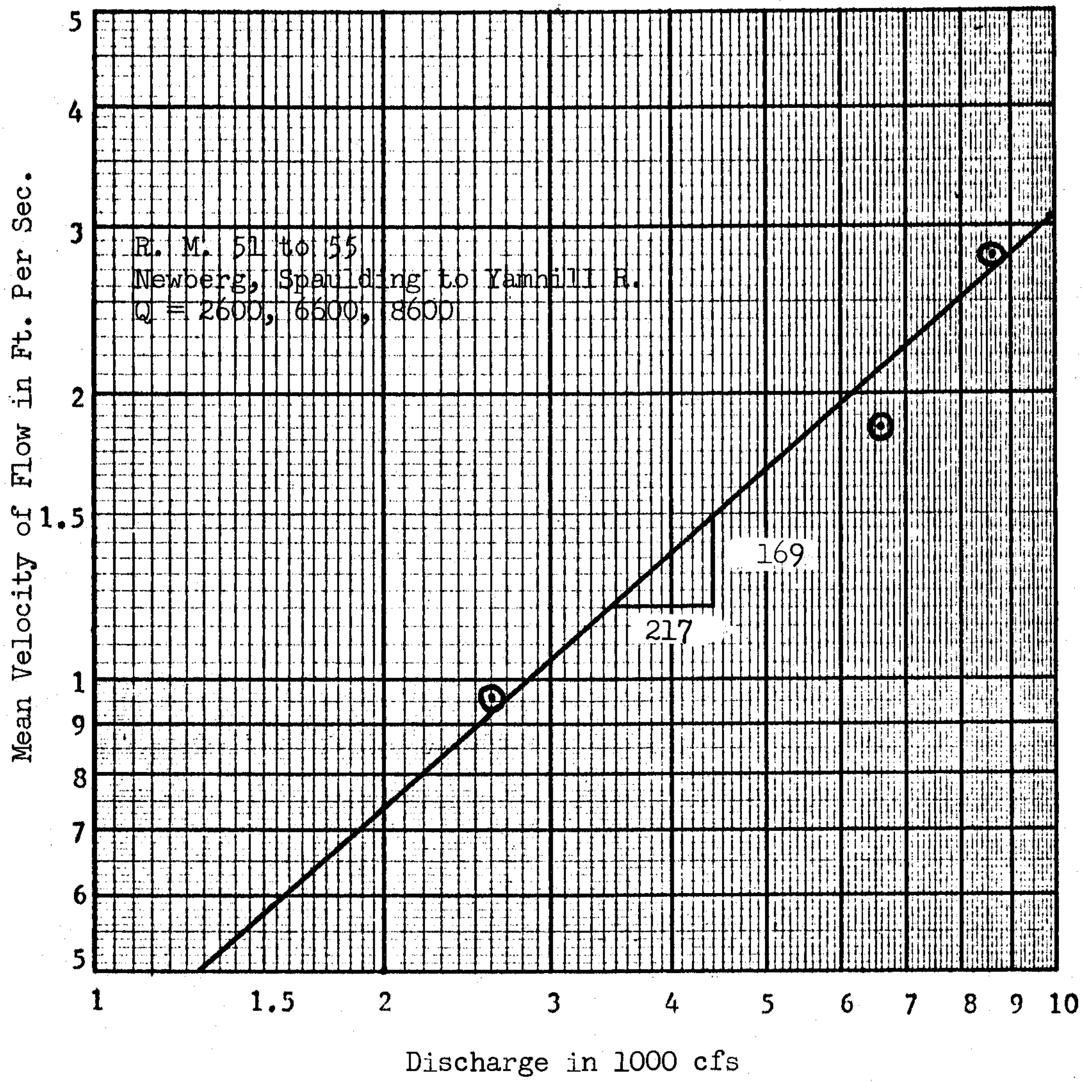
$$d = \frac{184}{376} = 0.489$$

@ Q = 2000, V = 1.6

$$1.6 = cQ^d$$

$$c = \frac{1.6}{41.2} = 0.03883$$

So $V = 0.03883\ Q^{0.489}$



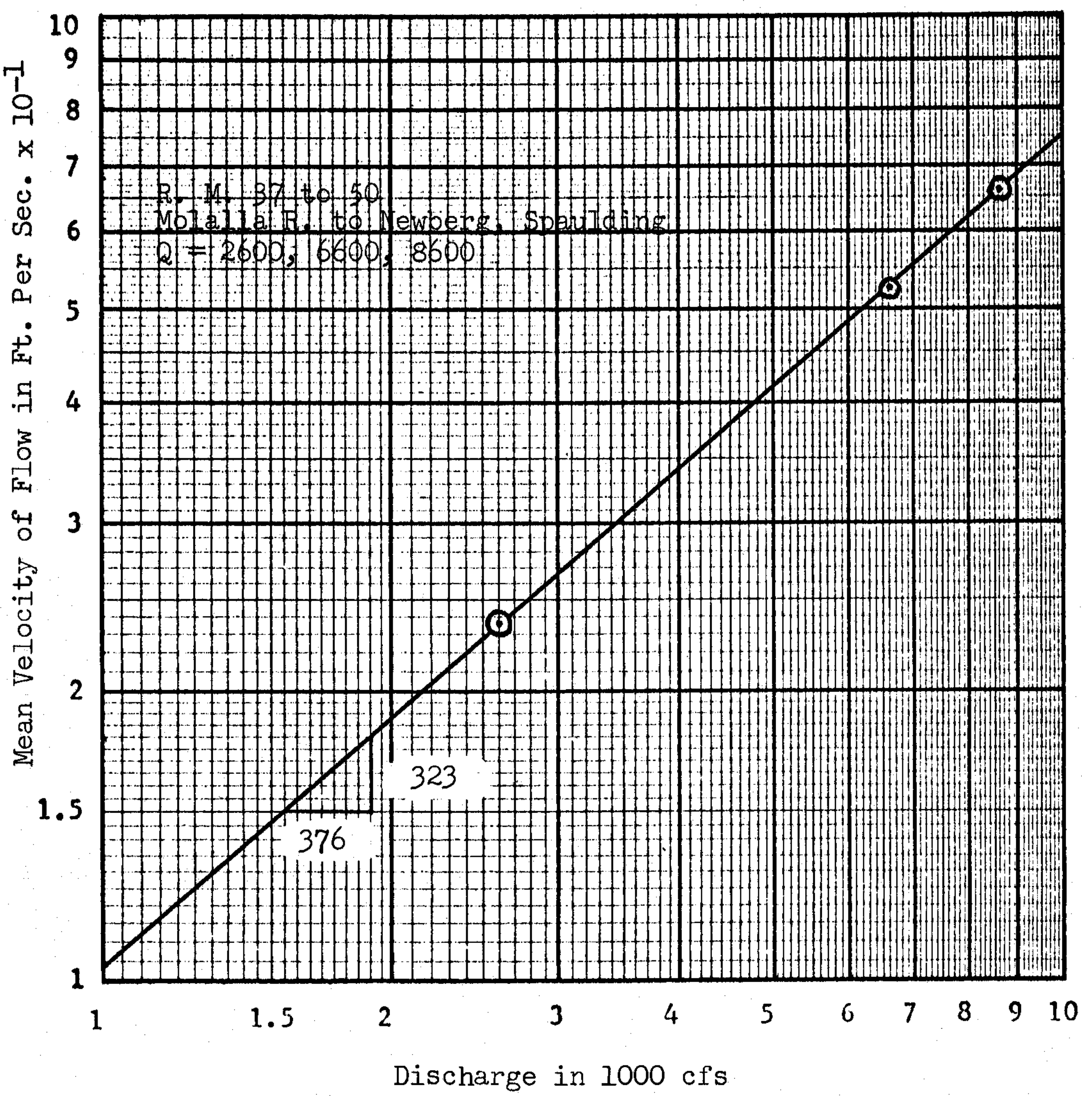
$$d = \frac{169}{217} = 0.779$$

@ Q = 6500, V = 2.0 ft./sec.

$$2.0 = cQ^d$$

$$c = \frac{2.0}{935} = 0.00214$$

So $V = 0.00214\ Q^{0.779}$



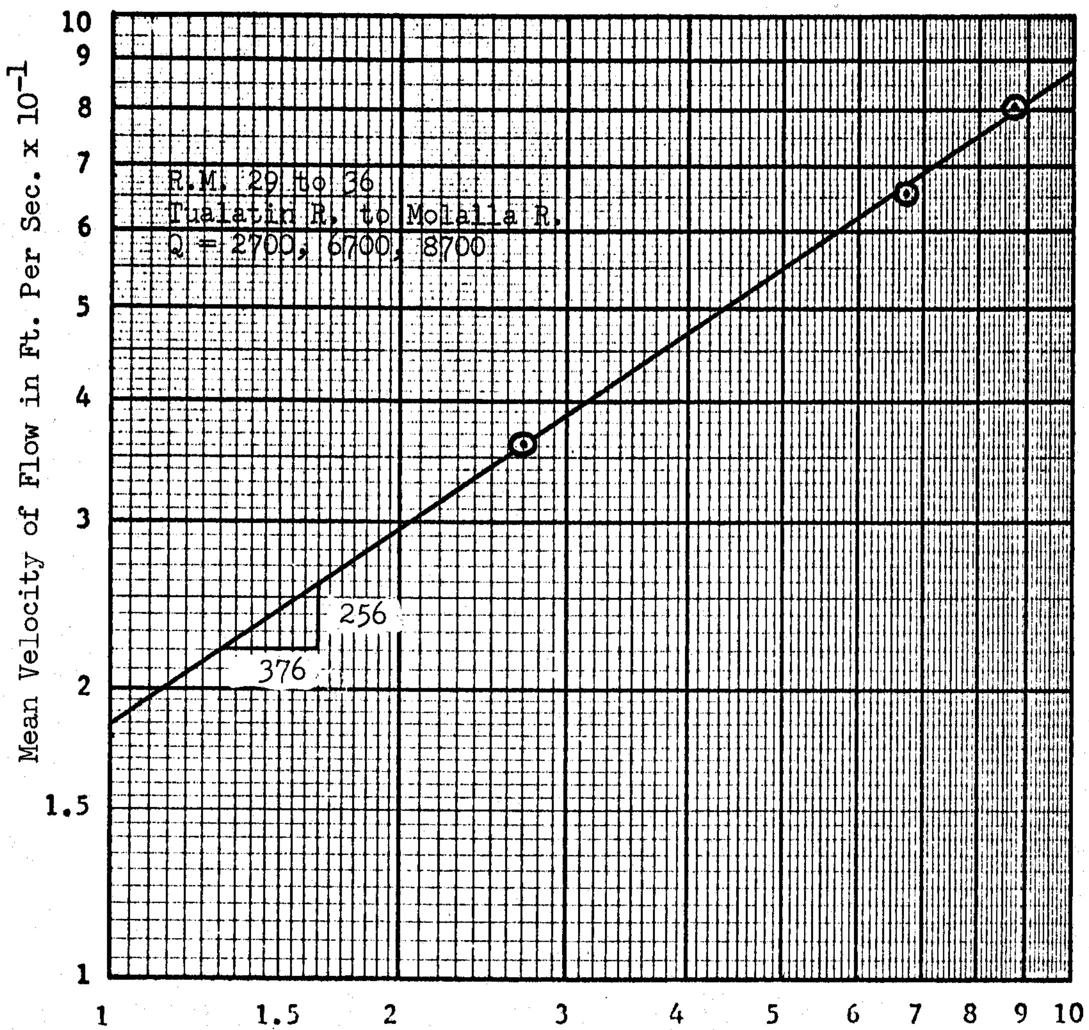
$$d = \frac{323}{376} = 0.859$$

@ Q = 1350, V = 0.135

$$0.135 = cQ^d$$

$$c = \frac{0.135}{490} = 0.0002755$$

So $V = 0.0002755\ Q^{0.859}$



$$d = \frac{256}{376} = 0.681$$

@ Q = 1250, V = 0.215

$$0.215 = cQ^{d}$$

$$c = \frac{0.215}{129} = 0.001666$$

So $V = 0.001666\ Q^{0.681}$