Water and Wastewater Treatment

CALCULATIONS FOR CHEMICAL
AND PHYSICAL PROCESSES

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Michael J. Humenick, Jr.

Department of Civil Engineering
Environmental Health Engineering
College of Engineering
The University of Texas at Austin
Austin, Texas

PREFACE

Solving problems is the basic function of an engineer. In particu-
lar, the performance of calculations may be the task upon which most
of a young engineer's time is spent. Classic textbooks in the field
of water and wastewater treatment devote most of their pages to
development and explanation of theory. Example calculations usually
receive little attention and detail.

It is apparent that there are enough texts in the field which
deal with theory. This book is devoted to the pragmatic idea that
performance and understanding of calculations should have equal
emphasis. Thus, I have written this book dealing only with process
calculations.

The book was conceived initially to bring together material I
wanted to present for a developing graduate course in physical and
chemical treatment. This book is organized wherein a problem is
stated and the solution follows immediately. When a formula is used
or background information may be of interest, adequate references
are cited. The appendix contains a wealth of information such as
physical and chemical properties, conversion factors, and computer
programs. If this book is to be used in coursework, the professor
may either require purchase of an additional text on theory and/or
present theory adequately during lecture periods. Some programs
require theory texts which could be used for more than one course
thus reducing book costs.

This work should be useful to engineers at all stages of their
careers. It has obvious application in formal coursework and in

on-the-job training. It will be useful during individual study for
professional engineer examinations. Also, engineers who are retrain-
ing or require updating in physical and chemical treatment will find
the book to be a good starting point.

  Some of the topics bring together information which probably
has not been accumulated nor presented in one place before. In par-
ticular, the calculations relating to coagulation-flocculation,
activated carbon adsorption, water softening and conditioning using
the Caldwell-Lawrence diagram, and areation should be especially
useful.

         Michael J. Humenick, Jr.
         Austin, Texas
         1977

INTRODUCTION

The equalization chapter solves problems using methods for design of flow and/or concentration equalization basins. Only one method applies to flow equalization and is relatively simple as compared to the several methods for concentration equalization. Problems include the use of a mass diagram, several analytical methods, and a general computer program.

The chapter on coagulation and flocculation proceeds from jar test results and calculations for chemical requirements and sludge production to equipment design. Problems deal with optimization of chemical doses, checking existing operations for conformance to design standards, and adjustment of operating conditions based on required changes in kinetics. Phosphate precipitation is discussed because of its importance in wastewater treatment.

Chemical precipitation, water conditioning and softening are examined starting with the fundamental equilibrium expressions for the carbonate and hardness systems. The use of activities is included. Softening calculations are presented at three increasing levels of accuracy (and difficulty). The calculations procede from stoichiometric methods, to a bar diagram method, and finally to the most accurate method, the Caldwell-Lawrence diagram.

Gravity sedimentation, thickening, and floatation starts with Stokes' Law considerations and procedes to examination of problems involving discrete particles and flocculant suspensions. Design procedures are performed for clarification and thickening of all

types of suspensions including tube settling and dissolved air
floatation.

The filtration chapter includes consideration of granular media,
diatomite, and vacuum filtration calculations. Design calculations
for headloss through the media, expansion and headloss during back-
wash, filter sizing, sand preparation, and underdrain systems are
performed for granular media filters. Laboratory methods and design
data are studied for vacuum filtration applications.

Activated carbon adsorption problems include study of batch and
continuous systems. Determination and use of adsorption isotherms
provide the basis for several problems. Several methods of column
design are presented which correspond to specific types of available
laboratory or full-scale data. Methods such as those proposed by
Fornwalt and Hutchins, Bohart and Adams, plus others are included.

The chapter on ion exchange deals with capacity determination
and design of water softening and demineralization systems. Also,
calculations for ion exchange equilibrium are performed.

In chlorination and disinfection, chlorine chemistry and dis-
infection kinetics are used to solve practical problems. Dosage
calculations, operating conditions, type of residual species are
studied in relation to system design. The effect of pH, tempera-
ture, and concentrations are also related to contact tank design
and performance.

Design of aeration systems is the principal focus for the
chapter on aeration. The problems include consideration of gas
solubility and compression, mass transfer calculations, mixing, and
standard tests to determine design coefficients. Aeration devices
include diffused and surface aeration and the use of pure oxygen.

CONTENTS

EQUALIZATION

PROBLEM 1-1. Determine the minimum size of a basin which provides enough capacity to equalize the flow of wastewater to a treatment plant. A sampling study has been used to establish the design diurnal flow pattern as shown in Fig. 1-1.
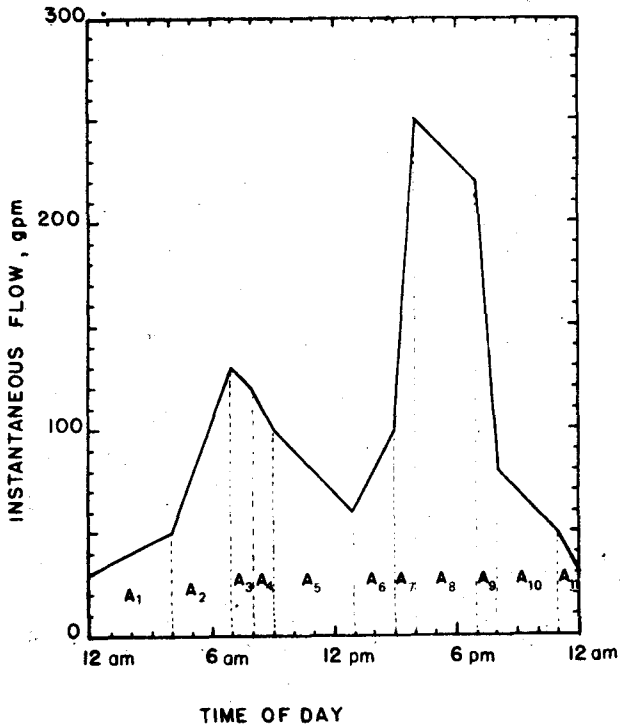

FIG. 1-1. Flow Variation. Problems 1-1 and 1-2.

1

Solution:

1. Determine the total daily volume of wastewater to be treated.

    The total flow is given by the area under the curve in Fig. 1-1:

    Total flow = $A_1 + A_2 + A_3 + \cdots + A_{11}$

    $\quad\quad\quad\quad = (4\ \text{hr})(60\ \text{min/hr})(30\ \text{gpm} + (1/2)(20\ \text{gpm}))$

    $\quad\quad\quad\quad + (3\ \text{hr})(60\ \text{min/hr})(50\ \text{gpm} + (1/2)(80\ \text{pgm})) + \cdots$

    $\quad\quad\quad\quad = 9{,}600 + 16{,}200 + 7{,}500 + \cdots = 146{,}400\ \text{gal}$

    Average flow = $(146{,}400\ \text{gal})/(24\ \text{hr/day})$

    $\quad\quad\quad\quad\quad = 61{,}000\ \text{gpd} = 101.7\ \text{gpm}$

2. Construct the mass diagram as shown in Fig. 1-2.
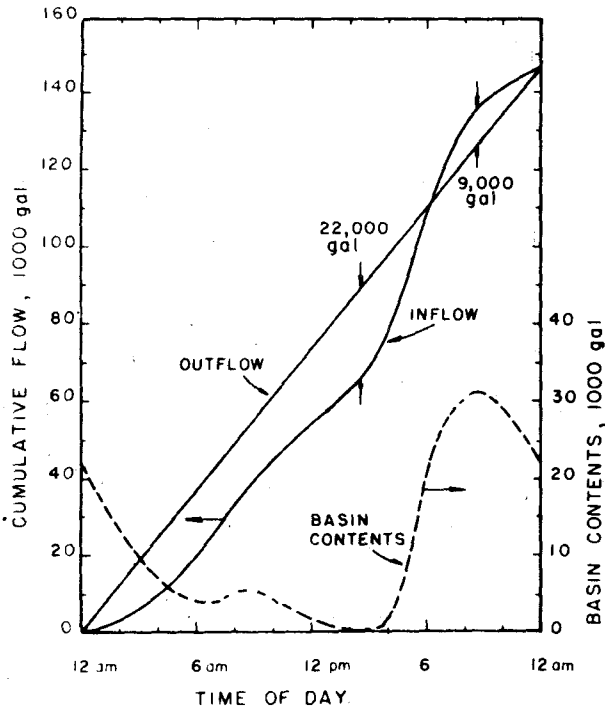

FIG. 1-2.   Mass diagram for cumulative basin inflow, outflow, and
contents.   Problems 1-1 and 1-2.

(a) A straight line from the lower left corner of the diagram to a total flow of 146,400 gal after 24 hr represents the constant rate of equalized flow leaving the basin.

(b) Cumulative inflow to the basin is determined by finding the area under the curve in Fig. 1-1 for the period of calculation. Thus,

Cumulative inflow at 4 am = A_1 = 9,600 gal

Cumulative inflow at 7 am = 25,800 gal = A_1 + A_2

$$= 9,600 + 16,200$$

3. Determine the maximum positive and negative deviations between the cumulative-inflow and cumlative-outflow curves. The sum of these two values equals the minimum required storage. Thus,

Minimum required Volume = 22,000 + 9,000 = 31,000 gal

PROBLEM 1-2. Using the data from Problem 1-1, calculate the amount of wastewater in the basin throughout the day.

Solution:

1. At 12 am, the basin must contain 22,000 gal because by about 2:30 pm the cumulative difference between basin inflow and outflow reaches a maximum of 22,000 gal.

2. The basin contents at any time is equal to the maximum negative deviation from the constant outflow line (22,000 gal) minus the deviation between the outflow and inflow curves. Thus, the dashed line in Fig. 1-2 is obtained:

Volume at 12 pm = 22,000 gal

Volume at 2:30 = 22,000 - 22,000 = 0 gal

Volume at 8:30 pm = 22,000 + 9,000 = 31,000 gal

PROBLEM 1-3. Determine the concentration-time relationship for an
equalization basin of constant volume, having a constant influent
rate and an influent concentration variation given by the function

$$C_1 = \overline{C}_1 + k\overline{C}_1 \sin \omega t \tag{1-1}$$

where C_1 is the influent concentration at time t, $\overline{C}_1$ is the average
influent concentration, k is a constant, the product $k\overline{C}_1$ is the
maximum influent concentration, and ω is equal to $2\pi/T$, where T is
the period for one cycle of the sine function. Assume that the
basin is completely mixed.

Solution:

1. The system may be represented as
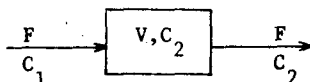
    Here C is a conservative material, F is the constant influent
    and effluent rate, and C_1 and C_2 are the influent and con-
    centrations, respectively. V is the basin volume.

2. A mass balance on the conservative material is

              Rate of accumulation = rate in − rate out

$$V(dC_2/dt) = FC_1 - FC_2 \tag{1-2}$$

3. Substituting the expression for C_1 and applying the boundary
    condition t = 0, $C_2 = \overline{C}_1$, the solution of Eq. (1-2) is

$$C_2/\overline{C}_1 = 1 + [k\tau\omega/(1 + \tau^2\omega^2)]e^{-t/\rho}$$
$$+ k \sin(\omega t - y)/(1 + \tau^2\omega^2)^{1/2} \tag{1-3}$$

    where $\tau = V/F$ and $y = \tan^{-1}\omega\tau$. As seen in Eq. (1-3), the solu-
    tion consists of transient and steady-state terms. For a con-
    tinuous system, the transient portion of the solution may be

neglected so that the basin performance is given by

$$C_2/\bar{C}_1 = 1 + k \sin(\omega t - y)/(1 + \tau^2\omega^2)^{1/2} \qquad (1\text{-}4)$$

PROBLEM 1-4. Use Eq. (1-4) to calculate the steady-state, maximum effluent concentration from a equalization basin with a detention period of 8 hr. The influent concentration varies according to the Eq. (1-1), where k = 0.7 and T = 12 hr.

Solution:

1. The maximum effluent concentration occurs when $\sin(\omega t - y) = 1$. Thus,

$$C_{2_{max}} = \bar{C}_1(1 + k/(1 + \tau^2\omega^2)^{1/2})$$

$$C_{2_{max}}/\bar{C}_1 = 1 + (0.7)/(1 + (8)^2(2\pi/12)^2)^{1/2}$$

$$= 1.162 \qquad (1\text{-}5)$$

Thus, the equalization basin has damped the peak influent con-centration from 70 percent greater than the average down to 16.2 percent of the average for the effluent concentration.

PROBLEM 1-5. Determine the effluent COD concentration from a constant volume, constant flow equalization basin using the influent concentration data given below and the method of Reynolds, et al. [1]. Basin detention period is 3 hr, and assume the initial basin COD is 500 mg/l.

Solution:

1. The equation to be solved is

$$C_{2_{t+\Delta t}} = C_{1_t}(1 - e^{-\Delta t/\tau}) + C_{2_t} e^{-\Delta t/\tau} \qquad (1\text{-}6)$$

where $C_{2_{t+\Delta t}}$ is the basin concentration after addition of the

flow for time Δt and with concentration C_{1_t}. C_{1_t} is the influent
concentration averaged over Δt, Δt is the time increment for
iterative calculations, and C_{2_t} is the basin concentration be-
fore addition of flow at concentration $\dot{C}_t$. τ is the basin
detention period.

2. The following data are values of COD for the influent at 30-min
   intervals: 435, 560, 510, 475, 500, 450, 425, 410, 515, 550,
   600, 610, 450, 300, 375, 350, 310, 480, 450, 400, 390, 330, 340,
   320, 370, 450, 525, 510, 570, 630, 600, 550, 650, 675, 530, 350,
   285, 240, 310, 375, 440, 410, 490, 445, 580, 715, 620, 655.

3. The method of calculation is an iterative procedure where C_2 is
   calculated for each time increment. Because the data are given
   in 30-min intervals, it is convenient to use $\Delta t = 30$ min.

4. With Δt and τ fixed, Eq. (1-6) is simplified to

$$e^{-\Delta t/\tau} = 3^{-30/(3)(60)} = 0.846$$

$$C_{2_{t+\Delta t}} = 0.1535C_{1_t} + 0.846C_{2_t} \qquad (1\text{-}7)$$

5. An example calculation of one iteration and a short table for
   some of the data follow. Remember that C_{1_t} is the average con-
   centration over t.

   (a) C_2 at 30 min $= 0.1535(435 + 560)/2 + (0.856)(500) =$
        499.6 mg/l

   (b) A summary of some iterations is given in the accompanying
        table.

PROBLEM 1-6. The mean influent concentration for the data of Prob-
lem 1-5 was 469 mg/l COD. Size an equalization basin so that the
effluent concentration is within 50 mg/l of the mean concentration
90 percent of the time. Use the method of Danckwerts and Sellers [2].

Problem 1-5 Data

t, min	C_1, mg/1	C_{1_t}	$C_{2_{t+\Delta t}}$
0	435		500.0
30	560	497.5	499.6
60	510	535.0	505.0
90	475	492.5	503.1
120	500	487.5	500.7
150	450	475	496.8

1. The equation to be solved is

$$\sigma_2^2/\sigma_1^2 = 1/\tau \int_0^\infty e^{-r/\tau} \; R(r) \; dr \qquad (1-8)$$

where σ_2^2 is the variance of the effluent concentration, σ_1^2 is
the variance of the influent concentration, τ is the basin
detention period, r is the lag time, and $R(r)$ is the auto-
correlation coefficient for the influent data which is defined
by

$$R(r) = \overline{(C_1 - \overline{C}_1)_t (C_1 - \overline{C}_1)_{t+r}} \; / \; \sigma_1^2 \qquad (1-9)$$

where $\overline{C}_1$ is the average influent concentration and the numerator
is the average value of the product of the deviations from the
average concentration separated by the time lag r.

2. Equation (1-8) can be evaluated graphically or analytically after
$R(r)$ is found. The following is a simple method to calculate
$R(r)$ as a function of r (a computer program for this method is
listed in the Appendix C).

(a) Find $C_1 - \overline{C}_1$ at uniform intervals of time, Δt, and label
     them d_1, d_2, etc.

(b) Find the differences, $D_1 = (d_1 - d_2)$; the differences of
     $D_2 = (d_2 - d_3)$, etc. Square each difference and add,
     giving ΣD^2.

(c) Find the sum $S_1 = (d_1 + d_2)$; the sum $S_2 = (d_2 + d_3)$; etc.
     Square each sum and add, giving ΣS^2.

(d) Now, the value of $R(r)$ at $r = \Delta t$ is

$$R(r) = \frac{\Sigma S^2 - \Sigma D^2}{\Sigma S^2 + \Sigma D^2} \qquad (1\text{-}10)$$

(e) To find $R(r)$ at other values of r, such as for $r = 2\Delta t$,
     find the sums $(d_1 + d_3)$, $(d_2 + d_4)$, etc.

3. It is advisable to use the computer program in Appendix C to
    calculate $R(r)$ for any significant amount of data. The method
    requires that the length of record for data should be about 10
    times the time-scale of the problem. Also, about 80 samples are
    the minimum and 150 the desirable number of samples to charac-
    terize the waste [3,4].

4. The accompanying table gives the results of calculating $R(r)$
    from the data given in Problem 1-5. A plot of $R(r)$ versus r
    is also shown in Fig. 1-3.

5. To evaluate Eq. (1-8), Fig. 1-3 may be graphically integrated
    or analytical expressions may be fitted to portions of the
    curve, and Eq. (1-8) then solved explicitly. Figure 1-4 shows
    how straight lines may be used to approximate the shape of
    Fig. 1-3.

6. Figure 1-5 shows the results of integrating Eq. (1-8) using the
    straight lines from Fig. 1-4.

7. If the effluent concentration must vary between $\pm$ 50 mg/l about
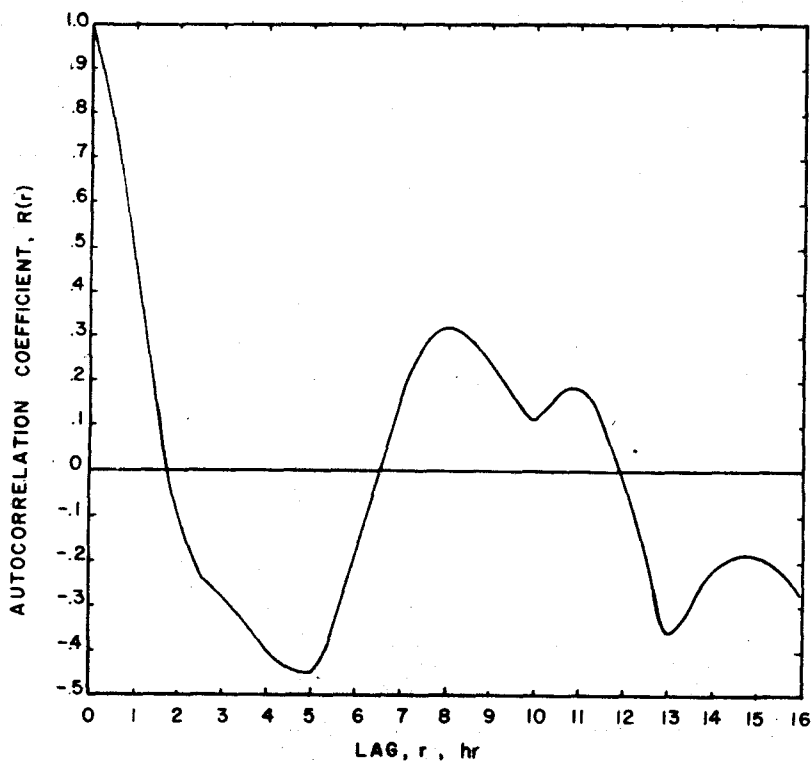   the mean value of 469 mg/l COD 90 percent of the time; by

Fig. 1-3.   Autocorrelation coefficient, R(r), vs r.   Problem 1-6.
Problem 1-6 Data

r, min	R(r)	r, min	R(r)
30	0.760	420	0.159
60	0.459	480	0.316
90	0.175	540	0.225
120	−0.113	600	0.114
180	−0.286	660	0.186
240	−0.402	720	−0.021
300	−0.446	780	−0.361
360	−0.162	840	−0.206

Oscillation of R(r) at larger values of r indicates that the
data are periodic rather than random.

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